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# Renewable Energy Production from Energy Crops and Agricultural Residues

Edited by
Luigi Pari

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Editor

**Luigi Pari**

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*Editor*
Luigi Pari
Council for Agricultural
Research and Economics,
Research Center for Engineering
and Agro-Food Processing (CREA-IT)
Italy

*Editorial Office*
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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Cover image courtesy of Luigi Pari.

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# About the Editor

**Luigi Pari** graduated in Agricultural Sciences and earned a PhD in Agricultural Engineering at the University of Bologna. In 1989, he became a researcher at the CREA IT “Consiglio per la ricerca in agricoltura e l’analisi dell’economia agraria, Centro per l’Ingegneria e Trasformazioni Agroalimentari” in Monterotondo, Italy. His primary field of work regards the development and optimization of energy crops and agroforestry residual biomass supply chains through the evaluation of commercial machineries. He is also focused on designing innovative solutions for the harvest, storage, and logistics for herbaceous energy crops (e.g., arundo donax, cynara cardunculus, fiber and sweet sorghum, canola) and forestry (e.g., poplar, eucalyptus, black locust), yet also tropical species (Jatropha curcas, dischrostachys cinerea) and fiber crops. He has also applied his knowledge acquired in developing countries through FAO and EU projects in Africa, Asia, and Latin America. He played the role of General Coordinator in 5 research projects and the role of Scientific Responsible in 40 research projects, both funded by the European Union. He designed and built around 20 prototypes of agricultural equipment for harvesting biomass crops, and he is the inventor of 7 patents. Moreover, he is a lecturer in different training, Doctoral, and Master’s courses. He is also a scientific evaluator for research projects in the European Community, Ministry of Agriculture, and the Tuscany Region, in addition to serving as a reviewer of scientific papers presented at the international journal *Biomass and Bioenergy*. He has also been a reviewer for and the World Conferences and Technology Exhibition on Biomass for Energy, the Journal of Biomass and Bioenergy, and the Journal of Applied Engineering in Agriculture (ASABE). He has participated in International and National Scientific Committees and Study Groups, was chairman at international conferences, is a member of the scientific committee of international conferences, and is the author of about 430 scientific publications.

# Preface to ”Renewable Energy Production from Energy Crops and Agricultural Residues”

The Special Issue ”Renewable Energy Production from Energy Crops and Agricultural Residues” had a replay from researchers all over the world. The latest findings were reported on cultivation, harvesting, storage, and transformation of relevant agricultural and forestry energy crops and agricultural residues.

An innovative approach was applied to energy crops and agricultural residues such as evaluation of the supply chain through GIS methodology, integrated logistic centers, land/crop availability, LCA, and carbon balance.

Among energy crops, both herbaceous (i.e., Camelina (2 papers), Crambe, and Miscanthus) and woody (i.e., Jatropha Curcas, Poplar, Eucalyptus (2 papers), Pine, and Willow (3 papers)) were deeply evaluated. Among agricultural residual biomass, research on straw, olive pruning (3 papers), cereal chaff, and maize cob were reported.

This Special Issue had the possibility to describe the state-of-the-art of ongoing research on energy crop and agricultural residues topics.

**Luigi Pari**
*Editor*

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Article

# An Innovative System for Maize Cob and Wheat Chaff Harvesting: Simultaneous Grain and Residues Collection

**Simone Bergonzoli [1], Alessandro Suardi [2,*], Negar Rezaie [2], Vincenzo Alfano [2] and Luigi Pari [2]**

1 Consiglio per la Ricerca in Agricotura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, 24047 Milan, Italy; simone.bergonzoli@crea.gov.it

2 Consiglio per la Ricerca in Agricotura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, 00015 Rome, Italy; negar.rezaei@crea.gov.it (N.R.); vincenzo.alfano@crea.gov.it (V.A.); luigi.pari@crea.gov.it (L.P.)

* Correspondence: alessandro.suardi@crea.gov.it

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**Abstract:** Maize and wheat are two of the most widespread crops worldwide because of their high yield and importance for food, chemical purposes and livestock feed. Some of the residues of these crops (i.e., maize cob and wheat chaff) remain in the field after grain harvesting. In Europe, just maize cob and grain chaff could provide an annual potential biomass of 9.6 Mt and 54.8 Mt, respectively. Collecting such a biomass could be of interest for bioenergy production and could increase farmers' income. Progress in harvest technology plays a key role in turning untapped by-products into valuable feedstocks. This article presents a study of the performance and the quality of the work of Harcob, an innovative system developed for maize cob collection. Furthermore, the feasibility of using the Harcob system to also harvest wheat chaff during wheat harvesting was also verified. The results showed that it was possible to harvest 1.72 t $ha^{-1}$ and 0.67 t $ha^{-1}$ of cob and chaff, respectively, without affecting the harvesting performance of the combine. The profit achievable from harvesting the corn cob was around 4%, while no significant economic benefits were observed during the harvesting of wheat chaff with the Harcob system. The use of cereal by-products for energy purposes may allow the reduction of $CO_2$ from fossil fuel between 0.7 to 2.2 t $CO_2$ $ha^{-1}$. The Harcob system resulted suitable to harvest such different and high potential crop by-products and may represent a solution for farmers investing in the bioenergy production chain.

**Keywords:** bioenergy; crop by-products; harvesting methods; maize cob; wheat chaff; combine harvesting

## 1. Introduction

Bioenergy plays a significant role in climate change mitigation [1] by replacing fossil fuels for energy production. The agricultural sector is one of the main suppliers of biomass through planting specific bioenergy crops or using cropland residues [2]. This component of crop is constituted by the non-edible plant parts that are not collected and usually left on the field [3]. Considering the European Renewable Energy Directive (RED II, directive 2018/2001/EU), the advantages of using agricultural residues for energy production are, on the one hand, the non-need for additional land and the non-competition with the food industry, and on the other hand to turn an untapped product with a disposal cost, into an economic advantage for farmers. Hence, bioenergy is a tool to improve the economic and environmental sustainability of agricultural sector. A potential source of biomass is represented by the residues of wheat, spelt (Triticum ssp., L.), and maize (Zea mays L.) [4,5]. Indeed, the EU-28 produced yearly 152 Mt wheat and spelt [6], and chaff, a heterogeneous mixture of glumes, dust, short straw pieces, broken grain seeds, and weed seeds represents a potential biomass of 38 Mt year$^{-1}$. Considering the lowest heating value of chaff of 15.1 MJ kg$^{-1}$ [7], and the removal rate of 0.33, for a stable soil balance [8], it is possible to estimate a theoretical energy availability of 191 PJ year$^{-1}$ [9]. In EU-28 more than 9 Mha of grain maize are cultivated yearly [10]. Considering an average yield of 1.7 t ha$^{-1}$ of cobs [11], and a net calorific value of 18.4 MJ kg$^{-1}$ [11], from corn cobs alone an amount of energy of 281 PJ year$^{-1}$ could be produced. Moreover, maize cobs have favorable properties, such as high calorific value and low ash content [12]. It is important to reiterate that the impact on soil nutrients and organic matter, and consequently on the of productivity levels should be considered in the planning of residue removal [13]. However, although a relationship between the amount of residue maintained on the soil and the soil organic matter (SOM) was found in previous studies [14,15]. due to the low nutrient content in cobs and wheat chaff, their removal is considered unlikely to affect soil fertility [9,12].

Turning residues into a valuable feedstock mainly depends on technological advances of harvesting techniques [12]. In some European regions, there are no markets or is it convenient to collect and use chaff and cob residues, and e on-field spreading or on-field burning are the most common methods to dispose them of, which is environmentally unsustainable [16]. Currently, only maize stalks and wheat straw, after grain harvesting, are cut, windrowed, baled, and brought to a storage site [17]. The maize cobs are rarely used for bioenergy purpose, because of the collecting difficulties and costs as well as for the chaff that remains below the straw and cannot be collected by the baler. The development of one-pass harvest equipment, able to manage corn grain as well as cobs, and possibly capable of collecting other residues such as wheat chaff, could reduce the number of field work operations and cost of collecting feedstocks [18].

The most complex aspect is to separate the cobs from the grain without affecting the harvesting efficiency of the combine. There are two main harvesting methods currently possible: the collection of whole corn cobs, with separation of the fractions on the farm, or the separation of the two fractions, grain and cobs, directly in the field during harvesting. In the first case, the grain and cobs must be separated at farm level using specific sheller machines [19]. On the other hand, the method of separating the two fractions directly during harvesting uses pneumatic and/or physical means to separate and convey the cobs and maize grain into two separate containers and expel the rest of the residues in the field. The maize cobs can be collected either in a cart pulled by the combine harvester or in a hopper mounted on the combine. In general, one-pass cob collection needs less equipment, work and passes over the field than other methods, even less if no wagon is required. Less field passes of the machines also result in less soil compaction, which is known to negatively affect soil productivity. This aspect represents an advantage due to the absence of contaminants such as dirt and rocks in the harvested cobs and its properties that make it suitable for bioenergy [20]. A substantial impulse to use cob for bioenergy can be represented by Harcob, a new harvesting system, developed by the Italian company Agricinque of Racca group (Marene, CN, Italy). The system consists of a device to separate maize cobs and from the other residues (leaves, stem, culm, etc.) and an additional tank (9 m$^3$) for storing collected materials. The system is patented and already commerciallized, but the use of this machine to harvest wheat chaff is not yet well developed. In Europe, there is currently no established practice to collect chaff during harvesting, even if there are already technologies developed for its baling together with straw, or separating it as a bulk product [21]. The collection and removal of chaff also represents an herbicide-free weed management technique, as chaff contains most of the harvested weed seeds. Chaff collection can prevent the weed seeds from entering the soil and reduce the spread of weed patches.

The purposes of the trial reported here were: (1) to evaluate the operating parameters of the Harcob system, the quality and effectiveness of its work during cob harvesting, (2) to verify the possibility of using the same combine harvester to gather wheat chaff (although it was developed to harvest the maize cob) with a new configuration. Moreover, an economic analysis of the harvesting of the two crop by-products was also performed. This approach will foster the utilization of two untapped biomass sources simplify the harvesting and reducing its cost.

## 2. Materials and Methods

### 2.1. Study Site

The study was conducted in October 2018 and July 2019 in the Northern Italy at Revello (44.709920 N and 7.435711 E), Cuneo province, for the harvesting of maize cob and wheat chaff, respectively. The farm is oriented to dairy farming and has a biogas power plant of 250 kWe fed by cow manure and litter, and maize residues (cob and stalks).

### 2.2. HarvestingSystem Harcob

The test was carried out using a modified axial-flow combine harvester (Axial-flow 7130; Case IH, Racine, WI, USA), capable of harvesting separately the maize grains and threshed cobs. The combine was equipped with a specific cob harvesting device, comprising a threshing and separation system, a dedicated cob tank and an unloading device (Figure 1).

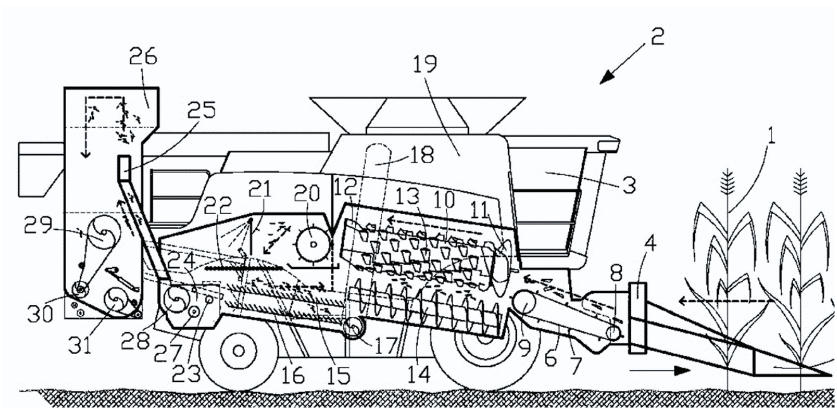


**Figure 1.** Scheme of the Harcob system for harvesting cobs applied to an axial combine harvester. Reproduced from patent n. EP2668838B1, Racca G. and Racca S. (Current Assignee: Gruppo Racca Srl.)-European Patent Office: 2012.

Crop residues (cob and chaff) are discharged at the distal end of the sieve, at the end of the traditional trashing system of the combine, directly on a transversal auger which feeds a system for chipping the biomass and pneumatically conveying the chips into a duct that terminates in the upper portion of a container arranged on the rear part of the machine. Three augers driven in rotation by hydraulic motors are arranged in the cylindrical container, of which: an auger in the central portion and a lower auger for continuously mixing chips to prevent them from compacting, thus making discharge faster; and a vertical auger that takes the product from the bottom of the container and conveys it upwards for it to be collected. The cob and the chaff are stored till are unloaded with an innovative auger system ensuring no blocking problems and allowing the discharging of cob (as well as chaff) and grain at the same time.

### 2.3. Pre-harvesting Activities

Both maize cob and wheat chaff harvesting tests were carried out following the same data collection methodology. Each test was performed in three blocks (replicates), belonging to the same field, of about 0.5 ha each. The combine harvester during the harvesting of maize and wheat has been set according to Table 1:

**Table 1.** Axial Flow combine harvester (CASE IH Axial Flow 7088, Racine, WI, USA) settings used during harvesting of maize and wheat.

| Crop | Wheat | Maize |
|---|---|---|
| Rotor Speed (rpm) | 750 | |
| Gap between Rotor and Separator (mm) | 15 | 20 |
| Cleaning Fan Speed (rpm) | 540 | |
| Spreader Speed (rpm) | 560 | |
| Openings of Upper Sieve (mm) | 17 | 12 |
| Openings of Lower Sieve (mm) | 14 | 9 |

Furthermore, before starting the wheat harvesting test the combine was modified as follows: the maize sieve (41 mm) was changed according to the dimension of the wheat seeds (28 mm). The crushing elements (knives) of the beating cylinder were also changed (Figure 2).

**Figure 2.** Knives for harvesting wheat chaff (**left**) and maize cob (**right**).

The modification must be view as an adaptation of the harvesting system to the different crop.

Pre-harvesting measurements were performed to determine plant characteristics, the total biomass available and the dry matter content in the different plant fractions (seeds, chaff/cob and straw). The pre-harvesting activities were the following:

- Ten sample areas (1 $m^2$ each) randomly chosen, corresponding to 10 $m^2$ in total, were hand harvested. The sample plot was chosen far from the edges to avoid the overestimation due to the "edge effect". The plants from the sampling areas were collected as whole plants from the ground level.

- Plants of each sample area were weighed directly in field using a precision scale.

Pre-harvesting data were necessary to determine the total potential biomass available, the amount of biomass losses due to cut height (stubble), and the harvesting losses when the harvesting stage was completed. Wheat and maize ears of each sample area were bagged and shipped to CREA institute in order to determine the single fractions using the laboratory thresher (PLOT 2375 Thresher, Cicoria Company, San Gervasio, Italy).

Three samples of grain, chaff/cob and straw were randomly collected in each experimental field, weighed and stored into vacuum-packs to measure the moisture content. Biomass moisture content (MC) was determined according to ISO 18134-2:2017 [22]. The bulk densities (kg $m^{-3}$) of the loose biomass of the cob/chaff stored in the Harcob tank was assessed by taking 10 randomly selected samples and was measured according to ISO 17828:2015 [23].

### 2.3.1. Harvesting System Productivity

The biomass remaining in the stubble was assessed by measuring the average cut height that was evaluated by measuring 100 random cut heights transversally to the field for each block. The working time study was performed according to the Comité International d'Organisation Scientifique du Travail en Agriculture (CIOSTA) methodology and the recommendations from the Italian Society of Agricultural Engineering (A.I.I.A.) 3A R1 [24]. Harvested areas were measured as well as the machines' operation time, and yield obtained per each experimental field during the harvesting tests in order to calculate the theoretical field capacity (TFC, ha $h^{-1}$), the effective field capacity (EFC, ha $h^{-1}$) of the equipment used and their field efficiency (FE, %) and material capacity (MC, Mg $h^{-1}$).

The field capacity corresponds to the number of hectares that can be harvested per hour and its measurement is used to schedule field operations, labor, power units, and to assess machine operating costs. The effective field capacity (EFC) of a machine in the field was calculated by dividing the hectare completed by the hours of actual field time. TFC depends only on the full operating width of the machine and the average travel speed in the field representing the maximum possible FC that can be obtained at the given field speed and full operating width of the machine is being utilized. EFC is less than TFC as a result of the various delays that may occur in the field during the work. The ratio of EFC to TFC represent the machine's FE.

FE is expressed as the percentage of a machine's TFC actually achieved under real conditions. It accounts for overlapping (failure to utilize the full operating width of the machine) and many other time delays like emptying grain and residues, traveling, turning, refilling the fuel tank, making adjustments, waiting for trucks and stops for the operator to rest. Other idle times due to activities that occur outside the field, such as travel to and from the field, major repairs or daily service, are not included in FE measurement.

The MC of harvesting machines is often measured by the quantity of material harvested per hour (t $h^{-1}$). It is obtained multiplying the machine's EFC and the average yield of crop per hectare.

Fuel consumption was recorded by using the measuring system of the combine harvester.

### 2.3.2. Harvesting Lost Calculation and Statistical Analysis

Grain and residues of both maize and wheat were harvested per each block and weighed separately in the farm scale by using different trailers. After wheat straw baling, the bales produced from each experimental block were weighed. The biomass losses were assessed differently for wheat chaff and maize cob.

Concerning wheat chaff, losses were measured by knowing the total biomass available in the field (assessed during the pre-harvesting stage), the biomass left in the field due to the cut height (assessed during post-harvesting stage) and the grain and by-product harvested and baled, employing the following formula:

$$\text{Harvesting losses (t ha}^{-1}) = \text{Rph} - \text{Se} - \text{St} - \text{B} - \text{T} \quad (1)$$

where Rph = Total amount of biomass assessed in pre-harvesting stage (t ha$^{-1}$); Se = amount of seeds (t ha$^{-1}$); St = stubble (t ha$^{-1}$) (wheat/maize stalks (t ha$^{-1}$) × cut height (w%)); B = amount of baled residue (t ha$^{-1}$) and T = amount of chaff collected (t ha$^{-1}$).

Maize cob harvesting losses were assessed by collecting and weighing the cob biomass left on the ground. Three random 10 m$^2$ plots were chosen per each block. Then, cobs present in each plot were collected and weighted with a portable dynamometer. Therefore, harvesting losses (%) were estimated as the ratio of residue losses (Mg ha$^{-1}$) to the sum of biomass yield (Mg ha$^{-1}$) and residue losses (Mg ha$^{-1}$) for each block. The total biomass yield potential was calculated summing the net biomass yield and biomass losses (Mg ha$^{-1}$).

### 2.4. Harvesting Cost Analysis

Ownership and operating costs were the focus of the economic analysis. Standard values provided by the CRPA methodology [25] and the data collected during the field tests (primary data) were used during the machine operating cost evaluation. Furthermore, data measured during the field tests was validated by interviews with agroindustry owners and their usual suppliers who provided additional cost items used in the cost analysis.

The hourly costs for all the equipment tested during the harvesting were calculated for both cereal crops according to [25,26]. Table 2 reports the parameters used during the cost analysis of the harvesting systems tested.

**Table 2.** Economic parameters used for the cost analysis of cereal straw and chaff, and Maize cob collections using Harcob technology.

| Parameters | Unit | Maize Cob Collection | Wheat Chaff Collection | | Straw Baling | |
|---|---|---|---|---|---|---|
| Machine | | Combine Harvester CASE IH Axial Flow 7088 | | | Deutz-Fahr Agrotron M620 | |
| Power | kW | 269 | | | 115.6 | |
| Operating Machine | | | | Harcob | | Baler-Deutz-Fahr Varimaster 690 |
| **Financial Cost** | | | | | | |
| Investment | € | 226,380.00 | | 75,000.00 | 85,000 | 32,000 |
| Service Life | year | 10 | | 10 | 12 | 8 |
| Service Life | h | 3000 | | 3000 | 14,000 | 2500 |
| Resale | % | 19 | | 18 | 28 | 23 |
| Resale | € | 43,260.00 | | 13,263.00 | 28,200 | 7225 |
| Depreciation | € | 183,120.00 | | 61,737.00 | 56,800 | 24,775 |
| Annual Usage | h y$^{-1}$ | 480 | | 480 | 294 | 294 |
| Interest Rate | % | 3 | | 3 | 3 | 3 |
| Labour Cost | € h$^{-1}$ | 11.5 | | - | 11.5 | - |
| Workers | n° | 1 | | - | 1 | - |
| **Fixed Costs** | | | | | | |
| Ownership Costs | € y$^{-1}$ | 18,312.00 | | 6,173.69 | 7,080.99 | 3,096.86 |
| Interest | € y$^{-1}$ | 4,044.60 | | 1,323.95 | 1,275.42 | 588.38 |
| Machine Shelter | m$^{-2}$ | 26.88 | | | 9.12 | 9.89 |
| Value of the Shelter | € m$^{-2}$ | 100.00 | | | 100.00 | 100.00 |
| Value of the Shelter | € y$^{-1}$ | 53.76 | | 0.00 | 27.36 | 29.67 |
| Insurance (0.25%) | € y$^{-1}$ | 565.95 | | 0.00 | 212.50 | 80.00 |
| **Variable Costs** | | | | | | |
| Repair Factor | % | - | | 45.00 | 80.00 | 90.00 |
| Repairs and Maintenance | € h$^{-1}$ | 48.29 | | 18.00 | 1.22 | 10.83 |
| Fuel Cost | € l$^{-1}$ | 0.57 | | - | 0.57 | - |
| Fuel Consumption | l h$^{-1}$ | 36.86 | 35.45 | - | 9.68 | - |
| Fuel Cost | € h$^{-1}$ | 21.16 | 20.35 | - | 5.56 | - |
| Lubricant Cost | € l$^{-1}$ | 3.03 | 3.03 | - | 3.03 | - |
| Lubricant Consumption | l h$^{-1}$ | 0.18 | 0.18 | - | 0.09 | - |
| Lubricant Consumption | € h$^{-1}$ | 0.55 | 0.55 | - | 0.27 | - |
| Salary | € h$^{-1}$ | 11.50 | 11.50 | - | 11.50 | - |
| Cost of Baling String | € h$^{-1}$ | - | - | - | - | 32.32 |

The calculation of the operating costs was per hour of work carried out, per unit area and per ton of product harvested. The share of harvesting costs was carried out through the market value [27] of each product and co-product produced according to Table 3. The economic allocation, per harvesting phase (combine harvesting and baling), comes from the ratio between each product revenue on the total revenues obtained, according to the following formula:

$$Ea = \frac{Mp * Y_i}{\sum_{i=1}^{3} R_i} \quad (2)$$

where Ea = Economic allocation of each product or co-product (i.e., grain, straw, chaff and cob) per harvesting phase (combine harvesting or baling); Mp = Market price of each product or co-product; $Y_i$ = Yield of each product or co-product and $R_i$ = Revenue obtained by multiplying Mp × $Y_i$.

**Table 3.** Economic allocation used for the cost analysis of products and by-products collected during both tests and each harvesting phase, with Harcob technology.

| Product | Market Price (€ $t^{-1}$) | Yield (t $ha^{-1}$) | Revenue (€ $ha^{-1}$) | Economic Allocation for Combine Harvester (%) | Economic Allocation for Baling (%) |
|---|---|---|---|---|---|
| Wheat seed | 198.50 | 10.93 | 2169.60 | 88% | 0% |
| Straw | 50.00 | 5.48 | 274.00 | 11% | 100% |
| Chaff | 50.00 | 0.67 | 33.5 | 1% | 0% |
| Total | | 17.08 | 2477.11 | 100% | 100% |
| **Product** | **Market price (€ $t^{-1}$)** | **Yield (t $ha^{-1}$)** | **Revenue (€ $ha^{-1}$)** | **Economic Allocation for Combine Harvester (%)** | |
| Maize seed | 185.00 | 13.12 | 2427.20 | 96% | |
| Cob | 65.00 | 1.72 | 111.80 | 4% | |
| Total | | 14.84 | 2539.00 | 100% | |

## *2.5. Avoided $CO_2$ Emission From Fossil Fuel*

In order to evaluate the $CO_2$ emissions from fossil fuel combustion avoided per unit area (t $CO_2$ $ha^{-1}$) using cobs and chaff for bio-energies, the equivalent energy production per residue was calculated as follows:

$$ER = Yi \times NC \quad (3)$$

where: ER = Energy content in residue per unit area (MJ $ha^{-1}$); Yi = Yield of each residue collected (kg $ha^{-1}$) and NC = net calorific value of the residue (MJ $kg^{-1}$).

Considering a net calorific value of diesel of 38.6 MJ $l^{-1}$, the diesel equivalent per unit area (l $ha^{-1}$) to residue collected was calculated as follows:

$$DE = ER/DD \quad (4)$$

where DE = diesel equivalent per unit area (l $ha^{-1}$); ER = energy content in residue per unit area (MJ $ha^{-1}$); DD = net calorific value of diesel (MJ $l^{-1}$).

Considering that 2.65 Kg $CO_2$ are emitted per liter of Diesel consumed (kg $CO_2$ $l^{-1}$), the avoided emission of $CO_2$ due to bioenergy produced per residue collected was calculated according to the following formula:

$$AC = D \times EC \quad (5)$$

where AC = avoided emission of $CO_2$ due to bioenergy produced per residue collected (kg $CO_2$ $ha^{-1}$); DE = Diesel equivalent per unit area (l $ha^{-1}$); EC = emission of $CO_2$ per liter of diesel (2.65 Kg $CO_2$ $l^{-1}$).

## 3. Results

### *3.1. Maize Seeds and Cobs Harvesting Test*

The average value of the stem diameter was 2.3 (±1.5) cm with a maximum value of 3.3 cm. The plant height showed a great variability ranging between 155 and 420 cm with an average value of 325.8 (±31.9) cm. The average weight of the total biomass was 50.7 (±6.4) t $ha^{-1}$, showing a great variability ranging between 42.8 to 55.1 t $ha^{-1}$. The ears yield was 19.5 (±2.2) t $ha^{-1}$ in average with 17.0 and 20.9 t $ha^{-1}$ of minimum and maximum values respectively. The average value of the ears/biomass ratio was 44.0%. The average value of the leaf moisture content (MC) was 32.5 (±2.9) %, while the stalks registered value of 72.2 (±2.8) %. Grain MC showed an average value of 18.9 (±2.2) %, while cob MC was 32.1(±3.4) %. The average bulk density of the cob resulted 132.36 (±11.58) kg $m^{-3}$.

#### 3.1.1. Combine Performance and Quality of the Work–Maize Seeds and Cob Harvesting

The combine harvester machine equipped with the Harcob system, allowed the collection of 13.12 t $ha^{-1}$ of grain and 1.72 t $ha^{-1}$ of maize cobs. The unharvested maize cobs that remained in the field were assessed to be equal to 0.58 t $ha^{-1}$ (25% of the total potentially harvestable cob biomass). The material capacity was 18.58 t $h^{-1}$ and 2.31 t $h^{-1}$ for grain and cob, respectively. The unloading of the maize grain and the cobs takes place at the same time because the cobs' tank has been dimensioned in order to be filled at the same time as the grain tank. This technical feature allows one to keep the unproductive times due to the unloading of the maize seed unchanged even after the introduction of a parallel production process to collect the cobs (Figure 3). The fuel consumption was equal to 27.1 l $ha^{-1}$. A summary of the results of the performance test are reported in Table 4.

**Figure 3.** Simultaneous unloading phase of Maize kernel and cob tanks using Harcob system.

**Table 4.** Results of the maize and cob harvesting test with combine harvester (CASE IH 7140, Racine, WI, USA) and Harcob system.

| Parameters | Mean | Dev. St. |
|---|---|---|
| Theoretical Field Capacity (ha $h^{-1}$) | 1.89 | ±0.29 |
| Effective Field Capacity (ha $h^{-1}$) | 1.36 | ±0.18 |
| Yield (t grain $ha^{-1}$) | 13.12 | ±0.28 |
| Material Capacity (t grain $h^{-1}$) | 18.58 | ±0.13 |
| Yield ($t_{dw}$ cobs $ha^{-1}$) | 1.72 | ±0.23 |
| Material Capacity (t cobs $h^{-1}$) | 2.31 | ±0.09 |
| Fuel Consumption (l $ha^{-1}$) | 27.1 | ±4.02 |
| Cob Losses (t $ha^{-1}$) | 0.58 | ±0.23 |

### 3.1.2. Cost Analysis of Maize Seeds and Cobs Harvesting

The cost analysis of maize harvesting highlighted that the cob collection with the Harcob device is 26% more expensive compared to the traditional maize seed harvesting in terms of both hourly and per unit area costs (Table 5).

**Table 5.** Operating costs of maize seeds and cob harvesting. Comparison between traditional and Harcob systems.

| Maize Seeds and Cob Harvesting Costs with Harcob Technology | | | | |
|---|---|---|---|---|
| | **Unit** | **Corn** | **Cob** | **Total Harvesting Cost** |
| Market price | € $t^{-1}$ | 185 | 65 | |
| Yield | t $ha^{-1}$ | 13.12 | 1.72 | |
| Cost Allocation | % | 96% | 4% | 100% |
| | € $h^{-1}$ | 155.95 | 7.18 | 163.13 |
| Combine Harvester + Harcob | € $ha^{-1}$ | 114.67 | 5.28 | 119.95 |
| | € $t^{-1}$ | 8.74 | 3.07 | |
| **Traditional Maize Seeds Harvesting Costs Without Cob Collection** | | | | |
| | **Unit** | **Corn** | | |
| Market Price | € $t^{-1}$ | 185 | | |
| Yield | t $ha^{-1}$ | 13.12 | | |
| Cost Allocation | % | 100% | | |
| | € $h^{-1}$ | 129.51 | | |
| Combine Harvester | € $ha^{-1}$ | 95.23 | | |
| | € $t^{-1}$ | 7.26 | | |

The higher investment required to purchase the Harcob system also has an impact on the cost of corn (€ $t^{-1}$) which resulted 20% higher than harvesting without Harcob. However, the Harcob system produced a revenue of 111.80 € $ha^{-1}$ higher than the traditional harvesting system permitting the collection of about 1.7 t cob per hectare (Table 2). Furthermore, subtracting the only harvesting costs to the total revenues obtained with each harvesting system, with Harcob the profit was 2419.05 € $ha^{-1}$ while with the traditional harvesting system the difference was 2331.97 € $ha^{-1}$. With Harcob it was possible to obtain an income of 87.08 € $ha^{-1}$ (4%) higher than using the traditional harvesting system without Harcob.

### *3.2. Wheat Seeds and Chaff Harvesting Test*

Pre-harvesting test permitted to assess a total amount of biomass per hectare of 25.9 (±0.34) tons, of which 11.5 (±1.01) tons of grain and 2.48 (±0.11) tons of chaff. The amount of straw was estimated in 8.58 (±1.08) tons per hectare of which 3.38 (±0.48) tons of stubble that remained in the soil due to the cutting height of the machine. The average value of the straw moisture content was 23.0 (±1.4) %. Grain and chaff moisture content were 12.4 (±0.4) %. The average bulk density of the chaff resulted 42.88 kg $m^{-3}$.

### 3.2.1. Combine Performance and Quality of the Work–Wheat Seeds and Chaff Harvesting

The Harcob system was developed for harvesting corn cobs. Given the growing interest of the agricultural, industrial and research sectors in unused wheat residues, once the necessary modifications to be made to the combine already described had been identified, specific harvesting tests were conducted to verify the possibility of also using the Harcob system for the separate harvesting of cereal husks. During the wheat harvesting tests the grain and chaff collected were 10.93 and 0.67 t $ha^{-1}$, respectively. The material capacity was 12.98 t $h^{-1}$ and 0.79 t $h^{-1}$ for grain and chaff, respectively. Performance test results are summarized in Table 6.

**Table 6.** Results of the wheat grain and chaff harvesting test with combine harvester CASE IH 7140 and Harcob system.

| Parameters | Mean | Dev. St. |
|---|---|---|
| Theor. Field Capacity (ha $h^{-1}$) | 1.42 | ±0.05 |
| Eff. Field Capacity (ha $h^{-1}$) | 1.19 | ±0.01 |
| Yield (t seeds $ha^{-1}$) | 10.93 | ±0.43 |
| Material Capacity (t seeds $h^{-1}$) | 12.98 | ±0.66 |
| Yield (t chaff $ha^{-1}$) | 0.67 | ±0.02 |
| Material Capacity (t chaff $h^{-1}$) | 0.79 | ±0.02 |
| Fuel Consumption (l $ha^{-1}$) | 29.86 | ±0.31 |

Results of pre-harvesting and harvesting tests were elaborated in order to define the mass balance and to assess the biomass losses. Harvesting tests carried out on wheat have shown the Harcob system's incapability of effectively separating the wheat chaff from the straw. In particular, the Harcob tank contained about 10% of straw mixed with chaff. Furthermore, the windrow of residues generated by the combine was made by 50% of chaff and 50% of straw.

Due to the results of the harvesting and the impossibility to distinguish chaff from straw, these two biomasses were considered together for the mass balance definition reported in Table 7. Results highlighted 4.87% of grain losses and 47.06% of chaff and straw losses (excluding the stubble part that remained uncollected in the soil).

**Table 7.** Wheat grain and residues losses assessment.

| Wheat Fractions | Potential Biomass * (tdw $ha^{-1}$ ) | Harvested Products (tdw $ha^{-1}$) | Biomass Losses (%) |
|---|---|---|---|
| Grain | 10.2 | 9.7 | 4.87 |
| Chaff | 2.2 | 0.6 | 47.06 |
| Straw | 5.2 | 3.3 | |
| Stubble | 2.1 | 2.1 | - |
| Total Residues | 9.5 | 6.0 | 47.06 |

* Fractions of the biomass available per unit area assessed with pre and post-harvesting analysis.

### 3.2.2. Cost Analysis of Wheat Seeds and Residue Harvesting

The wheat chaff harvesting cost resulted higher than the cob harvesting using the same system (Table 8). The higher investment required to purchase the Harcob system has an impact also on the cost of wheat (€ $t^{-1}$) which is 24% higher than harvesting without Harcob. Furthermore, Harcob device developed for maize cob harvesting resulted able to collect part of the wheat chaff separately by the straw, but with some chaff losses of about 47%. Comparing the total costs to harvest wheat with and without the Harcob system, it can be observed that the use of Harcob implied an extra cost of

14%. In the absence of a chaff market, assuming the market price of chaff comparable to that of straw (50 € $t^{-1}$), the harvesting of chaff with the Harcob system allowed to obtain a revenue of 33.5 € $ha^{-1}$ (Table 3) While, according to the economic allocation used for cost sharing among wheat products reported in Table 3, the profit obtainable by chaff collection with Harcob system resulted 31.4 € $ha^{-1}$.

**Table 8.** Operating costs of wheat grain and residues harvesting. Comparison between traditional and Harcob systems.

| **Wheat Harvesting Cost using Harcob Technology** | | | | | |
|---|---|---|---|---|---|
| | **Unit** | **Grain** | **Straw** | **Chaff** | **Total Cost Per Phase** |
| Market Rice | € $t^{-1}$ | 198.50 | 50.00 | 50.00 | |
| Yield | t $ha^{-1}$ | 10.93 | 5.48 | 0.67 | |
| Cost Allocation | % | 88% | 11% | 1% | 100% |
| Combine Harvester + Harcob | € $h^{-1}$ | 142.04 | 17.94 | 2.19 | 162.18 |
| | € $ha^{-1}$ | 139.26 | 17.59 | 2.15 | 159.00 |
| | € $t^{-1}$ | 12.74 | 3.21 | 3.21 | |
| Cost Allocation | % | - | 100% | - | 100% |
| Tractor + Baler | € $h^{-1}$ | - | 112.71 | - | 112.71 |
| | € $ha^{-1}$ | - | 36.15 | - | 36.15 |
| | € $t^{-1}$ | - | 6.60 | - | 6.60 |
| Total Cost of the Harvesting System | € $h^{-1}$ | 142.04 | 130.65 | 2.19 | 274.88 |
| | € $ha^{-1}$ | 139.26 | 53.74 | 2.15 | 195.14 |
| | € $t^{-1}$ | 12.74 | 9.81 | 3.21 | |
| **Traditional Wheat Harvesting Cost Without Chaff Collection** | | | | | |
| | **Unit** | **Grain** | **Straw** | **Chaff** | **Total Cost Per Phase** |
| Market Price | € $t^{-1}$ | 198.50 | 50.00 | 0.00 | |
| Yield | t $ha^{-1}$ | 10.93 | 5.48 | 0.00 | |
| Cost Allocation | % | 89% | 11% | 0% | 100% |
| Combine Harvester | € $h^{-1}$ | 114.15 | 14.41 | 0.00 | 128.56 |
| | € $ha^{-1}$ | 111.91 | 14.13 | 0.00 | 126.04 |
| | € $t^{-1}$ | 10.24 | 2.58 | 0.00 | |
| Cost Allocation | % | - | 100% | - | 100% |
| Tractor + Baler | € $h^{-1}$ | - | 112.71 | - | 112.71 |
| | € $ha^{-1}$ | - | 36.15 | - | 36.15 |
| | € $t^{-1}$ | - | 6.60 | - | 6.60 |
| Total Cost of the Harvesting System | € $h^{-1}$ | 114.15 | 127.12 | 0.00 | 241.27 |
| | € $ha^{-1}$ | 111.91 | 50.28 | 0.00 | 162.19 |
| | € $t^{-1}$ | 10.24 | 9.18 | 0.00 | |

### *3.3. Impact of Residuals on Cemissions*

The collection of agricultural residues such as cobs and chaff for energy purposes implies avoided $CO_2$ emissions due to reduced use of fossil fuels. In this study, considering a net calorific value of 18.4 MJ $kg^{-1}$ of cob [7] and 15.1 MJ $kg^{-1}$ of chaff [7], according to the product collected during the tests, the equivalent energy was estimated to be 31,648 and 10,117 MJ $ha^{-1}$ for cobs and chaff, respectively. This leads to an avoided Diesel consumption of 820 and 262 l $ha^{-1}$ due to cob and chaff for energy production, respectively. Maize cobs and wheat chaff for energy purposes would avoid greenhouse gasses emissions (GHG) from fossil fuel equal to 2.2 t $CO_2$ and 0.7 t $CO_2$, respectively.

## 4. Discussion

Since the beginning of the nineteenth century, before modern combine harvesters, corn was harvested as a whole ear of corn and shelled afterwards [28,29]. Even if cobs were all collected, harvesting was a labor-intensive job because the grain still had to be threshed. With the increase in harvesting mechanization, the trend had become to leave the cob in the field. It was only in the 1980s that Bargiel et al. developed a first cob collection system based on a mechanical separator that unloaded it onto a towed trailer [30], although, the system still had limits in terms of cob losses that resulted about 31% considering a cob purity of 89%. The low purity of the cob collected, affected also its bulk density that was 100 kg $m^{-3}$. Since 1980 several studies have analyzed various solutions for the harvesting of corn cobs, sometimes reaching high levels of purity of the harvested product and significantly reducing harvest losses [31], but where multiple passes were necessary, or trailers towed by tractors side-by-side the combine.

Moreover, as noted by [32] the fraction of available stover harvested by conventional means was rather low, between 37% and 57%. A combined single-pass harvesting system of corn grain and residues in single-pass would further reduce field operations and costs.

Shinners proposed a harvesting system of corn grain and stover in single-pass that resulted 39% less productive than the conventional grain harvest system. In addition, the authors of the study had highlighted clear difficulties for the system to manage both cereals and residues at the same time [32].

Hence, the Harcob system represents an innovation considering the possibility to perform a single-pass grain and cob harvesting with simultaneous unloading of the products (grain and cob) in two different trailers, without affect the harvesting performance of the combine, and without modifying the harvesting method and costs. The cob harvesting losses of 25% are comparable with the results of tests performed with an experimental corn cob separation system mounted on a John Deere 9750 STS combine in Iowa (USA), where this parameter ranged between 35% and 5% [31].

Harvesting tests were carried out also to collect wheat chaff even if first results highlighted the need for further improvement and modifications due to high losses and the level of impurities measured. The Harcob system was developed to be mounted in axial combine harvesters that can provide lower grain breakage percentage and higher productivity respect to the traditional harvesters with straw walkers but, on the other hand have stronger mechanical action on the straw. Even if Harcob system allows one to collect 0.6 t $ha^{-1}$ of chaff for bioenergy, the use of Harcob showed 47% of biomass losses. The amount of biomass losses could be explained by the straw crushing caused by the threshing system of the axial harvester. In fact, once the straw is cut in smaller parts, then the cleaning and ventilation system is not able to discriminate and separate the grain from the chaff and from the straw. The result was that part of the chaff went into the straw windrow.

Even if experiences of chaff harvesting are almost absent in the bibliography, there are already machines on the market developed for the separate collection of chaff and straw, mainly to avoid the spread of weed seeds, but also for their use in animal husbandry or for the production of biofuel and energy [21,33,34]. The experience carried out by Pari during chaff and straw collection by means a residue spreader tested in Sweden for chaff and straw baling, showed a residue harvesting losses between 31% to 47% [35]. This is to clarify that the harvesting efficiency of the Harcob system was similar to that of a system developed for the spreading of residues and that can partially, by changing the setting, allow a certain admixing of the chaff with the straw. For this reason, improvements will be necessary to optimise chaff harvesting with Harcob, reducing both product losses and increasing the separation capacity of the two fractions.

Even if maize harvesting by Harcob was 25% more expensive per unit area than a traditional system, it resulted more convenient than contractor harvesting cost in Italy where the harvesting cost varies from 135 to 150 € $ha^{-1}$. According to the test results, in case of maize grain and cobs harvesting, the tested device allows farmers to have a higher profit even if both hourly and per unit area costs are higher than those of a traditional system. Concerning the chaff harvesting costs no information were found for the Italian agricultural sector. However, the cost of wheat harvesting (grain and straw) is similar to traditional systems in Central (150–175 € $ha^{-1}$ including straw chopping) and Northern Italy (206–245 € $ha^{-1}$ including straw bailing) [36].

The risk of high bioenergy demand is the impacts of the indirect land use change (ILUC) which may occur when grazing land or farmland previously devoted to food production is turned over to the production of biofuels. This production change may expand agriculture land into areas with high carbon stock (i.e. peatlands, forests and wetlands), causing the release of greenhouse gases ($CO_2$ stored in soil and trees) and negating the benefits of using biofuels instead of fossil fuels, in terms of emission savings. Hence, the European Renewable Energy Directive (RED II) faces this risk. Consequently, alternative feedstock to produce bioenergy sources, such as cobs and chaff, are fundamental to sustain the agro-energy production chain.

The impact on the atmospheric $CO_2$ using biomass as fuel is negligible. Biomass utilization on a global scale could contribute to environmental protection, having in mind that biomass sources are $CO_2$-neutral because all the $CO_2$ from biomass combustion is absorbed during new biomass growing to be used for the same purpose [7]. The present study demonstrated that using residues the reduction of $CO_2$ from fossil fuel is ranging from 0.7 to 2.2 t $CO_2$ $ha^{-1}$. Even if the amount is low, they are very important because they are derived from renewable material.

## 5. Conclusions

Maize cob and wheat chaff are often less expensive untapped residues compared to dedicated energy crops. In fact, both maize cob and cereal chaff are co-products of grain production, and excluding harvest and nutrient replacement, no additional costs are necessary. However, the feasibility of using these feedstocks for bioenergy production is mainly related to the harvest methods used and biomass available and collectable per hectare. The scope of this study was to evaluate the operating parameters of the Harcob system and the quality and effectiveness of its work during cob harvesting and to verify the feasibility of harvesting the wheat chaff through an innovative system (although it was developed to harvest the maize cob). According to the methodology utilized in this study it was possible to harvest 1.72 t $ha^{-1}$ and 0.67 t $ha^{-1}$ of cob and chaff, respectively. This would allow farmers to obtain a revenue of 111 € $ha^{-1}$ from the sale of the cobs corresponding to an increase in profit of 4% compared to the harvesting of only corn seed using the traditional system. As far as the chaff collection through the use of the Harcob system has not shown real advantages from the economic point of view allowing farmers to obtain an increase in profit close to zero. This result is obviously influenced by the market price of the chaff which in this article has been assumed to be the same as that of straw. Although, the separate collection of the product, the increase in collection efficiency, and the presence of a specific market (for agricultural or industrial use) could make the use of by-product collection systems such as Harcob increasingly economically attractive.

In conclusion, the Harcob system could be considered suitable to harvest such different and high potential crop by-products and may represent a solution for farmers investing in the bioenergy production chain. Furthermore, the possibility of using the same combine harvester for two different cash crops in two different seasons will increase the profitability of the machinery. Aspects related to the improvement of the system for chaff harvesting should be investigated and included in future studies.

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Article

# Analysis of the Work Productivity and Costs of a Stationary Chipper Applied to the Harvesting of Olive Tree Pruning for Bio-Energy Production

**Alessandro Suardi [1], Francesco Latterini [1,*], Vincenzo Alfano [1], Nadia Palmieri [1], Simone Bergonzoli [2] and Luigi Pari [1]**

[1] Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, (RM), Italy; alessandro.suardi@crea.gov.it (A.S.); vincenzo.alfano@crea.gov.it (V.A.); nadia.palmieri@crea.gov.it (N.P.); luigi.pari@crea.gov.it (L.P.)

[2] Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano, 43, 24047 Treviglio, (BG), Italy; simone.bergonzoli@crea.gov.it

* Correspondence: francesco.latterini@crea.gov.it; Tel.: +39-06-90675248

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**Abstract:** Pruning residues could represent an important biomass resources for energy production. Only in Italy it has been estimated that an annual quantity of biomass of over 2600 kt of dry matter could be obtained from olive residues. Several machines developed for pruning harvesting are available in the market, most of which are tractor-driven, while limited knowledge is available on performance, quality of work and costs of harvesting logistics based on stationary chippers. The aim of the present paper is to analyze machine performance of a forestry stationary chipper applied to pruning harvesting for what concerns work productivity, quality of the comminuted product and harvesting operating costs. This system is actually applied by Fiusis Company, an Italian enterprise which manages a biomass power plant exclusively powered by olive trees' pruning residues, and it has never been analyzed in literature. The results obtained showed consistent work productivity, which resulted the highest ever found in olive pruning harvesting systems and equal to 5.23 ± 0.81 $t_{dm}\cdot h^{-1}$. This high work productivity allowed also to obtain a little economic gain from a matter, which is actually considered a problem for olive groves' owners and not a potential source of income. In particular, the use of a stationary chipper seemed very efficient in olive groves with a consistent amount of wooden residues to be processed and with big branches not harvestable by the most common towed pruning harvester. In addition, the stationary chipper has the advantage of avoiding the preliminary raking operation, which results in reduced costs for the farmer.

**Keywords:** olive groves; pruning; stationary chipper; harvesting system; hog fuel; pruning supply chain

## 1. Introduction

Fruit orchards cover over 10 million hectares across the EU and are mostly located in Mediterranean areas [1]. All orchards require regular pruning, which is performed at 1–3-year intervals. This operation generates a substantial amount of residues, estimated in the range of 1-5 tons per hectare [2], and an estimated annual quantity of pruning biomass of over 2600 kt of dry matter from the only olive groves in Italy [3] that could represent an important source of biomass for energy production [4]. However, these residues are usually field-burnt or mulched [5–7]. These solutions are not cost-effective [8]. Moreover, field burning causes uncontrolled greenhouse gases (GHG) emissions, and also, mulching, which presents positive aspects like reduced soil erosion and lower soil nutrients depletion, could imply other negative consequences; for example, increased possibility of disease diffusions [9,10].

For this reason, various European projects were focused on activities for the development of an efficient pruning supply chain for energy production [11–14]. One fundamental step in the development of such a supply chain is the identification of cost-effective harvesting technologies. In fact, harvesting is a key stage that influences the product quality, the type of logistics chain and the economic sustainability of the pruning supply chain [15].

Moreover, several agricultural equipment manufacturers developed 75 different models mostly consisting in adaptations of conventional mulchers; other available technologies are chippers, balers or integrated pruning-harvesting technologies [15].

Apart from integrated pruning-harvesting technologies which are still not widespread and not always applicable, other harvesting systems require pruning to be grouped in windrows to optimize biomass-harvesting and reduce losses. For this reason, most available harvesting systems need a preliminary raking operation, carried out by a tractor equipped with a towed rake. Some machines instead have integrated raking systems that are mainly used to compact the windrow and facilitate the pruning collections by the harvester [15]. Raking operations have a consistent influence on costs, biomass quality and biomass losses [16].

An interesting approach to avoid the raking phase is using a stationary chipper (SC). This machinery is typical of forest utilization sector [17–20] but can be applied also in pruning harvesting systems. It represents an interesting choice for fields with a consistent amount of pruning biomass and with big diameter of prunings or when the orchard's field is characterized by slope, which could not be addressed by the majority of self-propelled or towed chippers and balers.

Even if the use of a forestry stationary chipper is uncommon in the normal practice, and according to our knowledge, only one experience has so far been reported in the literature [21], the pruning harvesting system based on stationary chipper is currently used by the Italian firm "Ligna", a subsidiary company of "Fiusis S.r.l." (Calimera, Apulia Region, Italy), which is a 1 MWe biomass power plant in the Municipality of Calimera (Apulia Region, Italy). In Europe, Fiusis and Ligna represent a successful and unique example of a short supply chain (10 km radius) for the production of electricity exclusively obtained from the combustion of local olive tree prunings. Ligna is responsible for procuring the biomass produced by the nine municipalities bordering the Fiusis plant, which transforms it into electricity. The supply of biomass takes place through two types of harvesting systems: four Facma mod. Comby TR200 (Facma srl, Vitorchiano, Lazio Region, Italy) towed shredders for small olive groves (less than 400 trees, corresponding to about 6 ha) and a stationary chipper Caravaggi mod. BIO900 (Caravaggi srl, Pontoglio, Lombardia Region, Italy) for big orchards (more than 400 olive trees) or in slope terrains. The choice of the more adapt harvesting logistic to be used (based on the number of trees) is mainly made by Ligna, according to the results of ten years of experience in the sector. However, unlike pruning harvesting using a towed chipper, few scientific data are available about the harvesting logistic of prunings based on a stationary chipper [15]. This paper analyses the performance, quality of the work and costs of the olive tree pruning harvesting system developed by Fiusis and Ligna and based on the use of a stationary forestry chipper. Although widely used in the forestry sector, the use of a stationary chipper for harvesting and comminuting olive tree prunings is poorly documented, and therefore, the study is innovative and fills a gap in the literature where little information is currently available. Moreover, an economic evaluation of hog fuel production was conducted considering the overall chain, from biomass harvesting to transportation to the power plant. This is another innovative aspect of the present paper. In fact, in literature, there are few studies dealing with hog fuel or wood chips' transport costs and even less considering very short transport distances, such the present case's one.

## 2. Materials and Methods

### *2.1. Experimental Field and Prunings' Characteristics*

Experimental field was located in the Carpignano Salentino Municipality (Apulia Region, Italy). The experimental field was 2.49 hectares with an average slope of 2% and a planting layout of 12 m × 12 m. The average pruning's diameter, length and weight were 39.75 ± 12.66) mm and 1950 ± 524) mm and 4.13 ± 2.48) kg, respectively. A map of the olive grove is given in Figure 1.

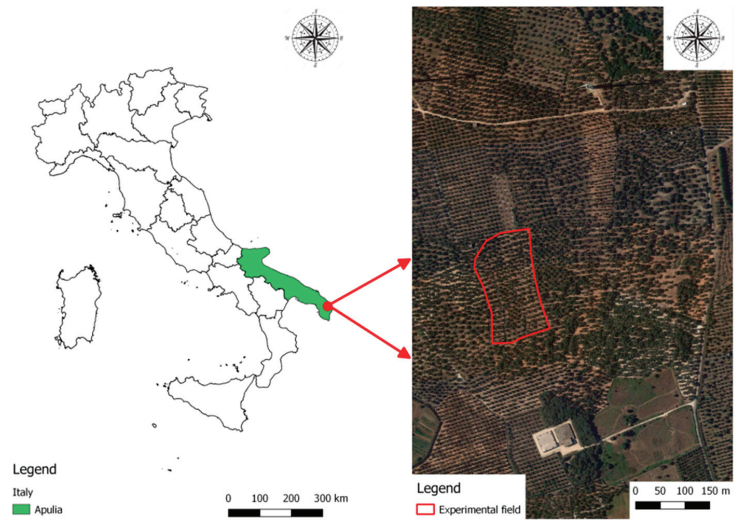


**Figure 1.** Area and experimental fields location. EPSG: 32633; CRS: WGS84-UTM33T.

The Fiusis plant is located at a distance of 9.3 km from the experimental field.

### *2.2. Harvesting System Description*

As previously written in the Introduction section, the analyzed pruning harvesting system is a nonconventional one. In fact, there was no preliminary raking operation, but instead, the pruning residues were collected and piled on the field side by a 66-kW tractor equipped with fork (Landini model Rex 90 S DT Cab, Argo Tractors SPA, Fabbrico, Emilia-Romagna Region, Italy). Near the pile, a Caravaggi BIO900 chipper is located (Figure 2). This is a stationary chipper 9.65-m-long, 3.90-m-high, and it weighs 10,000 kg. It is powered by a Diesel 129 kW motor. The rotor is 0.78-m-wide, and the machine is able to shred wooden materials up to diameters of 45 cm. The feeding of the chipper was provided by a hydraulic loader Agrisav CAS 1000 (Agri Sav, Savigliano, Piemonte Region, Italy) powered by a 129-kW tractor (same Virtus 140 dt Cab, same Deutz-Fahr, Treviglio, Lombardia Region, Italy). Comminuted biomass is heaped on the pile and then loaded by a 90-kW Manitou 940–120 LSU (Manitou, Ancenis, Loire Atlantique Department, France) lifter into the dumpster of a IVECO Trakker 190T36 (Iveco, Torino, Piemonte Region, Italy) truck in order to be transported to the Fiusis biomass power plant in Calimera Municipality.

### *2.3. Harvesting System Performance and Quality of the Work Evaluations*

Working times were measured according to ASAE S495 DEC99 [22]. Investigated parameters for what concerned work productivity were: theoretical field capacity (ha·h$^{-1}$), effective field capacity (ha·h$^{-1}$), material capacity ($t_{fm}$·h$^{-1}$ and $t_{dm}$·h$^{-1}$) and fuel consumption (l·h$^{-1}$ and l·$t_{fm}$$^{-1}$).

**Figure 2.** Stationary chipper Caravaggi and tractor with uploading equipment.

The field capacity of a farm machine is defined as the rate at which it performs its primary function, for example the number of hectares which can be harvested per time unit. Measurements or estimates of machine capacities are fundamental to plan field operations, power units, labor and also to evaluate machine operating costs. The effective field capacity (EFC) of the machines in the field were calculated by dividing the hectare harvested by the hours of actual field time. Theoretical field capacity (TFC) depends instead only on the full operating width of the machine and the average travel speed of this while operating in the field. It consists in the maximum achievable field capacity which could be obtained at the given field speed when the full operating width of the machine is being used. EFC is generally less than the TFC due to turns and other delays. The ratio of EFC to TFC is defined as machine field efficiency (FE).

FE is expressed as the percentage of a machine TFC actually achieved under real operating conditions. It accounts for failure to utilize the full operating width of the machine (the so called overlapping) and many other time delays which can occurred during harvesting operations. These cover turning, material unloading, traveling, refilling the fuel tank, making adjustments, waiting for trucks and operator rest stops. Delay activities which occur outside the field, like daily service, travel to and from the field and major repairs, are not considered in the field efficiency estimation.

The working capacity of harvesting machines is generally measured by the quantity of materials harvested in the time unit. This capacity is called the machine material capacity (MC), expressed as tons per hour. It is the product of the machine EFC and the average yield of crop per hectare.

The quality of the work of the harvesting system was evaluated also by analyzing the hog fuel quality in terms of bulk density ($kg \cdot m^{-3}$) according to ISO 17828:2015 [23], moisture content (%) according to ISO 18134-2:2017 [24] and particle size distribution analysis (%) according to [25].

Fuel consumption was measured by machine tank refilling until the full level at the end of each plot using a handheld fueling system with a flowmeter to identify the volume of fuel consumed ($l\ ha^{-1}$ or $l\ t^{-1}$ of biomass harvested). Each plot was started with the tank entirely full. The fuel consumed was proportioned to the harvested surface to define the fuel consumed per hectare.

It is valuable to underline that, even though the mentioned above method to estimate the fuel consumption is very common and presents the benefit to result very easy to apply in the field, and sometimes it represents the only method which can be applied, its precision has been questioned in many studies, most of all when the amounts to be measured are minute, and the measurement errors are difficult to evaluate [22].

Bulk density and moisture analysis were conducted according to the methodology proposed by Pari et al. [26]. Particle size distribution (PSD) was instead determined according to the European Standard ISO 17225-4:2014 [27].

*2.4. Harvesting Cost Analysis*

Operating costs of the harvesting system were analyzed, including transport costs to the Fiusis biomass power plant. The economic analysis was focused on both maintenance and operating costs, according to the parameters measured during the field tests (primary data) or by using standard values provided by the CRPA methodology [28]. Interviews with agro-industry owners and with their usual suppliers have provided further costs items and have validated the data measured during the field tests. The hourly costs for all the equipment tested during the harvesting were calculated according to [28,29] and using the Italian Ministry of Infrastructure and Transport guidelines for transport operation [30]. In particular, for what concerns field operations, the total yearly fixed costs, which were calculated starting from the machine price, were divided for the machineries' annual usage (expressed in hours) to obtain the hourly fixed cost. Hourly variable costs (maintenance, fuel, lubricant and manpower) were estimated using the mentioned-above methodologies. In such ways, we obtained the total hourly costs of the harvesting system. To have costs per surface unit (€·ha$^{-1}$), instead, the previously calculated total hourly costs were multiplied for the duration of agricultural operations needed for one hectare. Successively, this amount was divided for yield (expressed in t·ha$^{-1}$) to calculate the cost per biomass unit (€·t$^{-1}$). In such a way, it was possible to estimate the cost of each operation, i.e., accumulation by tractor with fork, comminuting by stationary chipper and truck load by lifter.

A similar procedure was made for transport costs taking into account maintenance costs and operating ones and considering an average transport speed of 50 km·h$^{-1}$. Main parameters for the cost analysis are given in Table 1.

**Table 1.** Main parameters used for the economic analysis of field operations and transport.

| Parameters | Unit | Landini Rex 90 S DT Cab | Caravaggi BIO900 | Agrisav CAS 1000 | Same Virtus 140 dt Cab | Manitou 940–120 LSU | IVECO Trakker 190T36 |
|---|---|---|---|---|---|---|---|
| Investment | € | 54,554.00 | 92,800.00 | 15,060.00 | 96,340.00 | 110,000.00 | 130,850.00 |
| Service life | yr | 10 | 10 | 10 | 10 | 10 | - |
| Usage | h·yr$^{-1}$ | 460 | 460 | 460 | 460 | 460 | - |
| Labor costs | €·h$^{-1}$ | 11.50 | 11.50 | 11.50 | 11.50 | 11.50 | 16.66 |
| Crew | n | 1 | 1 | 1 | 1 | 1 | 1 |
| Load | t | - | - | - | - | - | 16.8 |
| Distance to power plant | km | - | - | - | - | - | 9.3 |

## 3. Results and Discussions

The harvesting system based on the stationary chipper showed a very high harvesting efficiency, because the tractor with fork accumulated the pruning biomass without pauses near the uploading equipment that fed the chipper continuously. In fact, the FE resulted very high and equal to 99% due to an EFC very similar to the TFC. This is a very important aspect, because delay times are instead substantial in pruning harvesting for hog fuel production. As observed also by [21], in the case of the stationary chipping system, its use is nevertheless conditional on the concentration of residues. For this reason, the ability of the tractor driver equipped with a fork to accumulate the material to be chipped continuously without creating idle time for the chipper is a key aspect of achieving high levels of harvesting efficiency. For example, Spinelli et al., dealing with olive-pruning harvesting with a self-propelled harvesting machine, Favaretto Speedy Cut (Favaretto Paolo, Meolo, Veneto Region, Italy), reported that the effective field capacity was more or less 20% lower than the theoretical one [31].

There are not many experiences in literature related to the collection of pruning by a stationary chipper. According to our knowledge, only Borja Velázquez-Mart et al. report results of harvesting pruning by means of a transportable chipper fed by means of a mechanical crane (Jenz AZ 30 D of 74.5 kW (JENZ GmbH Maschinen- und Fahrzeugbau, Petershagen, Nordrhein-Westfalen Region, Germany) and a Ventura Wood-Terminator 7 (Ventura, Aiguaviva, Girona District, Spain) of 60 kW) [21]. According to the reported above paper's results, obtained during the harvesting trials of olive tree-pruning with a stationary chipper, registered a field capacity of 1.75 ha·h$^{-1}$ (0.572 h·ha$^{-1}$) [21]. This value is higher than those recorded in the present study (Table 2) that, on the other hand, is compatible to the value obtainable by applying the predicting model proposed by [21] to evaluate the field capacity of specific harvesting systems, according to the pruning biomass available in the field. So, for collection systems based on stationary chippers, and with an available biomass of 12.8 $t_{fm} \cdot ha^{-1}$, the model reported by [21] predicts a field capacity of 0.59 $ha \cdot h^{-1}$, which is compatible with the 0.6 $ha \cdot h^{-1}$ obtained in the present study.

**Table 2.** Results of the performance and work quality of the stationary harvesting Caravaggio mod. BIO 900.

| Variable | Unit | Value |
|---|---|---|
| Theoretical Field Capacity (TFC) | $ha \cdot h^{-1}$ | 0.61 ± 0.13 |
| Effective Field Capacity (EFC) | $ha \cdot h^{-1}$ | 0.60 ± 0.13 |
| Field efficiency (FE) | % | 99.0 |
| Yield | $t_{fm} \cdot ha^{-1}$ | 12.8 |
| Material Capacity (MC) | $t_{fm} \cdot h^{-1}$ | 7.26 ± 1.13 |
| Material Capacity (MC) | $t_{dm} \cdot h^{-1}$ | 5.23 ± 0.81 |
| Fuel Consumption | $l \cdot t_{fm}$ | 3.5 ± 0.40 |
| Fuel Consumption | $l \cdot h^{-1}$ | 25.1 ± 0.80 |
| Bulk Density | $kg_{fm} \cdot m^{-3}$ | 246 ± 11 |
| Moisture content | % | 28 ± 0.40 |
| d50 value for particle size distribution | mm | 9.17 |
| Particle size distribution class | - | P16 |

Although, an even more important parameter to consider is the material capacity (MC). In fact, the hourly productivity obtained during the test with Caravaggi mod. BIO900 was 7.26 $t_{fm} \cdot h^{-1}$ (5.23 $t_{dm} \cdot h^{-1}$), which is comparable to works in forest systems that were determined by ref [32–34], who reported productivities between 2.5 and 5.5 $t \cdot h^{-1}$ [21]. So, forestry stationary chippers permitted to obtain a high productivity compared to the mobile chippers was also observed by [21]. In fact, previous similar studies showed a material capacity of 6.01 $t_{fm} \cdot h^{-1}$ for a self-propelled SAT-4 (Valoriza Energia-Energy Agency, Villanueva de Algaidas, Andalusia Region, Spain) harvester and 6.77 $t_{fm} \cdot h^{-1}$ for a tractor-mounted Jordan (Jensen Service GmbH, Maasbüll, Schleswig-Holstein, Germany) machine [35]; moreover, only 0.72 $t_{fm} \cdot h^{-1}$ were reported for the Favaretto Speedy Cut [31], and similar values were found for various kinds of towed chippers; in particular: 1.37 $t_{fm} \cdot h^{-1}$ for the Promagri 2000 (Promagri, Casablanca, Casablanca-Settat Region, Morocco); 0.69 $t_{fm} \cdot h^{-1}$ for the Jounes Atila (Jonues I Fills Sl, Lleida, Catalonia Region, Spain); 1.27 $t_{fm} \cdot h^{-1}$ for the Serrat Olipack T1800 (Serrat, Castejón del Puente, Huesca Region, Spain) and 1.38 $t_{fm} \cdot h^{-1}$ for the Berti Picker C180 (Berti, Caldiero, Veneto Region, Italy) [21].

It is obvious that this kind of mechanization chain implies a high fuel consumption per time unit ($l \cdot h^{-1}$). This is because the stationary system employed multiple machines at the same time. On the other hand, thanks to the high work productivity, fuel consumption per biomass unit ($l \cdot {t_{fw}}^{-1}$) was limited and similar, even lower, than other machines for pruning harvesting [36].

For what concerns obtained biomass quality, hog fuel produced by the Caravaggi BIO900 belongs to the particle size class P16 (60% of the product with particles between 3.15 and 16 mm) and a fine fraction class F15 (fine fraction < 15%) Figure 3.

The d50 value (median value of the cumulated distribution curve) is 9.17 mm (Figure 4 and Table 2).

Thus, allowing this kind of hog fuel, for what concerns this parameter, for usage also in small domestic plants and not only in industrial ones [37]. The P16 quality class is not simple to be reached with pruning harvesting, which generally leads to the P31.5 or P45 class [38]. Additionally, bulk density and moisture content showed very interesting results, allowing to reach the A1 and A2 class standards, respectively, according to UNI EN ISO 17225-4 [27].

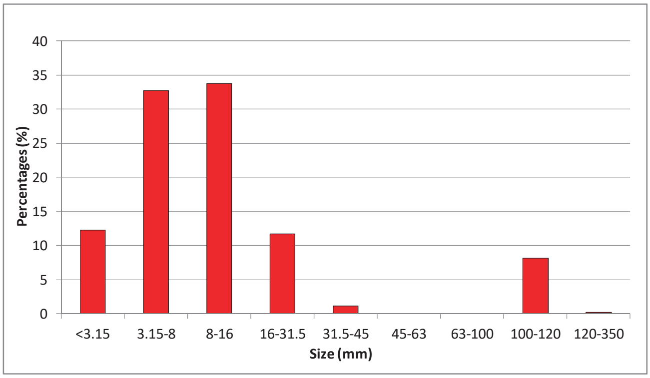


**Figure 3.** Particle size distribution analysis of the hog fuel produced by the Caravaggi mod. BIO900.

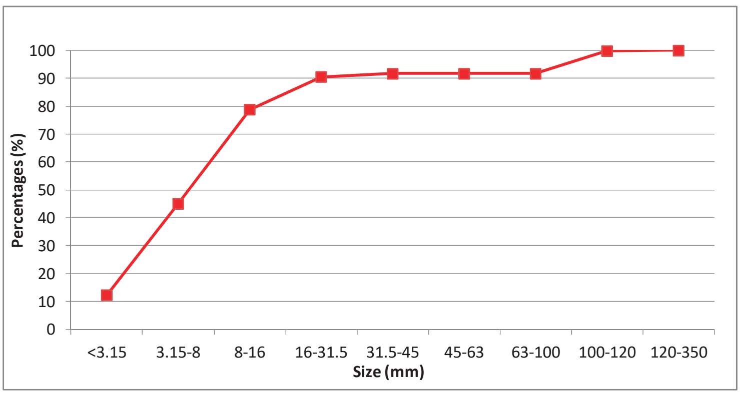


**Figure 4.** Cumulative distribution curves of the hog fuel produced by the Caravaggi mod. BIO900.

Results of the conducted analysis on work productivity and hog fuel quality are given in Table 2.

Focusing on harvesting systems' costs, a detail of these, not considering the transport operation, is given in Table 3, distinguishing, for each machine, fixed and variable costs. As it is possible to notice, Caravaggi BIO900 is the machine which presented the higher costs among the ones used in the investigated harvesting system.

**Table 3.** Harvesting systems' costs subdivided into fixed and variable costs for each applied machine.

| | Cost Item | Measure Unit | Caravaggi BIO900 | Landini Rex 90 S DT Cab | Agrisav CAS 1000 | Same Virtus 140 dt Cab | Manitou 940–120 LSU |
|---|---|---|---|---|---|---|---|
| Fixed costs | Reintegration quote | €·yr$^{-1}$ | 7638.91 | 3644.64 | 1206.74 | 6436.28 | 7360.67 |
| | Interests | €·yr$^{-1}$ | 1638.16 | 1089.92 | 270.79 | 1924.76 | 2195.90 |
| | Shelter | €·yr$^{-1}$ | 45.61 | 14.63 | 27.50 | 21.44 | 28.36 |
| | Insurance | €·yr$^{-1}$ | 232.00 | 136.39 | 37.65 | 240.85 | 275.00 |
| | Miscellaneous expenses | €·yr$^{-1}$ | 277.61 | 151.02 | 65.15 | 262.29 | 303.36 |
| | Total fixed costs per year | €·yr$^{-1}$ | 9554.69 | 4885.58 | 1542.68 | 8623.33 | 9859.93 |
| | Total fixed costs per hour | €·h$^{-1}$ | 20.77 | 10.62 | 3.35 | 18.75 | 21.43 |
| Variable costs | Maintenance | €·h$^{-1}$ | 7.41 | 1.02 | 1.20 | 1.81 | 2.07 |
| | Fuel | €·h$^{-1}$ | 7.20 | 5.04 | | 2.16 | 3.10 |
| | Lubricant | €·h$^{-1}$ | 0.30 | 0.19 | | 0.24 | 0.23 |
| | Manpower | €·h$^{-1}$ | 11.50 | 11.50 | 11.50 | 11.50 | 11.15 |
| | Total variable costs per hour | €·h$^{-1}$ | 18.91 | 17.76 | 12.70 | 15.71 | 16.54 |
| | Total costs per year | €·yr$^{-1}$ | 18253.80 | 13053.99 | 7385.92 | 15847.68 | 17469.68 |
| | Total costs per hour | €·h$^{-1}$ | 39.68 | 28.38 | 16.06 | 34.45 | 37.98 |
| | Total costs per hectare | €·ha$^{-1}$ | 66.14 | 47.30 | 26.76 | 57.42 | 32.77 |
| | Total costs per ton | €·$t_{fm}{}^{-1}$ | 5.47 | 3.92 | 2.22 | 4.75 | 2.71 |

In Table 4, a comparison of the harvesting systems' costs, without the transport operation, with similar studies is shown [31,32].

**Table 4.** Pruning harvesting systems' costs (no wood chips' transports included) and comparison with previous studies on similar topics.

| Harvesting System | Reference | Initial Investment (€) | Harvesting Cost | | |
|---|---|---|---|---|---|
| | | | (€·h$^{-1}$) | (€·ha$^{-1}$) | (€·$t_{fm}^{-1}$) |
| SAT-4 | [32] | 190,000.00 | 158.00 | 67.05 | 29.99 |
| Jordan | [32] | 250,000.00 | 149.00 | 263.20 | 22.53 |
| Favaretto | [31] | 180,000.00 | 77.20 | 97.87 | 58.70 |
| Caravaggi | this study | 368,754.00 | 156.55 | 230.38 | 19.07 |

As it is possible to notice in Table 4, this paper's system is the one with the highest amount of initial investment, and this is linked to the multiple machines needed for the implementation of such a harvesting system. Caravaggi, SAT-4 and Jordan systems showed similar hourly costs; instead, the Favaretto Speedy Cut presented a substantially lower one. However, it should be noted that Favaretto carries out the pruning, harvesting and shredding phases in a single operation. It is also important to stress that the mechanical pruning carried out by Favaretto is not always applicable or adapted to all the olive groves.

About costs per hectare, it is possible to see how the Caravaggi and Jordan showed very similar values, which were consistently higher than the Favaretto and SAT-4. On the other hand, the stationary harvesting system analyzed in the present paper showed the lowest cost per fresh material ton.

For what concerns the transport cost, conducted by an IVECO 190T36 truck for a distance of 9.3 km from the experimental field to the Fiusis power plant, authors found a cost of 10.93 €·$t_{fm}^{-1}$ (1.175 €·t$^{-1}$ km$^{-1}$). It is important to underline the substantial influence of the transport on overall harvesting system costs. In fact, the transport of the shredded material from the olive grove to the Fiusis power station (9.3 km) accounted for about 35% of the total costs. The transport costs obtained from this study are in line with the transport costs of hog fuel or wood chips to power plants of 1.08–1.18 €·t$^{-1}$km$^{-1}$ indicated by a sample of seven wood traders and freelance forestry practitioners working in Central and Southern Italy who were contacted by telephone during the study, as well as the validation obtained by representatives of the Fiusis Plant [39]. Furthermore, during the phone was identified a range of hog fuel prices paid by the power plants, which, in Central and Southern Italy, is actually between 35 and 50 €·t$^{-1}$ for the material conferred to the power plant gate. Considering the overall harvesting system costs (field operations and transport for a 10-km distance), this research showed a value of 30.00 €·$t_{fm}^{-1}$. A profitability analysis showed a positive value ranging from 5 to 15 €·$t_{fm}^{-1}$ depending on the hog fuel price paid from the power plant to the farmer or agro-forestry enterprise, which harvests pruning residues.

According to the findings of the present paper, in the case of the Fiusis power plant which developed a dedicated business unit for pruning harvesting, it is possible to assert that the cost per ton of biomass using the stationary chipper Caravaggi is equal to 30.00 €·$t_{fm}^{-1}$ considering also the transport costs within 10 km. After 27 km, the harvesting and transport costs results become higher than 50 € per ton of biomass, and so, considering the maximum market prices, the operation presents a negative value (Figure 5).

The detail of the harvesting systems' costs for each operation (accumulation of the pruning residues, biomass comminuting, truck load and transport), both considering and not considering transport operation, is given in Figure 6.

As it is possible to notice in Figure 6a, the majority of the costs are imputable to biomass comminuting, but also, the transport operation, as already mentioned, has a consistent impact on the overall costs of the harvesting system (Figure 6b). In detail, 47.30 €·ha$^{-1}$ (3.92 €·$t_{fm}^{-1}$) was necessary for pruning residue accumulations by tractor with an amount of 66.14 €·ha$^{-1}$ (5.47 €·$t_{fm}^{-1}$) was found for biomass comminuting, and a value 32.77 €·ha$^{-1}$ (2.71 €·$t_{fm}{}^{-1}$) was estimated for truck load by the Manitou lifter.

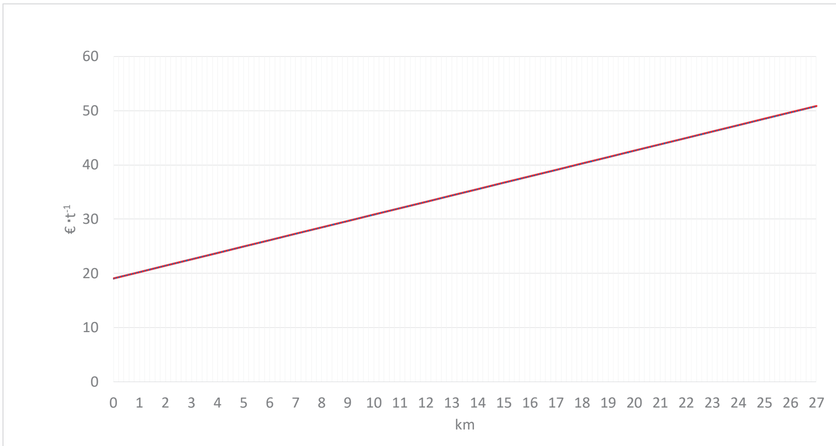


**Figure 5.** Economic thresholds of the transport of the pruning comminuted product of the Caravaggi mod. BIO900 in Italy (Calimera, LE).

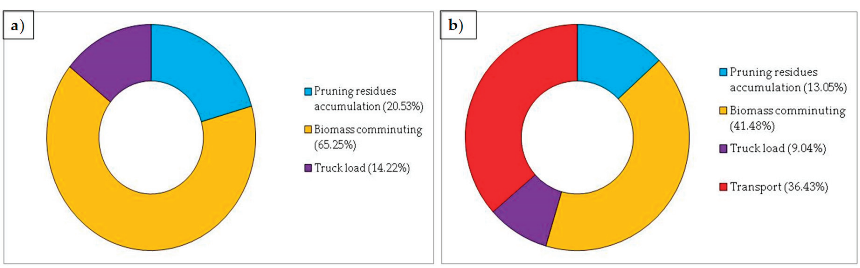


**Figure 6.** (**a**) Percentage of the total costs for field operations. (**b**) Percentage of the total costs considering also transport operation.

A very important consideration to be done evaluating this study's results is the influence of biomass yield on the economic performances of the harvesting system. Considering the high per hectare costs of the Caravaggi system, obviously linked to the multiple machines needed, a substantial amount of pruning residues to be processed is necessary in order to obtain the economic balance of the harvesting system. In particular, the Caravaggi system needs 4.61 $t_{fm}$·ha$^{-1}$ considering the best scenario (maximum hog fuel price of 50 €·$t_{fm}{}^{-1}$) and even 6.58 $t_{fm}$·ha$^{-1}$ considering the worst scenario (minimum hog fuel price of 35 €·$t_{fm}{}^{-1}$). With a biomass yield lower than these values, the investigated harvesting system seemed to be not profitable. Such important amounts of pruning residues are quite frequent in the study area, because olive groves are, in large part, age-old (often secular) trees in which pruning operation is carried out generally every two years. Obviously, this aspect has a strong influence on the logistic of pruning harvesting, and accurate planning is needed to allow for the continuous biomass supply for the power plant. On the other hand, this is an important consideration to be done in the optic of using such harvesting systems in a different context.

However, the investigated harvesting system showed very interesting performances for what concerns work productivity and, so, costs and biomass quality. In particular, the use of a stationary chipper, together with a tractor with fork for pruning residues bunching, seems very feasible for pruning harvesting in olive groves characterized by a considerable amount of biomass to be processed and also located on a hilly situation (slope higher than 20%) not easily affordable by towed shredders, towed chippers or integrated harvester. Moreover, this system allowed to avoid a raking operation.

Finally, there is an important consideration to be done on the harvesting system, which could lead to an additional improvement of its efficiency. This consists of the possibility of conveying comminuted material from the stationary chipper directly into the truck dumpster, instead of discharging it on the ground and then loading it with a Manitou lifter. This could allow, from the one hand, to avoid an operation, so reducing costs and improving the overall work productivity of the harvesting chain, and, on the second hand, it would also improve biomass quality, limiting soil contamination of the comminuted material and, so, reducing the hog fuel's ash content. In any case, future dedicated studies would be necessary to verify the feasibility of the proposed improvement

## 4. Conclusions

Summarizing, the use of a stationary chipper as a pruning harvesting system seemed to be a very interesting solution; in particular, in olive groves characterized by consistent biomass yields and considerable slopes. This system showed very high work productivity if compared to other similar studies on different machines and harvesting systems. This elevated productivity allowed to obtain a low hog fuel production cost, referred to as the biomass unit (€·$t_{fm}{}^{-1}$). Transport cost from the field to the nearest power plant strongly influenced overall costs, consisting of more than one-third of the total cost. Notwithstanding this, the investigated harvesting systems seemed to be feasible in the study area context, allowing to obtain also a little economic gain from the materials, which is actually considered a problem and not a possible resource.

Focusing on obtained the hog fuel quality, it is possible to notice good performances for the investigated parameters (moisture, bulk density and particle size distribution), which reached elevated quality standards. A deeper study on hog fuel quality, taking into consideration also chemical composition, ash content and heating value, is however needed to evaluate hog fuel quality and assessing its possible usage.

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## Abbreviations

| | |
|---|---|
| GHG | greenhouse gases |
| SC | stationary chipper |
| TFC | theoretical field capacity (ha·$h^{-1}$) |
| EFC | effective field capacity (ha·$h^{-1}$) |
| FC | field efficiency % |
| MC | material capacity (t·$h^{-1}$) |
| PSD | particle size distribution |
| WT | working time |
| B | biomass |

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# Energy Value of Yield and Biomass Quality of Poplar Grown in Two Consecutive 4-Year Harvest Rotations in the North-East of Poland

**Mariusz Jerzy Stolarski, Kazimierz Warmiński * and Michał Krzyżaniak**

Faculty of Environmental Management and Agriculture, Centre for Bioeconomy and Renewable Energies, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, 10-724 Olsztyn, Poland; mariusz.stolarski@uwm.edu.pl (M.J.S.); michal.krzyzaniak@uwm.edu.pl (M.K.)

* Correspondence: kazimierz.warminski@uwm.edu.pl; Tel.: +48-89-5233560

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**Abstract:** Bioenergy accounts for 61.7% of all renewable energy sources, with solid fuels accounting for 43% of this amount. Poplar plantations can deliver woody biomass for energy purposes. A field experiment with poplar was located in the north-east of Poland on good quality soil formed from medium loam. The study aimed to determine the yield, the energy value of the yield and the thermophysical properties and elemental composition of the biomass of four poplar clones harvested in two consecutive 4-year harvest rotations. The highest biomass energy value was determined in the UWM 2 clone in the second harvest rotation (231 GJ $ha^{-1}\cdot year^{-1}$). This value was 27–47% lower for the other clones. The biomass quality showed that poplar wood contained high levels of moisture and low levels of ash, sulphur, nitrogen and chlorine. This indicates that poplar can be grown in the north-east of Poland and that it gives a yield with a high energy value and beneficial biomass properties from the energy generation perspective.

**Keywords:** populus; biomass; yield energy value; lower heating value; ash content; sulphur

## 1. Introduction

Renewable energy sources (RES) are enjoying increasing interest, both on the global scale and in the European Union (EU-28) [1–6]. Energy from renewable sources accounted for 18.1% of the final gross energy consumption around the world in 2017 and 17.5% in the EU-28 [7]. It is noteworthy that bioenergy plays a major role as renewable energy in the EU-28 as it accounted for 61.7% of all RES, with solid fuels accounting for 43% of that amount. Bioenergy plays still a larger role as renewable energy in Poland as it accounted for 81.5% of all RES, with solid fuels accounting for 70.5% of that amount. Solid biomass is derived mainly as wood from forests and wood processing plants. Wood can also be obtained from plantations of woody crops (e.g., poplar, willow, black locust, eucalyptus) set up on agricultural land for biomass production in short harvest rotations. The production of biomass as feedstock for energy generation and industrial processes on short rotation woody crops (SRWC) plantations is still being developed in many countries in Europe [8–16], the USA and Canada [17–21].

Poplar is mainly grown in the southern regions of Europe [22–24]. Spain has the largest area of poplar plantations for paper production and (partly) for the power industry (135.7 thousand ha) in 2008 [22]. According to Bioenergy Europe data [25], poplar in the SRWC system in the EU-28 is grown on an area of 20,691 ha. The largest portion of this area is in Poland: approximately 9000 ha. Moreover, plantations of poplar in the SRWC system can be found in Hungary, Austria, Czech Republic, Romania and Sweden. This indicates that interest in the cultivation of poplar in the SRWC system is also growing in the north of Europe [26]. This stems mainly from the fact that paper mills are interested in obtaining this raw material for paper production; it is also an object of interest of plants converting biomass for energy generation. For example, in Poland, International Paper Kwidzyn initiated a poplar planting scheme with an area of 7.5 thousand ha [27,28]. Moreover, poplar is of great interest for future, large-scale biomass production to meet the demands of the bioenergy sector [26], in particular, in the cascade use of biomass in biorefineries. In this case, bioactive substances and other phytochemicals are first extracted and the post-extraction biomass is used for bioenergy production [29]. Poplar biomass can be burned in the form of wood chips, successfully processed to pellets [30] or gasified to obtain good-quality, low-contaminated syngas [31].

However, the production of poplar biomass in the north of Europe, including Poland, is still a relatively new issue and there is a shortage of data from long-term studies of the productivity of different cultivars or clones as well as energy value and quality of biomass. Therefore, the study aimed to determine the yield, energy value of yield and the thermophysical properties and elemental composition of the biomass of four cultivars of poplar harvested in two consecutive 4-year harvest rotations.

## 2. Materials and Methods

### 2.1. Setting up and Conducting the Field Experiment

The study was based on a field experiment with poplar located in the north-east of Poland, at the Didactic and Research Station (53°35′ N, 20°36′ E) of the University of Warmia and Mazury in Olsztyn. The experiment was conducted on good quality soil formed from medium loam. The soil pH was neutral-to-alkaline ($pH_{KCl}$ 7.14). The phosphorus, potassium and magnesium contents were: 69, 214 and 59 mg $kg^{-1}$.

Four clones of poplar *Populus balsamifera* L. were grown in the experiment: UWM 1, UWM 2, UWM 3, UWM 4. Eighty-eight 20-cm cuttings of each clone were planted in mid-April 2007. The experiment was performed in one-way strip design with four replications, 22 cuttings were planted on one plot. Each clone was planted on an area of 36.3 $m^2$, on a 6.6 × 5.5 m block. The poplar cuttings in this pilot experiment were planted at a high density of 24,000 $ha^{-1}$. Manual weeding was performed in the first (2007) and second (2008) year of growth; no plant protection procedures were conducted in the other years. No mineral fertilisers were applied in the year of setting up the plantation. Fertilisers at the following rates were sown in the second (2008) and fifth (2011) years of the experiment: 90 kg $ha^{-1}$ N, 13 kg $ha^{-1}$ P and 49.8 kg $ha^{-1}$ K. Poplar was harvested in two consecutive 4-year harvest rotations. The first rotation covered the years 2007–2010, the second—the years 2011–2014. The poplar was harvested in winter, i.e., in February/March 2011 and 2015.

### 2.2. Determination of the Biomass Yield, Energy Value of Yield and Biomass Quality

For the calculation of the biomass yield, all plants from each field were cut manually using a chainsaw. The plants were then all weighed to determine the biomass yield per plot and per 1 ha. While harvesting, all plants (main stem and branches) were cut with a chopper into wood chips and from this biomass blend, representative collective biomass samples (approx. 3 kg) were taken for each clone and placed in plastic bags and transported to a laboratory. In the laboratory, laboratory samples were taken for further analyses. The dry matter yield in two consecutive 4-year harvest rotations was calculated after the moisture content was determined. The moisture content in biomass was determined by drying and weighing, as per EN ISO 18134-1:2015. To this end, biomass was dried at 105 °C until a constant weight was achieved, using a laboratory dryer (FD BINDER, Tuttlingen) and precision scales of 1 mg graduation (Radwag). Subsequently, the dry biomass was ground in an analytic mill, with a 1-mm mesh sieve (Retsch SM 200, Haan). The prepared samples were used for determination of ash at 550 °C, volatile matter at 650 °C and fixed carbon in an ELTRA TGA-THERMOSTEP automatic thermogravimetric analyser as per PN-EN ISO 18122:2016-01 and PN-EN ISO 18123:2016-01. The higher heating value (HHV) of the poplar biomass was determined by the dynamic method in an IKA C2000 calorimeter. Subsequently, the HHV and the moisture content were used to calculate the lower heating value (LHV) for each poplar clone from each harvest rotation (PN-EN ISO 18125:2017-07).

The contents of carbon (C), hydrogen (H) and sulphur (S) were determined in poplar biomass with an automatic ELTRA CHS 500 analyser (PN-EN ISO 16948:2015-07 and PN-EN ISO 16994:2016-10). A nitrogen assay was conducted using Kjeldahl's method on a K-435 mineraliser and a B-324 BUCHI distilling device. The chlorine content was determined with an Eschka mixture.

The yield energy value of the poplar biomass was calculated as the product of the mean yield of fresh biomass (f.m.) for each clone from two consecutive 4-year rotations and the biomass LHV – from formula 1. Moreover, the biomass yield energy value was also converted to one year of plantation use.

$$Y_{ev} = Y_b \times LHV^{wb} \quad (1)$$

where:

- $Y_{ev}$—biomass yield energy value (GJ $ha^{-1}$),
- $Y_b$—biomass yield (Mg $ha^{-1}$ f.m.),
- $LHV^{wb}$—biomass lower heating value (wb—wet basis) (GJ $Mg^{-1}$).

### 2.3. Statistical Analysis

The variance analysis model with repeated measures was used, in which the clone was used as the constant and grouping factor, while subsequent harvest rotations were the factor of repeated measures. The level of significance of the analysis was established at $P < 0.05$. The arithmetic mean and standard deviation were calculated for each of the analysed features. Homogeneous groups were identified with the Tukey significance test (HSD). Significantly different values were denoted with letters in the following manner: A.B.C ... denote homogenous groups for clone; ***a.b*** ... denote homogenous groups for rotation; a.b.c ... denote homogenous groups for clone x rotation interaction. Moreover, Pearson's r correlation coefficients between the features under study were also determined. All statistical analyses were done with the STATISTICA software (version 13.3).

## 3. Results and Discussion

### 3.1. Biomass Yield and its Energy Value

Both the poplar biomass yield and its energy value were significantly differentiated by the clone, harvest rotation and the interaction of these attributes (Table 1). The significantly largest fresh and dry biomass yields were obtained from the UWM 2 clone—89.5 Mg $ha^{-1}$ and 40.0 Mg $ha^{-1}$ from the two 4-year rotations, respectively (Table 2). These figures for the UWM 3 and UWM 1 clones were lower by ca. 30% and 40%, respectively, and the yield from the UWM 4 clone was more than twice smaller than that of UWM 2. The average yields of fresh (87.4 Mg $ha^{-1}$) and dry biomass (40.6 Mg $ha^{-1}$ DM—dry matter) of poplar in the second 4-year rotation were significantly higher (by 260% and 278%, respectively) compared to the average yield from the first harvest rotation. The significantly largest average yields of fresh (119.7 Mg $ha^{-1}$) and dry biomass (54.5 Mg $ha^{-1}$ DM) were obtained from the UWM 2 clone in the second 4-year harvest rotation. Expressed per 1 year of the plantation use, they were 29.9 Mg $ha^{-1}$ $year^{-1}$ and 13.6 Mg $ha^{-1}$ $year^{-1}$ DM, respectively. However, the average dry biomass yield for the four poplar clones under study was lower in the second rotation: 10.1 Mg $ha^{-1}$ $year^{-1}$ DM, and it was very low in the first rotation: merely 3.6 Mg $ha^{-1}$ $year^{-1}$ DM

**Table 1.** Analysis of variance repeated measure for the analysed features *.

| Source of Variation | Degrees of Freedom | *P* Value for | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fresh Biomass Yield | Dry Biomass Yield | Yield Energy Value | Moisture | Fixed Carbon | Volatile Matter | Ash | HHV | LHV | C | H | S | N | Cl |
| Clone | 3 | <0.001 * | <0.001 * | <0.001 * | <0.001 * | 0.679 | 0.679 | 0.566 | 0.183 | <0.001 * | 0.075 | 0.132 | 0.948 | 0.783 | 0.218 |
| Error(1) | 12 | | | | | | | | | | | | | | |
| Rotation | 1 | <0.001 * | <0.001* | <0.001 * | <0.001 * | <0.001 * | 0.915 | 0.005 * | 0.014 * | <0.001 * | 0.001 * | 0.706 | 0.740 | 0.940 | <0.001 * |
| Rotation x Clone | 3 | 0.020 * | 0.015 * | 0.013 * | 0.086 | 0.847 | 0.848 | 0.001 * | 0.356 | 0.116 | 0.324 | 0.976 | 0.952 | 0.830 | 0.118 |
| Error(2) | 12 | | | | | | | | | | | | | | |

* asterisk indicatesstatistically significant values at $P < 0.05$.

**Table 2.** Yield and yield energy value of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Fresh Biomass Yield (Mg ha$^{-1}$) | | | Dry Biomass Yyield (Mg ha$^{-1}$) | | | Yield Energy Value (GJ ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 20.0 ± 5.3d | 83.0 ± 6.8b | 51.5 ± 34.1B | 9.1 ± 2.4d | 39.4 ± 3.2b | 24.2 ± 16.4B | 148.3 ± 39.1d | 663.6 ± 54.6b | 405.9 ± 278.9B |
| UWM 2 | 59.3 ± 10.9c | 119.7 ± 5.1a | 89.5 ± 33.2A | 25.6 ± 4.7c | 54.5 ± 2.3a | 40.0 ± 15.8A | 421.4 ± 77.7c | 922.6 ± 39.2a | 672.0 ± 273.9A |
| UWM 3 | 37.6 ± 8.9cd | 87.1 ± 3.4b | 62.3 ± 27.2B | 15.7 ± 3.7d | 40.0 ± 1.6b | 27.8 ± 13.3B | 254.2 ± 60.2d | 671.2 ± 26.3b | 462.7 ± 227.1B |
| UWM 4 | 17.6±10.3d | 59.7 ± 3.7c | 38.7 ± 23.6C | 8.0 ± 4.7d | 28.4 ± 1.8c | 18.2 ± 11.4C | 133.2 ± 78.1d | 484.6 ± 30.1c | 308.9 ± 195.6C |
| Mean | 33.6±19.1*b* | 87.4 ± 22.5*a* | 60.5 ± 34.2 | 14.6 ± 8.1*b* | 40.6 ± 9.8*a* | 27.6 ± 15.9 | 239.3 ± 132.5*b* | 685.5 ± 164.8*a* | 462.4 ± 270.2 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

In a different study conducted in Poland, the yield of poplar *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 in a 4-year harvest rotation was 8.2 Mg ha$^{-1}$ year$^{-1}$ DM [11]. The experiment cited above demonstrates the significant effect of different methods of soil enrichment on poplar yield; it was the highest on a plot in which lignin was applied in combination with mineral fertilisers (10.5 Mg ha$^{-1}$ year$^{-1}$ DM). The poplar yield on a control plot, with no soil enrichment, was lower by 48%. A higher yield from a poplar plantation was obtained in Italy [32]. A clone of *Populus deltoides* L. in a 2-year harvest rotation gave a yield of 11.7 Mg ha$^{-1}$ year$^{-1}$ DM. Moreover, extending the harvest rotation to three and four years had a significant positive effect on the poplar yield, causing it to increase to 15.0 and 18.4 Mg ha$^{-1}$ year$^{-1}$ DM. A similarly high yield of poplar in a 4-year harvest rotation (18.0 Mg ha$^{-1}$ year$^{-1}$ DM) was found for the clone *Populus maximowiczii* × *P. nigra* (NM6) in Canada [20]. A very high yield of six genotypes of poplar in three consecutive two-year harvest rotations was obtained in Italy by Sabatti et al. [33]. In that experiment, poplar was grown at an agricultural site with highly productive soil and a large amount of nitrogen fertilisation. Biomass production differed significantly among rotations starting from 16 Mg ha$^{-1}$ year$^{-1}$ DM in the first, peaking at 20 Mg ha$^{-1}$ year$^{-1}$ DM in the second, and decreasing to 17 Mg ha$^{-1}$ year$^{-1}$ DM in the third rotation. However, other authors have reported that seven clones of poplar of the *Populus* × *canadensis* and seven of the *Populus deltoides* species grown in Italy did not give such a high yield [34]. It was found after nine years of poplar cultivation and four harvest rotations that the average yield of biomass of the *Populus deltoides* species was 9.7 Mg ha$^{-1}$ year$^{-1}$ DM, and it was lower for clones of the *Populus* x *canadensis* species—5.6 Mg ha$^{-1}$ year$^{-1}$ DM. It was shown in the study cited above that the average yield for 14 poplar clones was 8.34 Mg ha$^{-1}$ year$^{-1}$ DM. The yield of poplar obtained in other studies also varied (1.6–28 Mg ha$^{-1}$ year$^{-1}$ DM) depending on the climatic conditions, the type of soil, species and clone, harvest rotation, age of the plantation, level of fertilisation and other agricultural procedures [35–39]. It was also demonstrated that the annual yield of poplar biomass increased with the age of plants up to a maximum between the third and fourth growing seasons [40]. In a study in Belgium, the average dry biomass yield of poplar established on degraded land and maintained as a low-energy input system during the fourth rotation was 4.3±3.4 Mg ha$^{-1}$ year$^{-1}$ DM across all clones, but the most productive clones yielded up to 10.5 Mg ha$^{-1}$ year$^{-1}$ DM [41]. Therefore, it can be claimed that the yield was very similar to that obtained in the current study.

The energy value of poplar yield (calculated as the product of fresh biomass yield and its LHV) harvested in two consecutive 4-year rotations was 462 GJ ha$^{-1}$, with a high standard deviation of 270 GJ ha$^{-1}$, which showed a high differentiation of this parameter between clones and harvest rotations (Table 2). The significantly largest yield energy value was obtained from the UWM 2 clone—672 GJ ha$^{-1}$ on average from the two 4-year rotations (Table 2). The mean value of this attribute for the UWM 3, UWM 1 and UWM 4 clones was lower by ca. 31%, 40% and 54%, respectively. The mean biomass yield energy value for the second 4-year rotation was higher by as much as 290% compared to the value from the first harvest rotation. The significantly highest yield energy value was found in the UWM 2 clone in the second harvest rotation: 230.6 GJ ha$^{-1}$ year$^{-1}$ (Figure 1). The energy value of UWM 1 and UWM 3 clones in the second rotation was nearly 170 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group b). Meanwhile, the attribute value for the UWM 4 clone was approx. 120 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group c). Furthermore, in the first rotation, only the yield energy value of the UWM 2 clone exceeded 100 GJ ha$^{-1}$ year$^{-1}$ (homogeneous group c), and the other clones were in the last (homogeneous group d). Different results of yield energy value resulted mainly from different yields and biomass LHV, both between the clones and the rotations, since the yield energy value was calculated based on these two parameters. In the first rotation, the yield and biomass LHV were significantly lower than those obtained in the second rotation. The higher biomass yield in the second rotation resulted from the fact that poplar plants developed a considerably more developed root system compared with the plants of the first rotation when the root system underwent systematic expansion. It should be concluded that the differences in yield energy value between the studied clones were of genetic background since poplars were cultivated in analogous climatic and soil conditions.

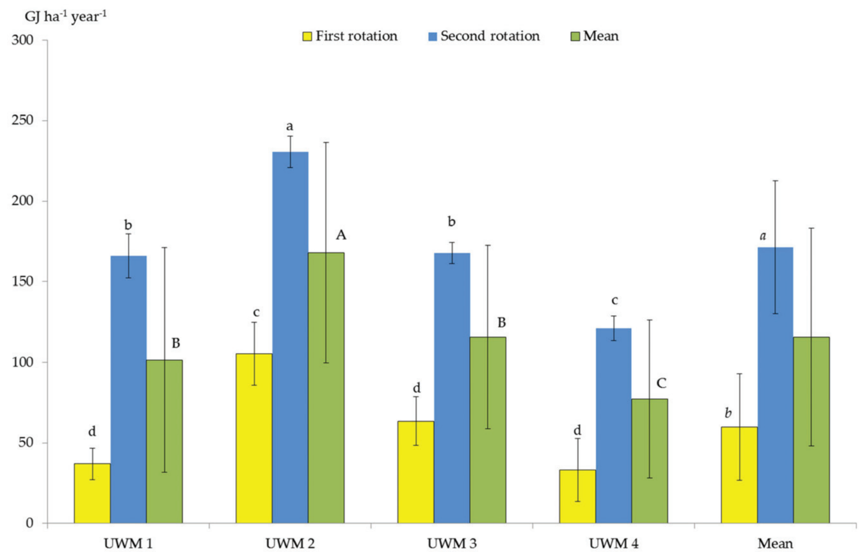


**Figure 1.** Yield energy value of four poplar clones in two consecutive 4-year harvest rotations converted to one year of the plantation use. A.B.C ... homogenous groups for clone; *a.b* ... homogenous groups for rotation; a.b.c ... homogenous groups for clone x rotation interaction; error bars represent standard deviations.

The highest yield energy value for *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 (177 GJ ha$^{-1}$ year$^{-1}$) in the authors' other study was achieved on soil enriched with lignin and mineral fertilisers. The value of the attribute with other soil enrichment combinations was lower by 11–48% [11]. A similar energy value of poplar yield of 188 GJ ha$^{-1}$ year$^{-1}$ was achieved in its production in a two-year harvest cycle [42]. In other studies conducted in Italy, the energy value of poplar biomass grown in different harvest cycles, with mineral fertilisation and irrigation, was much higher—257 GJ ha$^{-1}$ year$^{-1}$ [43] and 270 GJ ha$^{-1}$ year$^{-1}$ [15]. Nassi o Di Nasso et al. [44] analysed the effect of harvest rotation cycles (annual, biannual, triennial) on the energy balance of a 12-year-old short-rotation coppice poplar with mineral fertilization and obtained an even higher energy value of biomass of 450 GJ ha$^{-1}$ year$^{-1}$ after the first triennial cutting cycle. However, the energy value of the yield decreased to 350, 289 and 127 GJ ha$^{-1}$ year$^{-1}$ in the second, third and last triennial cutting cycle, respectively, which resulted in an average of 304 GJ ha$^{-1}$ year$^{-1}$ during the whole period of the plantation use. On the other hand, the energy value of poplar yield obtained in extensive cultivation in a 4-year harvest rotation was much lower (70.9 GJ ha$^{-1}$ year$^{-1}$) [45]. This was confirmed by a study conducted by Dillen et al. [41], which showed that the energy value of the yield of poplar grown on degraded land was about 92 GJ ha$^{-1}$ year$^{-1}$. However, when poplar was grown in Sweden (long harvest cycle), the gross energy yields over the plantation live cycle (24 years) were 4710 and 4430 GJ ha$^{-1}$, for fertilized and unfertilized poplar, respectively, which corresponded to 196 and 185 GJ ha$^{-1}$ year$^{-1}$, respectively [26]. Therefore, the mean yield energy value obtained in the current study in north-eastern Poland for the UWM 2 clone (168 GJ ha$^{-1}$ year$^{-1}$) and, especially, the much higher value in the second 4-year harvest rotation (231 GJ ha$^{-1}$ year$^{-1}$), should be seen as high and satisfactory.

### *3.2. Thermophysical Properties and Elemental Composition of Biomass*

The poplar biomass moisture content was significantly differentiated by the clone and harvest rotation, while the fixed carbon content was only significantly differentiated by the harvest rotation (Table 1). The average poplar biomass moisture content in the experiment was 54.8% wb (Table 3). The UWM 3 and UWM 2 clones contained significantly more moisture compared to the other two clones. Moreover, the moisture content in the first 4-year harvest rotation (56.2%) was significantly (by 2.8 p.p.) higher compared to the mean moisture content in the second harvest rotation. The average content of fixed carbon and volatile matter in 4-year poplar shoots was 18.6% DM and 79.4% DM, respectively. In another study by the authors, the fixed carbon and volatile matter content in 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was 20.8% d.m and 77.4% DM, respectively, and the moisture content was 55.7% [46]. Other studies have also confirmed that the moisture content in poplar upon harvest is high and exceeds 50%; sometimes even exceeding 60% [33,47–50].

**Table 3.** Moisture content, fixed carbon and volatile matter content in the biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Moisture Content (%) | | | Fixed Carbon (% DM) | | | Volatile Matter (% DM) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 54.7 ± 0.1 | 52.6 ± 1.2 | 53.7 ± 1.4B | 18.7 ± 0.2 | 18.1 ± 0.6 | 18.4 ± 0.6 | 79.5 ± 0.5 | 79.4 ± 1.1 | 79.4 ± 0.7 |
| UWM 2 | 56.9 ± 1.0 | 54.5 ± 0.2 | 55.7 ± 1.5A | 19.0 ± 0.7 | 18.2 ± 0.7 | 18.6 ± 0.8 | 79.5 ± 1.0 | 79.4 ± 0.9 | 79.5 ± 0.9 |
| UWM 3 | 58.3 ± 0.7 | 54.1 ± 0.2 | 56.2 ± 2.4A | 18.9 ± 0.4 | 17.9 ± 0.3 | 18.4 ± 0.6 | 79.7 ± 0.6 | 79.6 ± 0.5 | 79.7 ± 0.5 |
| UWM 4 | 54.7 ± 0.2 | 52.3 ± 1.0 | 53.5 ± 1.4B | 19.2 ± 0.2 | 18.4 ± 0.7 | 18.8 ± 0.6 | 78.8 ± 0.8 | 79.1 ± 1.1 | 78.9 ± 0.9 |
| Mean | 56.2 ± 1.7***a*** | 53.4 ± 1.2***b*** | 54.8 ± 2.0 | 19.0 ± 0.4***a*** | 18.2 ± 0. ***b*** | 18.6 ± 0.6 | 79.4 ± 0.7 | 79.4 ± 0.8 | 79.4 ± 0.8 |

± standard deviations; A.B.C ... homogenous groups for clone; ***a.b*** ... homogenous groups for rotation; a.b.c ... homogenous groups for clone × rotation interaction.

The ash content in poplar biomass was significantly differentiated by harvest rotations and the interactions between the harvest rotation and the clone and was 1.4% DM on average (Tables 1 and 4). The ash content in 4-year old poplar trees throughout the experiment ranged from 1.0 to 1.8% DM. On the other hand, HHV was significantly differentiated by the harvest rotation, and LHV was significantly differentiated by the clone and harvest rotation (Table 1). LHV of poplar biomass as measured in this experiment was 7.5 MJ $kg^{-1}$ (Table 4). The LHV values of UWM 4 and UWM 1 clones (homogeneous group A) were significantly higher compared to the other two clones (homogeneous group B). The LHV of poplar obtained in the second 4-year harvest rotation was significantly higher compared to the first harvest rotation. In another study, the average ash content in 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was slightly higher (1.8% DM), and the LHV was very similar (7.5 MJ $kg^{-1}$) [46]. Different LHV results in our study were determined by different moisture content and biomass HHV between the rotations since LHV was calculated based on these two parameters. In the second rotation, biomass moisture content was lower while HHV was higher, which resulted in a higher LHV when compared with those values obtained in the first rotation. Other studies have also shown that the ash content in poplar biomass may vary (0.98–3.12% DM) depending on the cultivar/clone, harvest rotation and other factors [33,47–49].

**Table 4.** Ash content, higher and lower heating value of biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | Ash Content (% DM) | | | Higher Heating Value (MJ kg−1 DM) | | | Lower Heating Value (MJ kg−1) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 1.5 ± 0.4a | 1.6 ± 0.4a | 1.6 ± 0.4 | 19.3 ± 0.1 | 19.6 ± 0.2 | 19.4 ± 0.2 | 7.4 ± 0.1 | 8.0 ± 0.2 | 7.7 ± 0.3A |
| UWM 2 | 1.2 ± 0.3b | 1.5 ± 0.4a | 1.3 ± 0.3 | 19.7 ± 0.2 | 19.9 ± 0.2 | 19.8 ± 0.2 | 7.1 ± 0.1 | 7.7 ± 0.0 | 7.4 ± 0.3B |
| UWM 3 | 1.0 ± 0.2b | 1.5 ± 0.2a | 1.2 ± 0.3 | 19.6 ± 0.1 | 19.7 ± 0.3 | 19.6 ± 0.2 | 6.8 ± 0.1 | 7.7 ± 0.1 | 7.2 ± 0.5B |
| UWM 4 | 1.8 ± 0.6a | 1.5 ± 0.4a | 1.6 ± 0.5 | 19.6 ± 0.1 | 19.7 ± 0.2 | 19.7 ± 0.2 | 7.6 ± 0.1 | 8.1 ± 0.2 | 7.8 ± 0.3A |
| Mean | 1.4 ± 0.4***b*** | 1.5 ± 0.3***a*** | 1.4 ± 0.4 | 19.6 ± 0.2***b*** | 19.7 ± 0.2***a*** | 19.6 ± 0.2 | 7.2 ± 0.3***b*** | 7.9 ± 0.2***a*** | 7.5 ± 0.4 |

± standard deviation; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

An assessment of the content of selected elements found that only the harvest rotation affected the C and Cl content (Table 1). Significantly higher carbon content (average 51.5% DM) and lower chlorine content (average 0.009% DM) were found in the second 4-year harvest rotation (Tables 5 and 6). The mean content of C, H, S, N and Cl in 4-year old poplar shoots was 51.1, 6.0, 0.028, 0.41 and 0.013% DM, respectively. A significant positive correlation was found between the S and N content (0.91) and between the ash content and N content (0.67) and S content (0.63) (Table 7). Moreover, a positive correlation was found between the fixed carbon content and the S, N and Cl content. The C, H, S and N content as determined in the authors' earlier examinations of 4-year old shoots of *Populus nigra* × *P. Maximowiczii* Henry cv. Max-5 was similar: 51.0, 5.8, 0.024, 0.44% DM [46]. The C, H, S and N content in other studies was also similar: 50.3, 6.1, 0.03 and 0.42% DM [50]. A slightly higher content of C, H, S (51.8, 6.4, 0.04% DM, respectively) and a lower content of N (0.16% DM) in biomass of *Populus* x *euroamericana* (Dode) Guinier (AF2) was found by Monedero et al. 2017 [49]. Considering the above, it could be concluded that poplar biomass may serve as fuel with potentially low $SO_2$ and particulate emission due to the low content of sulphur and ash. Moreover, the type of biomass conversion technology and equipment (e.g., boilers) used are of great importance here as well. It should be stressed that burning poplar biomass in small boilers with manual fuel feeding (old type) and stove, like any other solid fuel, may pose problems with black carbon, polycyclic aromatic hydrocarbons and volatile organic compounds emissions. Therefore, the use of modern automatic boilers for home heating and fluidal boilers in power plants and heat power plants is recommended. Such combustion technologies ensure low emissions of atmospheric pollutants [51–53]. Combustion of the studied poplar biomass should not cause any significant corrosion of boiler elements since this biomass contains low amounts of chlorine and the S/Cl ratio based on the current study averaged 2.2. It is accepted that high-temperature corrosion occurs intensively when the fuel chloride contents are over 0.2%, and the S/Cl ratio is below 2.2 [54,55].

**Table 5.** Content of carbon (C), hydrogen (H) and sulphur (S) in biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | C (% DM) | | | H (% DM) | | | S (% DM) | | |
|---|---|---|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 50.1 ± 0.2 | 51.1 ± 0.5 | 50.6 ± 0.6 | 5.9 ± 0.1 | 5.9 ± 0.1 | 5.9 ± 0.1 | 0.030 ± 0.002 | 0.028 ± 0.013 | 0.029 ± 0.008 |
| UWM 2 | 50.5 ± 0.9 | 52.0 ± 0.0 | 51.2 ± 1.0 | 6.0 ± 0.1 | 6.0 ± 0.1 | 6.0 ± 0.1 | 0.028 ± 0.004 | 0.024 ± 0.015 | 0.026 ± 0.010 |
| UWM 3 | 50.7 ± 0.4 | 51.4 ± 0.5 | 51.0 ± 0.5 | 6.0 ± 0.1 | 5.9 ± 0.1 | 5.9 ± 0.1 | 0.026 ± 0.004 | 0.026 ± 0.013 | 0.026 ± 0.009 |
| UWM 4 | 51.4 ± 0.6 | 51.8 ± 0.6 | 51.6 ± 0.6 | 5.9 ± 0.0 | 6.0 ± 0.1 | 6.0 ± 0.0 | 0.029 ± 0.005 | 0.030 ± 0.022 | 0.029 ± 0.014 |
| Mean | 50.7 ± 0.7***b*** | 51.5 ± 0.5***a*** | 51.1 ± 0.7 | 5.9 ± 0.1 | 6.0 ± 0.1 | 6.0 ± 0.1 | 0.028 ± 0.004 | 0.027 ± 0.014 | 0.028 ± 0.010 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

**Table 6.** Content of nitrogen (N) and chlorine (Cl) in biomass of four poplar clones in two consecutive 4-year harvest rotations.

| Clone | N (% DM) | | | Cl (% DM) | | |
|---|---|---|---|---|---|---|
| | First Rotation | Second Rotation | Mean | First Rotation | Second Rotation | Mean |
| UWM 1 | 0.46 ± 0.1 | 0.51 ± 0.3 | 0.48 ± 0.2 | 0.011 ± 0.003 | 0.009 ± 0.004 | 0.010 ± 0.003 |
| UWM 2 | 0.40 ± 0.1 | 0.34 ± 0.2 | 0.37 ± 0.1 | 0.018 ± 0.004 | 0.009 ± 0.003 | 0.014 ± 0.006 |
| UWM 3 | 0.39 ± 0.1 | 0.33 ± 0.2 | 0.36 ± 0.1 | 0.017 ± 0.004 | 0.009 ± 0.005 | 0.013 ± 0.006 |
| UWM 4 | 0.41 ± 0.1 | 0.47 ± 0.3 | 0.44 ± 0.2 | 0.024 ± 0.001 | 0.009 ± 0.008 | 0.017 ± 0.010 |
| Mean | 0.42 ± 0.1 | 0.41 ± 0.2 | 0.41 ± 0.2 | 0.018 ± 0.005*a* | 0.009 ± 0.004*b* | 0.013 ± 0.007 |

± standard deviations; A.B.C … homogenous groups for clone; ***a.b*** … homogenous groups for rotation; a.b.c … homogenous groups for clone x rotation interaction.

**Table 7.** Simple correlation coefficient between the analyzed features*.

| Item | Moisture | Fixed Carbon | Volatile Matter | Ash | HHV | LHV | C | H | S | N | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Moisture | 1.00 | | | | | | | | | | |
| Fixed Carbon | 0.58 * | 1.00 | | | | | | | | | |
| Volatile Matter | −0.04 | −0.72 * | 1.00 | | | | | | | | |
| Ash | −0.30 | 0.34 | −0.79 * | 1.00 | | | | | | | |
| HHV | 0.15 | 0.32 | −0.54 * | 0.36 | 1.00 | | | | | | |
| LHV | −0.97 * | −0.52 * | −0.08 | 0.38 | 0.07 | 1.00 | | | | | |
| C | −0.41 * | −0.25 | −0.19 | 0.15 | 0.51 * | 0.53 * | 1.00 | | | | |
| H | 0.11 | −0.08 | 0.07 | −0.16 | 0.15 | −0.08 | 0.36 | 1.00 | | | |
| S | 0.15 | 0.64 * | −0.79 * | 0.63 * | 0.50 * | −0.04 | −0.04 | −0.26 | 1.00 | | |
| N | 0.09 | 0.60 * | −0.81 * | 0.67* | 0.40 | 0.00 | −0.07 | −0.20 | 0.91 * | 1.00 | |
| Cl | 0.50* | 0.65 * | −0.29 | 0.06 | 0.11 | −0.48 * | −0.11 | 0.10 | 0.00 | 0.04 | 1.00 |

* asterisk indicatesstatistically significant values at $P < 0.05$.

## 4. Conclusions

This study found that the biomass yield, energy value and wood quality of *Populus balsamifera* grown in the north-east of Poland as energy feedstock was differentiated by both the clone of the *Populus balsamifera* species and by the harvest rotation and by the interaction of these factors. Both the biomass yield and its energy value in the first 4-year harvest rotation were found to be relatively low. A distinct 260–290% increase in these attributes was observed in the second 4-year rotation. Among the clones under study, the highest yield energy value was determined in the UWM 2 clone in the second harvest rotation. The values of this parameter for the other clones were 27–47% lower. Such large differences in the yield energy value resulted from varied yields and biomass LHV between harvest rotations and clones. The plants produced considerably higher yields in the second 4-year rotation, thus ensuring a higher yield energy value. An analysis of the biomass quality showed that poplar wood contained high levels of moisture and low levels of ash, sulphur, nitrogen and chlorine. This may be indicative of a good quality fuel with potentially low $SO_2$ and particulate emissions. Moreover, due to the low chlorine content and advantageous S/Cl ratio, poplar biomass combustion should not pose problems with corrosion of boiler elements. Based on the results of this study it can be concluded that poplar can be grown in the north-east of Poland and that it gives a yield with a high energy value and beneficial biomass properties from the energy generation perspective. However, further studies are necessary, both on experimental and commercial scales to perform a comprehensive assessment of economic, energy-related and environmental assessment of poplar biomass production in the SRWC system, which will be the object of future studies.

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## Nomenclature

| | |
|---|---|
| DM | dry matter |
| f.m. | fresh biomass |
| HHV | higher heating value (GJ $Mg^{-1}$ DM) |
| $LHV^{wb}$ | biomass lower heating value (wet basis) (GJ $Mg^{-1}$) |
| RES | renewable energy sources |
| SRWC | short rotation woody crops |
| wb | wet basis |
| Yb | biomass yield (Mg $ha^{-1}$ f.m.) |
| Yev | biomass yield energy value (GJ $ha^{-1}$) |

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# Camelina and Crambe Oil Crops for Bioeconomy—Straw Utilisation for Energy

**Michał Krzyżaniak *, Mariusz J. Stolarski, Łukasz Graban, Waldemar Lajszner and Tomasz Kuriata**

Department of Plant Breeding and Seed Production, University of Warmia and Mazury in Olsztyn, Olsztyn, 3,10-724 Plac Łódzki, Poland; mariusz.stolarski@uwm.edu.pl (M.J.S.); lukasz.graban@uwm.edu.pl (Ł.G.); waldemar.lajszner@uwm.edu.pl (W.L.); tomasz.kuriata@uwm.edu.pl (T.K.)

* Correspondence: michal.krzyzaniak@uwm.edu.pl; Tel.: +48-89-5246146

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**Abstract:** Agriculture can provide biomass for bioproducts, biofuels and as energy feedstock with a low environmental impact, derived from carbohydrate, protein and oil annual crops, as well from lignocellulosic crops. This paper presents the thermophysical and chemical features of camelina and crambe straw depending on nitrogen fertilisation rate with a view to their further use in a circular bioeconomy. A two-factorial field experiment was set up in 2016, with camelina and crambe as the first factor and the N fertilizer rate (0, 60 and 120 kg·ha$^{-1}$·N) as the second factor. Ash content in crambe straw (6.97% d.m.) was significantly higher than in camelina straw (4.79% d.m.). The higher heating value was higher for the camelina (18.50 MJ·kg$^{-1}$·d.m.) than for the crambe straw (17.94 MJ·kg$^{-1}$·d.m.). Sulphur content was also significantly higher in camelina than in crambe straw. An increase in nitrogen content with increasing fertilisation rate was visible in the straw of both species (from 1.19 to 1.33% d.m., for no fertilisation and for a rate of 120 kg·ha$^{-1}$·N, respectively). Crambe straw contained more than five times more chlorine than camelina straw. In conclusion, despite certain adverse properties, camelina and crambe straw can be an alternative to other types of biomass, both for direct combustion, gasification and in the production of second-generation biofuels.

**Keywords:** biomass; bioenergy; circular bioeconomy; oil crops; agricultural residues; thermophysical and chemical features

## 1. Introduction

The European Union is taking on increasingly ambitious challenges concerning a sustainable bioeconomy and closing the circulation of energy and materials used in production. It is estimated that the bioeconomy market is worth 2.4 billion euros and employs approx. 22 million people [1,2]. Moreover, the EU has set further ambitious goals concerning bioeconomy and sustainable development. The European Commission is developing new policies concerning renewable energies and agriculture (e.g. The European Green Deal, EU Biodiversity Strategy for 2030) and expects to spend approx. 1 trillion euros over the next 10 years. Moreover, the European Commission is developing the first European Climate Law, with a binding climate neutrality target [3]. There is a need for feedstock for biobased materials and bioenergy supported by the Renewable Energy Directive (RED II). In RED II, the biofuels, bioliquids and biomass fuels produced from food or feed crops should be zero in 2030. Moreover, the directive sets a target for 3.5% advanced biofuels in 2030 (0.2% in 2022, 1% in 2025) which need to be produced from non-food crops or lignocellulosic residues to be categorized as advanced [4].

Agriculture can provide various kinds of biomass for bioproducts, biofuels and as energy feedstock with a low environmental impact, derived from carbohydrate, protein and oil annual crops, as well from dedicated lignocellulosic crops [5–8]. Camelina (*Camelina sativa*) and crambe (*Crambe abyssinica*) are oilseed crops proposed by scientists and industry, adapted to the European climate and tested in many European research projects [9]. Their features include high oil levels in seeds and fatty acid profiles which are of interest to industry. Camelina contains 14–16% oleic acid, 15–23% linoleic acid, and 31–40% linolenic and 12–15% eicosenoic acids [10]. Crambe oil contains a high (>54%) share of erucic acid [11]. Owing to these features, oils of both these crops are used in lubricants, rubber additives, nylon, hydraulic fluids, jet fuel, biodiesel and other products [10,12–14]. Obviously, these crops are grown to obtain oil from seeds, but not only this component should be used. Crambe and camelina seeds account for 44–45% of the total harvested biomass, with straw accounting for the rest of the biomass [15]. This can be used for other energy-related purposes: thermal and electric energy and production of bioethanol and biogas, as well as in the production of biocarbon [16–18]. Considering the above, experiments concerning the yield, energy efficiency and economic efficiency, as well as the environmental aspects of, crambe and camelina production have been conducted in the University of Warmia and Mazury in Olsztyn since 2015 [5,15,19,20]. One of the experiments analysed energy input, energy output and energy efficiency indices in camelina and crambe biomass (seeds, oil, straw) production depending on the rate of mineral nitrogen (N) fertilizer application (0, 60 and 120 kg·ha$^{-1}$·N). The above studies focused mainly on the use of oils from the crops for chemical purposes. The research team decided to also determine the possibilities of utilising agricultural residues, i.e. straw. Therefore, the aim of this communication is to present the thermophysical and chemical properties of camelina and crambe straw depending on the nitrogen fertilisation rate with a view to its further use in a circular bioeconomy, mainly for energy.

## 2. Materials and Methods

### *2.1. Field Experiment*

A two-factorial split-plot design field experiment in four replicates was set up in 2016, with camelina and crambe species as the first factor and nitrogen fertilizer rate (0, 60 and 120 kg·ha$^{-1}$·N) as the second factor. The experiment was set up at the Didactic and Research Station in Łężany (N:53°57′, E:21°08′), owned by the University of Warmia and Mazury in Olsztyn (UWM). The soil was classified as Eutric Cambisols soil formed from silt founded on weakly loamy, silty sand. It was classified as quality class IVa. The sowing density was 500 plants·m$^{-2}$ for camelina and 200 plants·m$^{-2}$ for crambe. The plants were sown in the first week of April. Seeds and straw of both crops were harvested with a Wintersteiger plot harvester in the third week of August. Immediately after the harvest, straw was taken for laboratory analyses as bulk samples for each species and fertilisation rate (from four replicates).

### *2.2. Laboratory Analyses*

Representative 300 g samples of straw were placed in tightly-sealed plastic bags to prevent any changes in their moisture content in transport. After the samples were delivered to the laboratory, their moisture content was determined by drying at 105 °C until a constant weight was achieved followed by weighing [21]. Dried straw was ground in a mill and reduced from the collective sample to a laboratory sample (ca. 50 g) in accordance with PN-EN 14780:2011 [22]. The obtained samples were ground in an analytic mill to a diameter of under 1.0 mm for further analyses.

The ash content, fixed carbon and volatile matter content was determined with a TGA THERMOSTEP thermogravimetric oven manufactured by ELTRA, used in accordance with PN-EN ISO 18123:2016-01 [23].

A C-2000 calorimeter (IKA WERKE) was used to determine the higher heating value by the dynamic method [24]. The nitrogen content in the biomass was determined by Kjeldahl's method as per the norm modified by Zinneke, on a K-435 mineraliser and a B-324 BUCHI distilling device. The contents of carbon, hydrogen and sulphur were determined with an ELTRA CHS 500 automatic analyser [25,26]. Chlorine in the biomass was determined with an Eschka mixture by Mohr's method. All analyses were performed in three replicates.

### 2.3. Statistical Analysis

A two-way analysis of variance was carried out to determine the effects of species, nitrogen fertilization rate and the interactions between these factors for all analysed features of straw. The level of significance of the analysis was established at $p < 0.05$. Homogeneous groups for the examined features were determined by Tukey's multiple-comparison test (HSD). All analyses were done with STATISTICA 13.3 software (Tibco Inc.).

## 3. Results and Discussion

Table 1 presents *p*-values of the camelina and crambe straw depending on the experimental factors, including species (factor A), fertilisation level (0; 60; 120 kg·ha$^{-1}$) (factor B) and interaction between these factors (A × B). Based on the results, it was found that all the traits (dependent variables) significantly differed by at least one experimental factor or factor interaction. The camelina and crambe straw (factor A) did not only differ with respect to their moisture and nitrogen contents. For the fertilisation rate, no significant differences were noted in the straw quality (fixed carbon, elemental carbon and sulphur content). Only two traits, i.e. the fixed carbon and elemental carbon contents, were not changed by the A × B interaction. Detailed differences in the studied traits are presented in further in the study results, tables and figures.

**Table 1.** *p*-value of tested traits for camelina and crambe (factor A) straw depending on nitrogen fertilisation rate (0, 60, 120 kg·ha$^{-1}$·N) (factor B); fixed carbon (FC), volatile matter (VM), higher heating value (HHV), lower heating value (LHV). Significance at $p < 0.05$.

| Source of Variation | Moisture | FC | Ash | VM | HHV | C | H | S | N | Cl |
|---|---|---|---|---|---|---|---|---|---|---|
| Species (A) | 0.06 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.06 | <0.001 |
| N rate (B) | <0.001 | 0.20 | <0.001 | 0.007 | <0.001 | 0.08 | 0.02 | 0.18 | <0.001 | <0.001 |
| A × B | <0.001 | 0.10 | <0.001 | <0.001 | <0.001 | 0.19 | 0.004 | <0.001 | <0.001 | <0.001 |

The moisture content of freshly harvested straw was not differentiated by crop species and was 55.68% (Table 2). The moisture content in straw obtained at the rate of 120 kg·ha$^{-1}$·N variant (57.06%) was significantly higher than at the other two rates. The crop × N-rate interaction also significantly differentiated the biomass moisture content, which ranged from 51.75% to 57.64%, for Camelina N0 and Camelina N120, respectively. High moisture content in straw after biomass harvest is caused by the fact that camelina pods and crambe fruits dry faster than the rest of the plant. Moreover, seed shattering is weaker when the crops are harvested at an early phase of ripeness [10,27]. Delaying seed harvest results in large losses, especially in the case of crambe (more than 25%) [20]. Therefore, plants should be collected earlier and straw should be left to dry naturally in swaths before being baled.

The mean fixed carbon content was 20.23% d.m. and was differentiated only by the crop species (Table 2). Its content in camelina straw was higher than in crambe straw—20.90% and 19.56% d.m., respectively. Volatile matter was significantly differentiated both by the principal factors and by the interaction. A significantly higher content of these compounds was found in the straw of camelina (74.32% d.m.) than in crambe (Table 2). An increase in the nitrogen fertilisation rate also brought about a significant decrease in volatile matter content compared to no fertilisation, by 0.20 and 0.35 p.p., respectively. On the other hand, considering the interaction of both these attributes, one can claim that the straw of camelina contained more volatile matter than crambe (range 73.27–74.74% d.m.).

**Table 2.** Moisture content, fixed carbon (FC), volatile matter (VM) and ash content of camelina and crambe straw depending on the nitrogen rate.

| Source of Variation | | Moisture (%) | FC (% d.m.) | VM (% d.m.) | Ash (% d.m.) |
|---|---|---|---|---|---|
| Species (A) | Camelina | 55.48 ± 2.8 | 20.90 ± 0.1 [a] | 74.32 ± 0.4 [a] | 4.79 ± 0.4 [b] |
| | Crambe | 55.87 ± 0.5 | 19.56 ± 0.2 [b] | 73.47 ± 0.2 [b] | 6.97 ± 0.1 [a] |
| N rate (B) | 0 | 53.72 ± 2.2 [b] | 20.32 ± 0.7 | 74.08 ± 0.7 [a] | 5.60 ± 1.4 [c] |
| | 60 | 56.26 ± 1.0 [b] | 20.20 ± 0.7 | 73.73 ± 0.5 [ab] | 6.07 ± 1.1 [a] |
| | 120 | 57.06 ± 0.7 [a] | 20.16 ± 0.9 | 73.87 ± 0.2 [b] | 5.96 ± 1.0 [b] |
| A × B | Camelina 0 | 51.75 ± 0.2 [d] | 20.97 ± 0.1 | 74.74 ± 0.1 [a] | 4.30 ± 0.01 [d] |
| | Camelina 60 | 57.05 ± 0.7 [ab] | 20.78 ± 0.02 | 74.19 ± 0.1 [b] | 5.03 ± 0.1 [c] |
| | Camelina 120 | 57.64 ± 0.03 [a] | 20.94 ± 0.2 | 74.03 ± 0.2 [bc] | 5.03 ± 0.06 [c] |
| | Crambe 0 | 55.68 ± 0.2 [c] | 19.67 ± 0.2 | 73.42 ± 0.2 [cd] | 6.91 ± 0.003 [b] |
| | Crambe 60 | 55.47 ± 0.2 [c] | 19.62 ± 0.2 | 73.27 ± 0.05 [d] | 7.11 ± 0.1 [a] |
| | Crambe 120 | 56.47 ± 0.5 [b] | 19.39 ± 0.07 | 73.72 ± 0.07 [c] | 6.90 ± 0.02 [b] |
| Mean | - | 55.68 ± 2.0 | 20.23 ± 0.7 | 73.89 ± 0.5 | 5.88 ± 1.2 |

± standard deviation; [a], [b], [c], … letters means that values are statistically different (Tukey's test at $p < 0.05$).

Ash content was also differentiated by the crop species, N rate and the interaction of these factors (Table 2). Ash content in crambe straw (6.97% d.m.) was significantly higher than in camelina straw (4.79% d.m.). It was significantly the lowest in non-fertilised straw (5.60% d.m.), and significantly the highest in fertilised straw (at the rate of 60 kg·ha$^{-1}$·N). Nitrogen fertilisation (both rates) significantly increased the ash content in camelina straw by 0.73 p.p. However, the ash content in crambe straw was significantly higher and ranged from 6.90% d.m. to 7.11% d.m. In general, nitrogen fertilisation brought about a slight, though significant, increase in ash content in the straw of both crop species, although the species-related differentiation of the attribute was more noticeable in this case. The ash level in camelina straw was much lower. This is important from an energy generation and industrial perspective because of the adverse effect of ash on further biomass use, especially for combustion. According to some studies, ash deposition decreases the combustor utilization efficiency, damages the combustor equipment and causes maintenance problems [28,29]. However, the ash content in biomass is usually much lower than in fossil fuels, especially in the biomass of dedicated energy crops, followed by straw and agricultural residues [30,31].

The higher heating value (HHV) was differentiated significantly by the main factors of the experiment and their interaction. The value of this attribute for the camelina straw was significantly higher (18.50 MJ·kg$^{-1}$·d.m.) than for crambe straw (17.94 MJ·kg$^{-1}$·d.m.) (Figure 1). Non-fertilised straw and straw of both species fertilised at 60 kg·ha$^{-1}$·N had significantly higher HHVs than straw fertilised at 120 kg·ha$^{-1}$·N. For interactions of both factors, the two highest HHVs were, significantly, for camelina straw non-fertilised and fertilised at a lower rate (18.80 and 18.54 MJ·kg$^{-1}$·d.m., respectively). Significantly, the lowest value of the attribute was determined for crambe straw in variants with no fertilisation and with fertilisation at 120 kg·ha$^{-1}$·N: 17.76 and 17.94 MJ·kg$^{-1}$·d.m., respectively.

Since camelina and crambe straw contain high moisture levels at harvest, they should be left to dry naturally in swaths before baling to achieve higher LHV, and, in consequence, higher energy gain per 1 ha. In the authors' other studies, it was found that the energy gain from naturally dried straw can be 32.8–36.3 and 37.9–41.4 GJ·ha$^{-1}$, depending on the fertilisation rate, and is ca. 54% and 52% of the energy present in total harvested biomass (harvested straw and seeds), for camelina and crambe, respectively [15].

The mean elemental carbon content was 50.72% d.m. and it was significantly differentiated by the crop species (Table 3). The element content in camelina straw (51.70% d.m.) was higher than in crambe straw (49.73% d.m.). However, hydrogen content was significantly differentiated by both the main factors and by their interaction. The hydrogen content was higher by 0.22 p.p. in camelina straw than in crambe straw. Significantly higher hydrogen content was found in straw from plots with no fertilisation and from those fertilised at 120 kg·ha$^{-1}$·N (6.44% d.m. in both variants) than from the plot fertilised at 60 kg·ha$^{-1}$·N (6.34% d.m.). An analysis of the species × N rate interaction shows a significantly higher hydrogen content in straw from camelina plots with no fertilisation and fertilised at the higher rate. The other values made up a second homogeneous group with the element content ranging from 6.29% d.m. to 6.34% d.m.

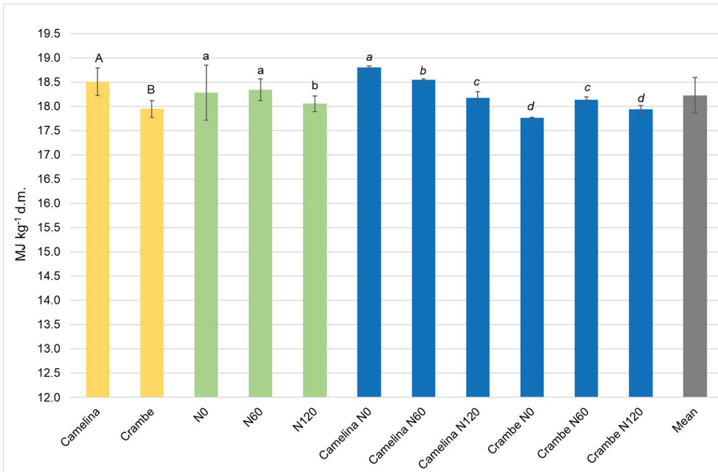


**Figure 1.** Higher heating value of camelina and crambe straw depending on fertilization rate; error bars-standard deviation; letters indicate that values are statistically different (Tukey's test at $p < 0.05$).

Sulphur content was significantly higher in camelina straw (0.284% d.m.) than in crambe straw (0.216% d.m.) (Table 3). Nitrogen fertilisation alone did not change this attribute for the straw of these species, and the mean value was 0.250% d.m. However, significant differences were observed when interactions of both factors were taken into account. Camelina straw contained more sulphur, with its content decreasing with increasing fertilisation rates, whereas sulphur content in crambe was significantly lower and not differentiated by the fertilisation rate (the last homogeneous group, with a sulphur content of 0.210–0.222% d.m.).

**Table 3.** Elemental composition of camelina and crambe straw depending on nitrogen rate (carbon, hydrogen, sulphur, nitrogen and chlorine).

| Source of Variation | | C (% d.m.) | H (% d.m.) | S (% d.m.) | N (% d.m.) | Cl (% d.m.) |
|---|---|---|---|---|---|---|
| Species (A) | Camelina | 51.70 ± 0.7 $^{a}$ | 6.50 ± 0.1 $^{a}$ | 0.284 ± 0.013 $^{a}$ | 1.27 ± 0.03 | 0.097 ± 0.01 $^{b}$ |
| | Crambe | 49.73 ± 0.4 $^{b}$ | 6.32 ± 0.05 $^{b}$ | 0.216 ± 0.006 $^{b}$ | 1.27 ± 0.14 | 0.531 ± 0.06 $^{a}$ |
| N rate (B) | 0 | 51.03 ± 1.4 | 6.44 ± 0.1 $^{a}$ | 0.249 ± 0.038 | 1.19 ± 0.1 $^{a}$ | 0.312 ± 0.3 $^{b}$ |
| | 60 | 50.34 ± 0.9 | 6.34 ± 0.04 $^{b}$ | 0.254 ± 0.048 | 1.29 ± 0.06 $^{b}$ | 0.343 ± 0.3 $^{a}$ |
| | 120 | 50.79 ± 1.2 | 6.44 ± 0.2 $^{a}$ | 0.246 ± 0.028 | 1.33 ± 0.04 $^{c}$ | 0.288 ± 0.2 $^{c}$ |
| A × B | Camelina N0 | 52.21 ± 0.6 | 6.56 ± 0.02 $^{a}$ | 0.284 ± 0.008 $^{ab}$ | 1.29 ± 0.01 $^{b}$ | 0.083 ± 0.006 $^{d}$ |
| | Camelina N60 | 51.02 ± 0.6 | 6.34 ± 0.01 $^{b}$ | 0.297 ± 0.008 $^{a}$ | 1.23 ± 0.01 $^{c}$ | 0.095 ± 0.006 $^{d}$ |
| | Camelina N120 | 51.88 ± 0.02 | 6.59 ± 0.1 $^{a}$ | 0.271 ± 0.008 $^{b}$ | 1.29 ± 0.01 $^{b}$ | 0.112 ± 0.006 $^{b}$ |
| | Crambe N0 | 49.85 ± 0.2 | 6.33 ± 0.02 $^{b}$ | 0.215 ± 0.003 $^{c}$ | 1.09 ± 0.01 $^{d}$ | 0.540 ± 0.006 $^{b}$ |
| | Crambe N60 | 49.67 ± 0.7 | 6.33 ± 0.06 $^{b}$ | 0.210 ± 0.002 $^{c}$ | 1.35 ± 0.01 $^{a}$ | 0.590 ± 0.006 $^{a}$ |
| | Crambe N120 | 49.69 ± 0.5 | 6.29 ± 0.05 $^{b}$ | 0.222 ± 0.004 $^{c}$ | 1.36 ± 0.01 $^{a}$ | 0.463 ± 0.006 $^{b}$ |
| Mean | - | 50.72 ± 1.2 | 6.41 ± 0.1 | 0.250 ± 0.037 | 1.27 ± 0.10 | 0.314 ± 0.2 |

± standard deviation; $^{a}$, $^{b}$, $^{c}$, ... letters means that values are statistically different (Tukey's test at $p < 0.05$).

The nitrogen content in the straw of both species was at the same level of significance and was 1.27% d.m. (Table 3). An increase in nitrogen content with increasing fertilisation rate was visible in the straw of both species (from 1.19 to 1.33% d.m.) for no fertilisation and for the rate of 120 kg·ha$^{-1}$·N, respectively. The interaction of both factors showed that, significantly, the highest content of the element was in the straw of crambe on fertilised plots (1.35 and 1.36% d.m., for the N rate of 60 and 120 kg·ha$^{-1}$, respectively), and the lowest was in the straw of non-fertilised crambe.

The chlorine content was also differentiated significantly by the crop species, N rate and the interaction of these factors (Table 3). Crambe straw contained more than five times more chlorine than camelina straw. Significantly, the highest chlorine content was found in straw from plots fertilised at 60 kg·ha$^{-1}$·N, whereas it was significantly the lowest on plots fertilised at 120 kg·ha$^{-1}$·N. For the interaction of these factors, significantly, the lowest chlorine content was determined for camelina grown with no nitrogen fertilisation (0.083% d.m.) and fertilised at the rate of 60 kg·ha$^{-1}$·N (0.095% d.m.). Significantly, the largest amount of this element was found in crambe straw obtained at the fertilisation rate of 60 kg·ha$^{-1}$·N (0.590% d.m.).

Nitrogen, chlorine and sulphur have an adverse effect on the thermal and thermochemical conversion of biomass as well as on the environment and human health. The straw of annual plants usually contains up to six times more ash and four times more chlorine and sulphur than dedicated energy crops and woody biomass. However, it contains less sulphur and nitrogen than coal, although it may contain up to twice as much chlorine [31–33]. Chlorine is undesirable in biomass as it causes corrosion, whereas sulphur and nitrogen cause the emission of sulphur and nitrogen oxides to the atmosphere in the process of biomass combustion. Shao et al. [28] reports that the water-soluble potassium and chlorine in biomass fuels are the most problematic elements during biomass combustion and can result in severe ash deposition/fouling/slagging and high-temperature corrosion.

## 4. Conclusions

Cereal (e.g., wheat or barley) straw is commonly used as an energy feedstock in Europe. However, it is also used for other purposes, e.g. as animal bedding or in mushroom production. Moreover, it has been pointed out in numerous studies that at least 25% of straw should return to the soil to maintain the organic substance balance and to prevent organic carbon depletion. Therefore, a shortage of cereal straw caused by competition from other sectors, as well as the needs of sustainable agricultural production, can be compensated for by camelina and crambe straw, which have similar thermophysical and chemical properties. Obviously, as in the case of cereal straw, only adequate amounts of straw should be collected and used to avoid unfavourable effects on soil properties. Both camelina and crambe straw offer similar energy values to cereal straw. Moreover, the content of compounds that are undesirable in heat generation is similar in camelina, crambe, cereal and rapeseed straws. Despite certain adverse properties, camelina and crambe straw can be an alternative to other types of biomass, both for direct combustion, gasification and in the production of second-generation biofuels. This fact is of great importance due to the increasing demand for bioproducts and bioenergy as well as the obligation to reduce the utilisation of edible parts of crops (e.g. cereal grain and oilseeds, potato tubers or sugar beet, etc.) in bioproduct production and bioenergy generation.

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Article

# Equipping a Combine Harvester with Turbine Technology Increases the Recovery of Residual Biomass from Cereal Crops via the Collection of Chaff

**Alessandro Suardi [1], Walter Stefanoni [1,*], Vincenzo Alfano [1], Simone Bergonzoli [2] and Luigi Pari [1]**

1 Consiglio per la Ricerca in Agricoltura e l'analisi dell'Economia Agraria (CREA)-Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare, 16, 00015 Monterotondo (RM), Italy; alessandro.suardi@crea.gov.it (A.S.); vincenzo.alfano@crea.gov.it (V.A.); luigi.pari@crea.gov.it (L.P.)

2 Consiglio per la Ricerca in Agricoltura e l'analisi dell'Economia Agraria (CREA)-Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano, 43, 24047 Treviglio (BG), Italy; simone.bergonzoli@crea.gov.it

* Correspondence: walter.stefanoni@crea.gov.it; Tel.: +39-0690-675-205

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**Abstract:** In cereal crops, chaff is a valuable lignocellulosic by-product that accounts for more than 50 Mt $y^{-1}$ in Europe and is suitable for bioenergy purposes. Chaff is usually not collected due to the lack of combine harvesters that have the capability to handle it properly. The present two years experimental study investigated the hypothesis that the overall biomass collected in wheat crop can be increased by equipping the combine harvester with an aftermarket device. Chaff, discharged from the combine harvester-cleaning system, is collected by the turbine that delivers it either on the swath or on a lateral trailer towed by a tractor. The performance of all machines involved in the harvesting (combine harvester, tractor, baler, and trailer) were assessed. The chaff was collected in bales with the straw (A mode) and separately on a trailer (C mode). Comparisons with non-collected treatment (B mode) were performed in order to estimate the total chaff collected and the biomass losses. The results showed that 1.79 t FM $ha^{-1}$ per year of chaff could be collected when baled with the straw, whereas 1.27 t FM $ha^{-1}$ were collected separately on a trailer. Both field and material capacity were not negatively affected by the chaff collection. Therefore, our study confirmed the hypothesis that turbine technology is a valid solution for increasing the total residual biomass collected in cereal cropping for energy purposes.

**Keywords:** wheat; straw; weed seed; biocommodity; threshing; bioenergy

## 1. Introduction

The development of the bioeconomy in the last years has increased the biomass demand, not only for energy purposes but also for chemicals and material applications [1]. The European policy for energy encourages the utilization of agroforestry residues, limiting the energy crops plantations [2]. Moreover, traditional sources for bioenergy production would not be enough to meet the future energy needs and to respond to the new targets of EU 2030 framework for climate and energy policies [3,4]. In this scenario, it is crucial to exploit biomass resources that are currently unexploited, such as agricultural residues [5].

Among the agricultural residues, cereal chaff has gained interest due to its availability and properties. Chaff is commonly defined as the by-product of cereal harvest comprehensive of glumes, hulls, short straw, damaged kernels, and weed seeds. During threshing, the chaff fraction sieved by the cleaning shoe underneath the straw walkers is blown to the rear of the combine harvester [6]. This material is normally either left to fall on the ground below the straw swath or is spread. In both cases, the chaff cannot be collected by the straw baling press pick-up, in the following baling operation.

According to the statistical office of the European Union EUROSTAT, about 295 Mt of cereal grains are harvested yearly in EU28 [7]. Considering a mean value of chaff-to-grain ratio of 0.17 [8], more than 50 Mt $yr^{-1}$ of chaff is available and harvestable in Europe. However, such a resource is generally left on the ground after cereal threshing and is lost.

Nevertheless, chaff could be a valuable source for an energetic utilization, either when baled with straw [9] or when pelleted after being separated from the straw [10]. Moreover chaff can be a valuable feedstock in a second generation bioethanol process [11].

Although cereal straw and chaff have low nutritive value they could be used as substantial feed resource for beef cows [8] or as a hay substitute in winter feeding [12]. The main use of straw in animal farming is for littering but since the use of combine harvesters has taken over manual trashing, the chaff is no longer included into the straw, as before. The lack of absorbent capacity provided by chaff has dictated the reduction in straw usage as a natural bedding for feedstock. In fact, unless specific equipment is used, the chaff is usually not collected by combines in the field and is incorporated into the soil during the preparation of the field for following year crop [13]. However, the incorporation of residual organic matter, particularly the chaff, is also reported to be correlated to root diseases and *Pythium* spp. populations that result in root system damages in the new seedlings [14].

On the other hand, agronomic advantages are also experienced when the chaff is removed. In fact, the collection of the chaff during cereal harvesting can reduce the weed seed stock in the soil by removing weed seeds before they are returned to the field [15]. The recognition that during grain harvest, the seeds of important crop weeds are intact and attached to the upright plant and can be "harvested", led to the introduction of Harvest Weed Seed Control (HWSC) systems in Australia [16]. The most widely adopted system is the narrow windrow burning. It consists of a grain harvester, mounted chute, to concentrate all the exiting chaff and straw residues into a narrower windrow that is subsequently burnt. In order to avoid in-situ burning, other methods are currently used. (i) The chaff cart method, which consists of a wagon towed by the combine that collects the chaff exiting the trashing system and temporarily accumulates it in the bin for discharge, when full. (ii) Bale direct systems (BDS), which are large square balers that are directly attached to the harvester that makes bales from the chaff and straw residues exiting the grain harvester. (iii) The Harrington seed destructor (HSD), which uses a cage mill mounted on a trailer to crush the weed seed carried by the chaff flow [17,18].

Recently, with the aim to fight the herbicide-resistant weeds, Klaus Jakobsen and Christoph Glasner et al. (2019) [19,20] investigated if hot exhaust gas from a combine harvester could be used to reduce germination or kill weed seeds during the harvesting process, in order to develop an integrated system in the combine harvester.

On the contrary, the growing interest in the exploitation of these residues for industrial uses has pushed some constructors to develop systems for the recovery of the chaff. Nowadays, several solutions for chaff harvesting are available on the market, and others are still at a prototype stage [21].

Conceptually, they are based on two management methods—collection of chaff together with straw and collection of chaff separately from the straw. In the first case, chaff is discharged either on top or inside of the straw swath then baled together with the straw. In the separate collection method, the chaff is delivered to dedicated collection systems, such as trailers towed by a tractor or by the combine itself, or integrated containers in the back of the combine, or non-stop baling systems. These management methods implement different chaff delivery systems, including augers, blowers, and conveyor belts. The combination of management methods and delivery systems determine different mechanical solutions that can be summarized as follows—windrowing systems, turbine systems, dedicated back container systems, one pass harvest and baling systems, and modified chaff spreader systems.

The interest in chaff collection is a recent phenomenon, as a result, there is a limited number of agricultural machine constructors that offer mechanical solutions for the recovery of the chaff. In general, the solutions provided for the discharge on the swath (windrowing system or turbine system) or inside the swath (modified chaff spreader) have a limited investment cost, and they are easily adaptable to all types of combine harvester without the influence of the harvesting performance (working time).

On the contrary, a separate collection would allow a wider range of possible uses of chaff and straw and possible higher market prices as well. However, chaff recovery systems like turbine systems with trailer and chaff-cart or one pass harvest and baling systems could have negative effects on the maneuverability of the machines, with possible increase in the working time and, therefore, a reduction of the harvesting performance. Additionally, these solutions imply higher purchasing costs [21].

Due to a lack of scientific data about the chaff collection feasibility, performance, and quality of the work carried out by the machine available in the market, during the H2020 AGROinLOG project [22], Research Centre for Engineering and Agro-Food Processing (CREA) carried out straw and wheat chaff harvesting tests in Le Faulx (Pannecè, France), using a combine harvester equipped with the turbine system, named "Turbopaille", developed by the French company Thievin. The wheat residue harvesting tests were carried out in July 2018 and July 2019, which aimed to quantify the amount of residue that can potentially be collected (chaff and straw), the machines performance, fuel consumption of all machines involved in the harvesting chain, as well as the potential yield of seeds, straw, and chaff, and the losses in the two-years experiment.

## 2. Materials and Methods

### *2.1. Field Test and Crop Characteristics*

Both two-years tests were carried out on the same field in Le Flaux (Pannecè, France) (47°29′16.4″N 1°13′26.1″W) (Figure 1). The sowing of wheat took place in the 43$^{rd}$ week in both years at a density of 225 kg ha$^{-1}$, a 50% blend of the two cultivars was used—Absalon and Syllon. In both years, the same regime of fertilization and pest control was followed. The harvest in 2018 was performed during the 29$^{th}$ week, while in 2019 it was performed in the 30$^{th}$ week. During the week before the harvest, a homogeneous area of about 6 ha was selected and delimited to perform the tests.

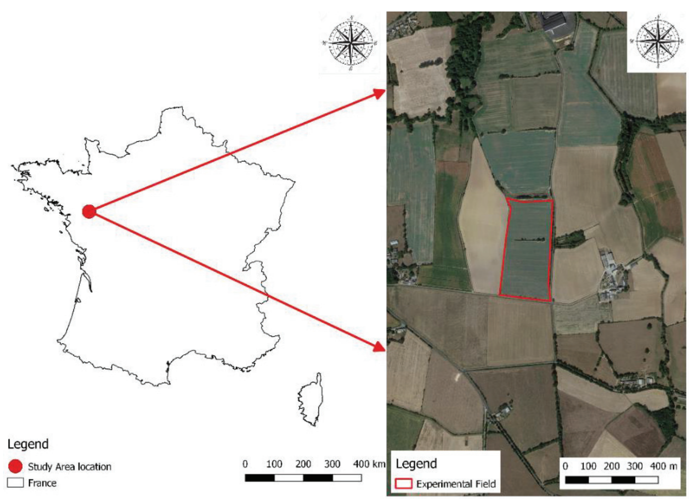
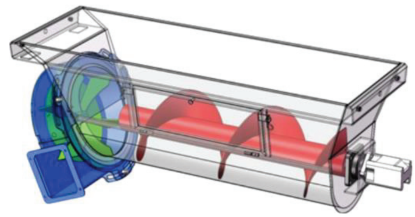



**Figure 1.** Study area location and field test.

### *2.2. Thievin System Description*

The Thievin system for the chaff recovery, named "Turbopaille" [23], was mounted in the rear part of the combine harvester. It had a dedicated tank provided with an endless screw, which pushed the chaff in the inlet of a turbine. Here, the turbine increased the pressure of the air and the chaff was forced out through a pipe (Figure 2).

(**a**) (**b**)

**Figure 2.** (**a**) Thievin system "Turbopaille" for chaff collection and (**b**) schematic representation.

The Thievin system can work in three different arrangements—discharging of the chaff over the straw swath (A Mode); spreading of the chaff by applying a V-shaped spreader (B Mode); chaff discharging by PVP pipes on a trailer towed by a tractor alongside the combine harvester (C Mode) (Figure 3).


(**a**)


(**b**)

**Figure 3.** *Cont.*

(c)

**Figure 3.** The Thievin system working arrangements—unloading of the chaff on the straw swath (**a**); chaff spreading mode (**b**); and unloading of the chaff on a trailer (**c**).

In 2018, only the A mode (chaff on the swath) and the B Mode (chaff spreading) were tested, while in 2019 the C Mode (discharge on trailer) was also analyzed. In the two-years experiment, all machines were the same except the combine. However, the setting and the drivers were the same in all machines (Table 1).

**Table 1.** Equipment used during the tests.

| Harvesting Phase | 2018 | 2019 |
|---|---|---|
| Seed threshing | Combine: New Holland CX840<br>Thievin system: A and B mode | Combine: New Holland CX8.70<br>Thievin system: A, B and C mode |
| Biomass baling | Tractor: Deutz-Fahr Agrotron M620<br>Baler: Deutz-Fahr Varimaster 690 | Tractor: Deutz-Fahr Agrotron M620<br>Baler: Deutz-Fahr Varimaster 690 |
| Separate chaff collection | Not performed | Tractor: John Deere 8270R<br>Trailer: Thievin Cortal 240 |

According to the working arrangements, the biomass discharged on the windrow and baled afterward, was made of straw and chaff in the A mode, and only straw in both B and C modes. Therefore, the amount of chaff baled was calculated as difference between the total weight of biomass baled with system A and system B, while the amount of chaff collected separately in C mode was weighted in the local farm scale.

### *2.3. Experimental Design and Pre-Harvest Sampling*

In both years of testing, split plot experimental designs were used. Before harvesting, the experimental field was divided into three blocks in order to have three replicates per treatment (2 treatments in 2018—A and B modes; and 3 treatments in 2019: A, B, and C modes) (Table 2). The width of each experimental unit (plot) was 4 times the combine header width, in order to assess the combine performance in four adjacent passes per plot (3 turning times). Total surface was about 4.2 ha (0.7 ha each plot) in 2018 and about 3.6 ha (0.4 ha on average each plot).

The first pass of the combine in each side of the experimental field was not considered in order to avoid possible edge effects on the crop. One day before the combine harvesting, the whole plants of 10 sample areas of 1 $m^2$, each randomly chosen, were hand harvested from the ground level. Stems and ears were weighed separately. Successively, all ears and a representative sample of stems were put in sealed bags and shipped to the laboratory of CREA for further measurements, as theoretical yield of grain and chaff, dry weight, and humidity content.

**Table 2.** Experimental design (2 treatments in 2018: A and B modes; and 3 treatments in 2019: A, B, and C modes).

| Year | Block 1 | | | | Block 2 | | Block 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Plot A1 chaff on swath | Plot B1 chaff spreading | Plot C1 chaff on trailer | Plot C2 chaff on trailer | Plot B2 chaff spreading | Plot A2 chaff on swath | Plot B3 chaff spreading | Plot A3 chaff on swath | Plot C3 chaff on trailer |
| 2019 | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| 2018 | Y | Y | N | N | Y | Y | Y | Y | N |

Y: test performed; N: test not performed.

## *2.4. Harvesting Tests*

The harvesting tests concerned the threshing and the baling steps performed in each experimental unit (plot). Machines performance was measured in terms of working times (h ha$^{-1}$) and fuel consumption (l h$^{-1}$), grain and residues yield (t ha$^{-1}$), moisture content (%), and bulk density of biomass (kg m$^{-3}$). Moreover, after harvesting, the average cutting height (cm) and the losses (t ha$^{-1}$) were assessed.

### 2.4.1. Machines Performance

Working time study was performed according to the standards ASAE S496.2 [24]. This allowed to determine the effective field capacity (EFC) (ha h$^{-1}$), which is the rate at which it performs its primary function and the theoretical field capacity (TFC) (ha h$^{-1}$), which is the maximum possible field capacity without the accessory times.

The material capacity (MC), i.e. the quantity of grain or wheat residues harvested per time unit (t h$^{-1}$), was also assessed.

Fuel consumption of all machines involved (combine and tractors) was calculated by refilling the tank at the end of each plot. A graduated cylinder was used for the measurements of the volume of the fuel needed per single operation.

### 2.4.2. Biomass Yield and Characterization

The total yield of grains, straw, and chaff (collected separately in C Mode) per plot was measured using the farm scale. After the harvesting, three samples of grain and residues were collected from all treatments, for moisture content determination. Chaff bulk density was assessed in-situ, according to the technical standard ISO 17828:2015 [25]. Briefly, a 0.05 m$^3$ metal basket was filled with chaff, then jolted three times vertically and filled again. The extra chaff was removed by swinging a small scantling over the container, then the basket was weighted. The measurement was repeated 5 times per plot. The net weight of the basket was previously recorded. Per treatment, five bales were randomly chosen and measured in weight and volume, for the determination of the mean bulk density.

## *2.5. Post-Harvest Measurements*

The average cutting height value of the combine header (height of the stubbles) was derived by averaging 100 measurements, randomly taken in a diagonal transect selected on-field. The amount of biomass not harvested was assessed by cutting and weighing the stubbles from 10 sample areas (1 m$^2$ each) that were randomly chosen. Among them, five samples were collected for moisture content.

In the laboratory, the kernels were first separated in a stationary thresher (Cicoria mod. Plot 2375) from the rest of the ears (rachis, lemma, glumes, and palea). In addition to the residual material previously assessed in laboratory, the turbine technology allowed for collection of other kinds of light-weighted residuals produced by the cleaning mechanisms of the combine, such as short straw, damaged seeds, and weed seeds. On-field samples of the residuals produced by the Thievin system were further investigated in order to estimate the contribution of the light-weighted residuals to the total extra biomass collected. Dry weight and the humidity content of stems, kernels, and chaff were assessed according to the standard EN ISO 18134-2:2017 [26]. Briefly, three samples per plot were weighted for fresh weight and then dried in a ventilated oven at 105 °C ± 2 °C, until constant weight. Afterwards, the dried weight was recorded.

Seed, chaff, and straw losses in each plot were assessed as difference between the theoretical yield of biomass was estimated with the pre-harvest plots and the effective amount harvested.

### *2.6. Statistical Analysis*

A statistical analysis was performed in order to discriminate the differences among the treatments of the same year; while the comparison of the same treatment in the two years was not taken into account.

All data were subjected to the analysis of variance (ANOVA), using the R 3.6.1 software to separate statistically different means ($P \leq 0.05$) [27]. Tukey's HSD post-hoc test was performed to calculate the statistical differences between the means [28].

## 3. Results and Discussion

### *3.1. Combine Performance*

Apart from the MC (that was affected by different yield in the two years), the performance of all machines involved in the treatments in both years were similar (Table 3). In fact, the combine performance was not influenced by the working arrangements, contrary to the hypothesis speculated by Unger and Glasner (2019) [29]. The performance was not affected in the C mode either, where the combine harvester and tractor with the trailer had to work side-by-side. In fact, no statistical differences were found among the treatments.

**Table 3.** Combine performance in 2018 and 2019 according to the working arrangements (treatments).

| Treatment | Theoretical Field Capacity (ha h$^{-1}$) | | Effective Field Capacity (ha h$^{-1}$) | | Material Capacity (t FM h$^{-1}$) | |
|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| A mode | 2.57 ± 0.13 | 2.56 ± 0.01 | 2.24 ± 0.11 | 1.98 ± 0.02 | 13.98 ± 0.13 | 17.27 ± 0.56 |
| B mode | 2.71 ± 0.09 | 2.61 ± 0.06 | 2.41 ± 0.10 | 2.04 ± 0.06 | 14.39 ± 0.13 | 17.25 ± 1.13 |
| C mode | np | 2.69 ± 0.12 | np | 2.03 ± 0.11 | np | 17.10 ± 0.77 |

np: not performed.

Combine harvester fuel consumption, measured only in 2019, was on average 21.63 l h$^{-1}$ (46.7 l ha$^{-1}$), with no significant differences among treatments.

### *3.2. Baler Performance*

Considering the baling phase, statistically significant differences were found in the EFC (which included accessories times, such as the turning time and unloading time) and the MC between the A and B modes in both years. Baling the swaths with a higher biomass content (A mode: straw and chaff) was significantly slower than baling the swaths with less biomass (B mode: only straw) (Table 4). Contrary to the expectations, no differences were found when the chaff was collected separately on the trailer (C mode). This may have been caused by an efficiency of the turbine system that is used for loose chaff recovery, as further explained in paragraph 3.3.1. In 2019, the TFC, EFC, and MC were lower than that in 2018, due to a higher biomass yield.

**Table 4.** Baler performance in 2018 and 2019 according to the treatments (common letters within columns denote the absence of significant difference ($p < 0.05$)).

| Treatment | Theoretical Field Capacity ($ha\ h^{-1}$) | | Effective Field Capacity ($ha\ h^{-1}$) | | Material Capacity ($t\ FM\ h^{-1}$) | |
|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| A mode | 5.23 ± 0.65 | 4.64 ± 0.31 | 3.46 ± 0.28 b | 3.09 ± 0.13 b | 20.79 ± 0.7 a | 20.20 ± 2.0 a |
| B mode | 5.99 ± 0.16 | 4.82 ± 0.09 | 4.05 ± 0.16 a | 3.45 ± 0.10 a | 18.73 ± 0.7 b | 15.09 ± 0.7 b |
| C mode | np | 4.93 ± 0.13 | np | 3.33 ± 0.09 ab | np | 19.16 ± 2.5 ab |

np: not performed

In 2018, the fuel consumption during baling was not affected by the treatments. On the contrary, the tests in 2019 showed a higher fuel consumption during the baling in treatment A (Table 5). It was about double when analyzed in relation to the surface ($l\ ha^{-1}$) and the time ($l\ h^{-1}$). Considering the biomass baled ($l\ t^{-1}$), such results were found only in comparison to treatment C, while no statistical differences were observed in treatment B (Table 5).

**Table 5.** Baler fuel consumption in 2018 and 2019 according to treatments (common letters within columns denote the absence of significant differences ($p < 0.05$)).

| Treatment | Fuel Consumption ($l\ ha^{-1}$) | | Fuel Consumption ($l\ h^{-1}$) | | Fuel Consumption ($l\ t^{-1}$) | |
|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| A mode | 4.65 ± 0.91 | 6.21 ± 1.5 a | 16.09 ± 3.36 | 19.13 ± 4.33 a | 0.77 ± 0.15 | 0.94 ± 0.12 a |
| B mode | 4.66 ± 0.11 | 2.81 ± 0.64 b | 19.02 ± 1.44 | 9.68 ± 3.87 b | 1.01 ± 0.13 | 0.64 ± 0.23 ab |
| C mode | np | 2.43 ± 0.94 b | np | 8.04 ± 2.90 b | np | 0.41 ± 0.09 b |

np: test not performed

### 3.3. Biomass Assessment

#### 3.3.1. Yield

Productivity in 2019 was higher than in 2018. The total biomass estimated in pre-harvest plots was about 1.9 t $ha^{-1}$ higher in 2019. The wheat ears were 56% of the total biomass (44% straw) in both years, with the same ratio in the ears of the seeds (about 78%) and the chaff (22%), as showed by the laboratory threshing (Table 6).

**Table 6.** Theoretical biomass in the wheat field assessed in 2018 and 2019.

| Year | Theoretical Biomass (FM) | |
|---|---|---|
| | 2018 | 2019 |
| Total biomass (t $ha^{-1}$) | 16.76 ± 1.44 | 18.69 ± 1.77 |
| Straw (t $ha^{-1}$) | 7.39 ± 0.73 | 8.33 ± 0.75 |
| Wheat ears (t $ha^{-1}$) | 9.37 ± 0.77 | 10.36 ± 1.34 |
| Seeds (t $ha^{-1}$) | 7.32 ± 0.60 | 8.18 ± 1.06 |
| Chaff (t $ha^{-1}$) | 2.04 ± 0.17 | 2.18 ± 0.28 |

Although the agricultural protocol (see paragraph 2.1) was the same in both years, differences in the biomass yield were recorded. Consistent with the theoretical yield, in 2019, the seeds harvested were on average 1.8 t FM $ha^{-1}$ higher than that in 2018. In both years, there were no statistically significant differences in seed yield, among treatments (Table 7).

**Table 7.** Seed harvested according to the treatments in 2018 and 2019.

| Treatment | Seed Harvested (t ha$^{-1}$ FM) | |
|---|---|---|
| | 2018 | 2019 |
| A mode | 6.26 ± 0.19 | 8.15 ± 0.32 |
| B mode | 6.04 ± 0.06 | 7.85 ± 0.40 |
| C mode | np | 7.87 ± 0.10 |
| Mean | 6.17 ± 0.21 | 7.96 ± 0.30 |

np: not performed

With regards to the biomass collected, there were statistically significant differences between treatment A (bales made of straw and chaff) and B (only straw), confirming the contribution of chaff as additional biomass, raising the total weight of biomass harvested. In fact, the difference between the biomass baled in the two treatments allowed to assess the chaff baled, respectively, 1.39 t FM ha$^{-1}$ (30% extra biomass) in 2018 and 2.19 t FM ha$^{-1}$ (50% extra biomass) in 2019 (Figure 4). Similar tests performed by the Institut National de la Recherche Agronomique (INRA) as part of the local project 'Systèmes de Cultures Innovants' and the Federation Nationale des Cooperatives d'Achat et d' Utilisation de Materiel Agricole (CUMA), in 2011 and 2012, with turbine systems, provided lower means, respectively 1.5 t FM ha$^{-1}$ and 1.15 t FM ha$^{-1}$ [30,31].

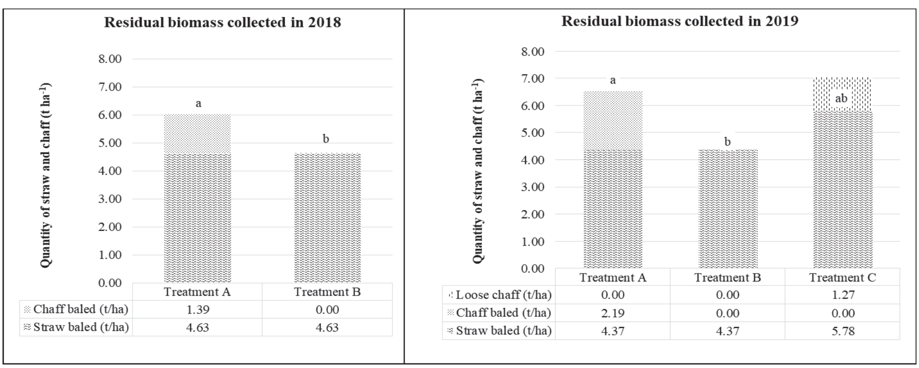



**Figure 4.** Biomass collected (in FM) per treatments during the tests carried out in 2018 and 2019. Treatment A—straw and chaff baling; treatment B—only straw baling (chaff spreading on the ground); and treatment C—straw baling and separate chaff collection on trailer. By including the chaff in the bales, 1.39 t FM ha-1 and 2.19 t FM ha-1 could be collected in 2018 and 2019, respectively. On the other hand, only 1.27 t ha-1 of loose chaff could be collected in the 2019 test. Different letters in the graph denote the presence of significant differences ($p < 0.05$) in the quantity of straw and chaff collected among treatments.

Trials performed by Rönnbäck and Lundin with a different technology [9] showed a 14% extra biomass by admixing chaff into the straw swath, representing about half of the available chaff that was harvested.

Although the biomass baled in A was 0.78 t FM ha$^{-1}$ higher than the biomass baled in C, contrary to what was expected, there were no significant differences in the baled biomass between treatment A and C (chaff on trailer tested only in 2019).

In treatment A, the effective additional biomass collected by using the Thievin system totally met the theoretical value of the chaff estimated from the pre-harvest tests. On the other hand, the chaff collected in the trailer was 0.92 t ha$^{-1}$ (42.2%) lower than the theoretical amount of chaff. In this case, the Thievin was required first to collect the chaff into the dedicated tank and then to lift it for discharge into the trailer. Therefore, in order to accomplish the additional second task, the turbine system demands more energy due to the need to push the collected biomass up onto the trailer. The intake rate of the chaff in the dedicated tank of the Thievin system (Figure 2) was probably higher than its capacity to discharge it into the trailer, thus, some chaff remained mixed with straw and then baled. In order to reduce these drawbacks in the case of separate collections of chaff, the following considerations could be taken into account—increase the energy provided to the turbine, increase the diameter of the PVC pipe, and eventually, decrease the biomass intake rate of the combine by either reducing the speed of the combine or using a narrower header. In fact, the last strategy is also reported by the French Company Thiérart that provides a similar Turbine technology for chaff collection. Specifically, Thiérart highlights that its device is suitable for combine headers measuring less than 5.5 m wide [32].

Nevertheless, 1.27 t FM ha$^{-1}$ of chaff collected separately with the C mode is close to the mean value of 1.3 t FM ha$^{-1}$ and 1.5 t FM ha$^{-1}$ reported, respectively, by CUMA and INRA, using a back container system [30,31].

### 3.3.2. Bulk Density and Humidity

The average bulk density of the round bales (1.8 m in diameter and 1.2 m width) was, respectively, 111 kg FM m$^{-3}$ and 131 kg FM m$^{-3}$ for the A (straw and chaff) and B modes (only straw) in 2018, while in 2019 they were, respectively, 124 kg FM m$^{-3}$, 121 kg FM m$^{-3}$, and 131 kg FM m$^{-3}$ for the A, B, and C modes, with no statistical difference among treatments. The average bulk density of the chaff was 62.08 kg FM m$^{-3}$ (measured only in 2019, treatment C), which was in line with the 56 kg FM m$^{-3}$ reported by McCartney et al. (2006) [8]. The moisture content of the different fractions is reported in Table 8.

**Table 8.** Moisture content in bales and in different fractions of the wheat.

| | Moisture Content (%) | |
|---|---|---|
| | **2018** | **2019** |
| Stems | 10.5 ± 0.6 | 11.9 ± 0.8 |
| Stubbles | np | 11.1 ± 1.3 |
| Ears | 10.0 ± 0.1 | 10.8 ± 0.5 |
| Chaff | 9.3 ± 0.2 | 9.2 ± 0.9 |
| Seeds | 10.3 ± 0.2 | 9.1 ± 0.1 |
| Bales | 9.78 ± 0.4 | 11.0 ± 0.7 |

np: not performed

### 3.3.3. Biomass Losses

Considering the cutting height of 15.7 ± 2 cm (2018) and 12.2 ± 1.5 cm (2019), the stubbles left on the ground accounted for 1.98 ± 0.15 t FM ha$^{-1}$ and 1.71 ± 0.25 t FM ha$^{-1}$, respectively. The biomass losses are reported in Table 9.

**Table 9.** Biomass losses as fresh matter (seed, chaff, and straw) according to the different treatment modes, in 2018 and 2019.

| | Seed Losses (t FM ha$^{-1}$) | | Chaff Losses (t FM ha$^{-1}$) | | Straw Losses (t FM ha$^{-1}$) | |
|---|---|---|---|---|---|---|
| Treatment | 2018 | 2019 | 2018 | 2019 | 2018 | 2019 |
| A mode | 1.06 ± 0.24 | 0.04 ± 0.32 | 0.65 ± 0.59 | 0.00 ± 0.66 | 0.78 ± 0.36 | 2.26 ± 0.22 |
| B mode | 1.28 ± 0.06 | 0.33 ± 0.40 | 2.04 ± 0.0 | 2.18 ± 0.0 | 0.78 ± 0.36 | 2.25 ± 0.22 |
| C mode | np | 0.32 ± 0.10 | np | 0.90 ± 0.08 | np | 0.84 ± 0.93 |

np: not performed

As expected, biomass losses were higher in the case of chaff spreading (treatment "B"), where only 42% of the theoretical total residues (straw and chaff) were baled in 2019 (49% in 2018). In the case of the discharge of the chaff over the swath (treatment "A"), the total losses accounted for only 38% in 2019 (36% in 2018).

By collecting the chaff on the trailer separately from the straw (treatment "C"), the total loss of the residual biomass was 33%. In this case, only 59% of the available theoretical chaff was collected (41% losses). The accurate analysis of the chaff samples revealed that 15.5 ± 0.5% was made of short straw and no weed seeds were found. This was due to the conventional cropping system adopted (chemicals are allowed) that did not permit the assessment of the weed seeds removal capacity of the Thievin technology.

According to findings of Glasner et al. (2019) [20], the percentage of weed seeds that can be removed by bailing could change over time. In fact, once the chaff is discharged on the swath, after one day, only 45% of weed seeds remains on top of it, while 35% is found within the swath and the remaining 20% is already lost in the ground. Hence, if the removal of the weed seeds is the main purpose of turbine technology application, it is very important to consider both the timing and the harvesting chain.

Weed seeds removal is only an additional benefit provided by chaff collection, although it is a valid strategy for weed control. Actually, the turbine technology is meant for the collection of lightweight biomass residuals but the main purpose of using it might change, according to the farmer and the policies used. Nowadays, in Europe, weed seed removal is not the main purpose of chaff collection. More efforts are put in fostering the utilization of such a considerable quantity of residual biomass (50 Mt $y^{-1}$) that could be used as raw material for industrial or energy purposes.

The collection of chaff separate from the straw (C Mode) implies higher costs due to the tractor and the trailer involvement that can only be compensated, either in the case of organic farming (removing the weed seeds) or in the presence of a dedicated market for chaff (e.g., litter for poultry farming), where the market price of chaff is sufficiently higher than straw. On the other hand, the collection of chaff as a loose product might gain interest in the biogas sector. Such a supply chain is still not completely developed, but the high methanogenic potential of the chaff, which ranges from 200 to 260 $Nm^3$ $t^{-1}$ [33], paves the way for further developments. Due to the similar methanogenic value of maize-silage, it can be speculated that partial subrogation is possible for cost reduction and lower environmental impact.

On the contrary, the biomass collected in Treatment A (straw and chaff) can have the same market value as the straw for energy. In fact, the net calorific value and the ash melting behavior of admixed straw with chaff do not change significantly, although a 1% increase in ash content is reported [9]. Moreover, Wiwart et al. (2017) [34] reports that spelt chaff has a low heating value (LHV) of 15.1–16.8 MJ $kg^{-1}$ (e.g., wood pellets 16.3 MJ $kg^{-1}$). Similar LHV for chaff is reported in Pari et al. (2018) [35], but further investigations are needed, specifically in combustion behaviors, in order to reduce the ash content of 9.75 ± 0.14 (w/w), by mixing the chaff with other raw materials.

In addition to combustion, biorefinery industries have a growing interest in lignocellulosic biomass residuals, for the production of 2nd generation bioethanol. Wheat straw and chaff could represent a good source, since they are abundantly produced in Europe and all over the world. Furthermore, both straw and chaff are collected from food crops, like wheat or even from other cereal crops, therefore, no competition for land use occurs.

## 4. Conclusions

The two-years test aimed to assess if a significant higher quantity of extra-biomass can be retrieved from the field by including the chaff. Chaff is a considerable portion of the by-products of cereal cropping that is usually left on the ground. The system tested in France permitted the collection of chaff in two different ways—either by direct discharge on the swath or on a trailer towed by a tractor alongside the combine harvester.

The potential total biomass assessment in the two-years test resulted in slightly different findings. In 2019, the biomass was found to be higher than that in 2018, by 1.93 t FM $ha^{-1}$, while no differences among the ratio between stems, spikes, seed, and chaff were found.

Interestingly, in both years, the Thievin did not significantly affect the combine performance. On average, the EFC of A and B modes was 2.12 ha $h^{-1}$, which was similar to the C mode (2.03 ha $h^{-1}$). Even the combine fuel consumption (in 2019) was not affected by the treatments; the mean value recorder was 46.7 l $ha^{-1}$.

Differences among the treatments were found during the phase of baling, particularly in 2019. The EFC was found to be 11.65% higher in treatment B, with respect to treatment A and this was consistent with the total biomass recorded.

In 2019, the EFC in treatment C was not statistically different from the others; while fuel consumption was similar to B but lower than that in A by 57.97%.

The chaff discharged on the swath and baled with straw was 1.39 t FM $ha^{-1}$ in 2018 and 2.19 t FM $ha^{-1}$ in 2019, which accounted for 30% and 50%, respectively, as additional biomass. Regarding the possibility to collect the chaff separately, additional treatment in 2019 was introduced, which yielded 1.27 t FM $ha^{-1}$ more biomass, though, it was lower than the amount of chaff collected in the A mode.

In conclusion, our findings supported the hypothesis that the turbine technology was a valid solution for increasing the total biomass collected in cereal cropping. However, further economic and technical investigations in different conditions and on different cereal species, as well as comparisons with similar technologies available on the market, are strongly encouraged.

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Article

# Machine Performance and Hog Fuel Quality Evaluation in Olive Tree Pruning Harvesting Conducted Using a Towed Shredder on Flat and Hilly Fields

**Alessandro Suardi [1], Francesco Latterini [1,*], Vincenzo Alfano [1], Nadia Palmieri [1], Simone Bergonzoli [2], Emmanouil Karampinis [3,4], Michael Alexandros Kougioumtzis [3,4], Panagiotis Grammelis [3] and Luigi Pari [1]**

1. Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, RM, Italy; alessandro.suardi@crea.gov.it (A.S.); vincenzo.alfano@crea.gov.it (V.A.); nadia.palmieri@crea.gov.it (N.P.); luigi.pari@crea.gov.it (L.P.)
2. Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano, 43, 24047 Treviglio, BG, Italy; simone.bergonzoli@crea.gov.it
3. CERTH Centre for Research and Technology-Hellas, Egialias 52, GR 15125 Athens, Greece; karampinis@certh.gr (E.K.); kougioumtzis@certh.gr (M.A.K.); grammelis@certh.gr (P.G.)
4. Laboratory of Steam Boilers and Thermal Plants, Department of Mechanical Engineering, National Technical University of Athens, Heroon Polytechniou 9, Zografou Campus, GR 15780 Athens, Greece

* Correspondence: francesco.latterini@crea.gov.it; Tel.: +39-06-9067-5248

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**Abstract:** Pruning residues from olive groves represent an important biomass source. Until now, the management of pruning residue has generally represented a disposal problem rather than an opportunity for additional revenue. The main problem is the lack of a well-organized pruning biomass supply chain. In particular, harvesting is a key stage that influences the product quality, the type of logistics chain, and the economic sustainability of the pruning supply chain. The aim of the present paper was the evaluation of the machine performance of the Facma Comby TR200 towed shredder. The harvesting tests took place in Agios Konstantinos, Fthiotida, Central Greece. Two different experimental fields were used for the evaluation of this harvesting system; these fields were characterized by different slopes to check the convenience of using such a towed shredder on both hilly slopes and flat terrains. Analysis was conducted focusing on both the work productivity and costs. Moreover, an evaluation of the obtained hog fuel quality was performed. The Facma Comby TR200 showed good work performances on both flat (2.60 $t_{dm} \cdot h^{-1}$) and hilly (2.74 $t_{dm} \cdot h^{-1}$) land, even if a consistent influence of the pruning biomass yield on the work performances was reported. The biomass quality could be consistently improved by modifying the pick-up systems to avoid the collection of inert materials (soil and rocks). In fact, the analysis showed a high ash content in the comminuted material (4% dry basis). Finally, the economic aspects of this study's results were in line with those reported in the literature. The applied harvesting system showed a cost equal to 29.88 and 16.59 €$\cdot t_{fm}{}^{-1}$ on flat and hilly land, respectively.

**Keywords:** pruning harvesting; olive groves; biomass quality; slope; work productivity

## 1. Introduction

Olive tree groves are a distinctive feature of the Mediterranean landscape, and in Europe they represent the ancestral crops of countries such as Italy, Greece, and Spain. wherein these countries olive oil production has represented an export-oriented industrial activity for at least two millennia [1]. Considering the large amount of pruning residues that derive from olive groves' maintenance, these could be important sources of biomass, akin to pruning residues from other crops [2–7]. However, until now, the management of pruning residue has generally represented a disposal problem rather than an opportunity for additional revenue, even if its potential has already been stated [8–10].

The main problem is the lack of a well-organized pruning biomass supply chain, a situation that is common all over Europe [11,12].

In most of Europe, the largest pieces of pruned wood, i.e., over 50 mm in diameter, are used for firewood [13]. Small branches and shoots, which instead could be very important for energy production, are usually removed from the orchard using a tractor with a fork or manually piled up, and then disposed of or burned, with consequent negative economic and/or environmental impacts. An alternative is that pruning residues are mulched and left on the ground and/or incorporated into the soil [11]. One possible solution to this problem under a bio-Economy point of view is the demonstration of the feasibility of integrated biomass logistics centers (IBLCs) [14]. IBLCs are business strategies designed to allow agro-industries to link to the growing bio-based economy by "taking advantage of unexploited synergies," such as facilities and personnel, as well as inputs (e.g., local unexploited agricultural residues, such as prunings) and outputs [15]. The EU project AGROinLOG aims to involve the agrarian sector in the supply of solid biofuels in Europe. AGROinLOG activities in Greece were properly aimed at the development of an IBLC for the use of olive tree pruning residues for energy purposes. Dealing with the development of pruning supply chain harvesting is a key stage that influences the product quality, the type of logistics chain, and the economic sustainability [13]. For this reason, in recent years, manufacturers of agricultural equipment have focused their attention on the development of pruning residue management systems that offer different solutions based mainly on shredding and baling technologies [16]. Shredding machines generally derive from conventional mulchers equipped with a storage bin or with a blower, where the latter is designed to direct the flow of comminuted residue to an accompanying trailer. Such implements are relatively cheap and are designed for being towed or carried by farm tractors in the 50–70 kW class [8].

The evaluation of various machines' performance in pruning residues harvesting is a critical aspect for the implementation of biomass value chains [17,18]. Except for aspects related to the physic-chemical features of the biomass, comminuting and storage have a strong influence on other important variables, such as the amount of contaminants (soil, stones), particle size, and bulk density. Biomass losses and contamination are clearly related to the setting of the pick-up system. Low-lying pick-up mechanisms lead to lower harvesting losses but increase the inlet of soil particles to the detriment of biofuel quality [13,19]. Moreover, the shape, size, number, and type of comminuting devices, as well as the machine settings, can substantially affect the biomass quality [20–23]. An incorrect comminuting can lead to major problems with the wood fuel, for example high dry matter losses, high ash content, reduction in energy value, and self-ignition [24,25]. The particle size distribution of woody biomass plays a key role in the production of high-grade fuel because it is directly linked to the bulk density, the storage behavior, and the transport costs, moreover it can also create difficulties with fuel feeding at the combustion plant. The usage of a wrong machine can lead to uneven-sized chips with a significant percentage of oversized or undersized particles, and any attempt to decrease one class could lead to an undesirable increase in the other, even with the application of refining devices [19,26–28]. Based on the previous discussion, the aim of the present study was the evaluation of the machine performance of the Facma Comby TR200 towed shredder (Facma srl, Vitorchiano, Lazio, Italy).

For this paper, the Facma Comby TR200 performance was analyzed in two different experimental fields characterized by different slopes. This allowed for determining the possibility of using such a towed shredder in both hilly and flat terrains.

Analysis was conducted by focusing on the work productivity, obtained biomass quality, and harvesting costs. There is not much information in the literature about the harvesting behavior of this machine on hilly land; this is an issue because a comparison of the performance and fuel consumption of the machine in different field conditions is useful for clarifying the convenience of its use for the local farmers and the implementation of a new pruning supply chain. Moreover, an evaluation of the obtained biomass was conducted to evaluate the market possibilities of the olive tree prunings as hog fuel. Finally, interviews were conducted with some Italian enterprises and cooperatives involved in wood chips and hog fuel production to better understand the characteristics of the hog fuel market and hence illustrate to the reader the possible solutions and practical adjustments for the development of hog fuel from the pruning residues value chain. Considering the absence of a hog fuel or wood chip market in Greece, the study referred to the Central and South Italy context, which is very similar to the Greek one for olive grove distribution and importance.

## 2. Materials and Methods

The applied research procedure, which is described in detail in the subsequent paragraphs, is summarized in Figure 1.

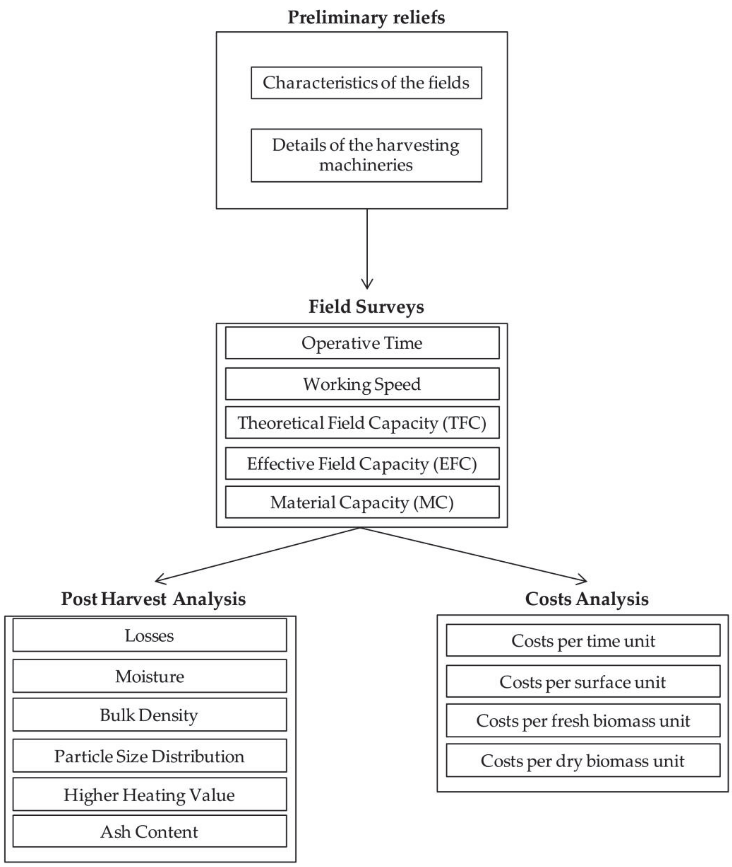


**Figure 1.** Graphical block diagram of the research procedure.

### *2.1. Study Area*

Agios Konstantinos' agriculture depends mainly on olive tree production. Agios Konstantinos has around 750 ha [29] of olive groves, with more than 160,000 olive trees, producing two main edible olive varieties (Kalamon and Amfissis). The vast majority (80–90%) of the trees belong to the Amfissis variety. It is considered a very productive variety but is quite susceptible to diseases. Olive farmers in Agios Konstantinos prune their olive trees once every year. In comparison with other olive areas in Greece, Agios Konstantinos has olive groves with a high biomass productivity [30]. The current common practice used to manage olive prunings in Agios Konstantinos is mainly burning them in open fires inside the olive groves, or less frequently, mulching them on the soil. Thus, the investigation of harvesting solutions for untapped biomass sources, such as olive tree prunings, is of high significance.

Two experimental fields were selected in Agios Konstantinos, Fthiotida (NUTS 3), one characterized by a flat slope and the other by a hilly slope. The study area location is shown in Figure 1. In the following paragraphs of the paper, the flat slope field is indicated with "FL" and the hilly field is indicated with "HL."

Details of the two experimental fields are given in Table 1.

**Table 1.** Main characteristics of the olive groves.

| Characteristic | Unit | Flat Slope (FL) | Hilly Slope (HL) |
|---|---|---|---|
| Surface | ha | 0.6 | 1.67 |
| Exposition | | — | Northwest |
| Prevalent Slope | % | 2.50 | 19.70 |
| Minimum Slope | % | 1.50 | 15.80 |
| Maximum Slope | % | 3.60 | 21.80 |
| Layout (Width between rows × distance between trees) | m × m | 10 × 10 | 10 × 10 |
| Olive variety | | Amfissis | Amfissis |
| Number of olive trees | | 76 | 175 |
| Average pruning Ø | cm | 3 | 3 |
| Average pruning lenght | cm | 204 | 215 |
| Average windrow width | cm | 140 | 162 |
| Average windrow height | cm | 55 | 55 |

As shown in Table 1 and Figure 2, besides the different slope, there were no substantial differences between the two olive groves regarding the planting patterns and main characteristics of the residues (diameter and length of the branches).

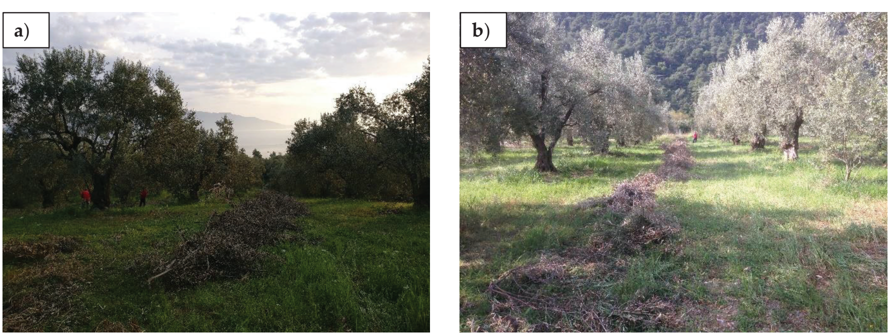


**Figure 2.** (**a**) Windrows on the flat slope field. (**b**) Windrows on the hilly slope field.

### *2.2. Harvesting System Description*

Before pruning harvesting, a preliminary windrowing step is usually necessary. This can be performed either manually or with a raking machine. In this work, windrowing for both the flat and hilly olive groves was conducted using an ABIMAC-rake-modified Girolivo (Abimas srl., Savigliano, Piemonte, Italy) powered by a 44 kW Ford 4610 tractor (Ford Motor Company spa, Dearborn, MI, USA).

The tractor used to power the Facma Comby TR200 (Figure 3) was instead an Ebro Model 85 (96 kW) (Ebro, Barcelona, Catalonia, Spain). The Facma Comby TR200 consisted of a towed shredder with a 2 m working width. The machine was composed of a pick-up system located on the front of the machine, a horizontal rotor for biomass comminuting that was able to work biomass to an 8 cm diameter, a metallic grid located between the rotor and the dumpster with the function of filtering biomass according to a desired size, and a rear dumpster of 5 $m^3$ for comminuted the biomass collection. The machine was 3.72 m long, 1.80 m high, and weighed 2200 kg. According to the manufacturer, the Facma Comby TR200 needs to be towed by a tractor of at least 56 kW (75 hp). Therefore, it is important to underline that the tractor used in the tests was substantially oversized.


**Figure 3.** The Facma Comby TR200.

## *2.3. Data Collection*

### 2.3.1. Field Work Evaluation

In each experimental field, the performance of the machines was evaluated through the study of the working times according to the standards ASAE S495 DEC99 [31]. The working times were measured and used to determine the actual and theoretical amount of area that could be served per unit time by the machine. These were termed the effective field capacity (EFC) ($ha \cdot h^{-1}$) and the theoretical field capacity (TFC) ($ha \cdot h^{-1}$), respectively. The EFC was also computed by dividing the hectares processed by the operative time (OT), i.e., the raw time needed to complete the harvest, including accessory times. These accessory times included the turning times, namely the time needed for maintenance, regulations, refueling, and unloading the dumpster. The TFC is the theoretical maximum field capacity without the accessory times. Lastly, the material capacity (MC) was computed as the quantity of pruning harvested per unit time ($t \cdot h^{-1}$).

The fuel consumption was determined through machine tank refilling until a full level was achieved at the end of each experimental unit using large, graduated cylinders to define the volume of fuel consumed ($L \cdot ha^{-1}$ or $L \cdot t^{-1}$ of biomass harvested).

### 2.3.2. Post Harvest Measurements and Data Analysis

Other important parameters were evaluated after the end of the harvesting operation.

After the harvesting, the biomass collected was weighed using a farm scale to determine the yield of biomass ($t_{fm} \cdot ha^{-1}$).

After the harvesting phase, the harvesting loss (%) was assessed using three transects per experimental field (large like the width of the harvester per 5 m long) that were randomly identified along the rows. All the biomass left on the ground inside the transects was collected by hand and weighed in the field using a dynamometer. Therefore, the area of each transect was normalized relative to a one-hectare surface to determine the amount of biomass left on the ground and not collected.

Five samples of 500 g of comminuted product were collected per experimental field to determine the moisture content (%) in accordance with EN ISO 18134-2:2017 [32]. The bulk density (kg·m$^{-3}$) was determined in both experimental fields in accordance with ISO 17828:2015 [33].

Furthermore, five samples of comminuted product of 500 g each were collected from a pile of mixed material collected from the two experimental fields to characterize the hog fuel regarding the particle size distribution analysis in accordance with the International Standard EN ISO 17225-4:2014 [34]. Samples of each field were retrieved and analyzed in CERTH/CPERI's laboratories in Ptolemaida by applying the established standards to determine the ash content (%) according to EN ISO 18122 [35] and the higher heating value (HHV, MJ·kg$^{-1}$) according to EN ISO 18125 [36] by using a Parr 6200 Calorimeter (Parr Instrument Company, Moline, IL, USA).

Statistical analysis was conducted using ANOVA and Tukey's HSD test.

### 2.4. Cost Analysis

The economic analysis focused on both ownership and operating costs in accordance with the parameters measured during the field tests (primary data) or by using standard values provided by the Centro Ricerca per le Produzioni Animali (CRPA) methodology [37]. The main economic parameters used for the machine operating costs analysis are reported in Table 2.

**Table 2.** Main economic parameters used for the economic analysis.

| Parameters | Unit | Facma Comby TR200 | Ford 4610 | Ebro Model 85 | Abimac Girolivo |
|---|---|---|---|---|---|
| Investment | € | 21,000.00 | 38,690.00 | 80,166.00 | 12,900.00 |
| Service life | yr | 10 | 10 | 10 | 10 |
| Usage | h·yr$^{-1}$ | 460 | 460 | 460 | 460 |
| Labour cost | €·h$^{-1}$ | | 11.50 | 11.50 | |
| Workers | n | | 1 | 1 | |

## 3. Results

### 3.1. Machine Performance and Quality of the Woody Comminuted Product

Regarding the work performance of the raking phase, for FL and HL, no significant differences in the field capacity and fuel consumption were found. The shredding phase also showed no significant differences in hilly and flat lands regarding the fuel consumption and harvesting losses of biomass. On the other hand, substantial differences were found regarding field capacities and working speed, which were higher for FL. However, the amount of biomass collected from HL was significantly higher than from FL, though the material capacity ($t_{fm}$·h$^{-1}$) between the two treatments did not vary.

Focusing on the obtained biomass quality, the moisture content was similar from both FL and HL with an average value of 27%. Similar results were found for the bulk density, with no statistically significant differences between the FL and HL values. Detailed results of the machine performance and hog fuel characteristics are reported in Table 3.

**Table 3.** Results of the statistical analysis regarding the machine performance of a pruning harvesting system on flat and hilly slopes and regarding hog fuel characteristics.

| Machine Performance | Unit | Pruning Rake (FL) | Pruning Rake (HL) | Facma Comby TR200 (FL) | Facma Comby TR200 (HL) |
|---|---|---|---|---|---|
| Theoretical Field capacity | $ha \cdot h^{-1}$ | 1.13 | 1.57 | 2.98 ± 0.39 * | 1.56 ± 0.10 * |
| Effective Field capacity | $ha \cdot h^{-1}$ | 0.60 | 0.88 | 1.57 ± 0.16 * | 0.79 ± 0.21 * |
| Field efficiency | % | 0.53 | 0.56 | 0.52 ± 0.70 | 0.51 ± 0.12 |
| Working speed | $km \cdot h^{-1}$ | — | — | 3.85 ± 0.57 * | 1.94 ± 0.13 * |
| Biomass yield | $t_{fm} \cdot ha^{-1}$ | — | — | 2.29 ± 0.54 * | 5.01 ± 1.61 * |
| Biomass yield | $t_{dm} \cdot ha^{-1}$ | | | 1.67 ± 0.38 * | 3.66 ± 1.13 * |
| Material capacity | $t_{fm} \cdot h^{-1}$ | — | — | 3.56 ± 0.68 | 3.75 ± 0.44 |
| Material capacity | $t_{dm} \cdot h^{-1}$ | — | — | 2.60 ± 0.50 | 2.74 ± 0.32 |
| Losses | % | — | — | 23 ± 12 | 27 ± 7 |
| Fuel consumption | $L \cdot ha^{-1}$ | 3.01 | 2.11 | 8.1 ± 0.3 | 18.5 ± 3.9 |
| Fuel consumption | $L \cdot t_{fm}^{-1}$ | 0.74 | 0.75 | 3.7 ± 0.7 | 3.8 ± 0.8 |
| Fuel consumption | $L \cdot t_{dm}^{-1}$ | 1.01 | 1.03 | 5.1 ± 1.0 | 5.2 ± 1.1 |
| Fuel consumption | $L \cdot h^{-1}$ | 1.81 | 1.85 | 12.7 ± 0.8 | 14.2 ± 1.7 |
| **Hog Fuel Characteristics** | **Unit** | **Pruning Rake (FL)** | **Pruning Rake (HL)** | **Facma Comby TR200 (FL)** | **Facma Comby TR200 (HL)** |
| Bulk density | $kg \cdot m^{-3}$ | — | — | 229 ± 8 | 224 ± 14 |
| Moisture content | %, w.b. | — | — | 27.3 ± 1.39 | 27.8 ± 1.42 |
| Ash content | %, d.b. | — | — | 4.00 ± 0.11 | 4.20 ± 0.19 |
| Higher heating value | $MJ \cdot kg^{-1}$, d.b. | — | — | 19.58 | 20.27 |

w.b.: wet basis, d.b.: dry basis; * $p < 0.05$, ** $p < 0.01$ (procedure: Tukey's HSD method).

The particle size distribution (PSD) analysis showed that the hog fuel produced using the Facma Comby TR200 belonged to the particle size class P16 (60% of the product with particles between 3.15 and 16 mm) and a fine fraction class F15 (fine fraction < 15%), and the d50 value (median value of the cumulated distribution curve) was 11.13 mm. Details of the particle size distribution analysis are given in Table 4.

**Table 4.** Particle size distribution (PSD) of the Facma Comby TR200 hog fuel.

| Particle Size | PSD | Cumulative Distribution |
|---|---|---|
| **[mm]** | **[%]** | **[%]** |
| < 3.15 mm | 12 | 12.00 |
| 3–15–8 mm | 27.69 | 39.69 |
| 8–16 mm | 26.37 | 66.06 |
| 16–45 mm | 17.53 | 83.59 |
| 45–63 mm | 0.59 | 84.18 |
| > 63 mm | 15.82 | 100.00 |

### 3.2. Cost Analysis

A detailed view of the costs for both experimental fields subdivided into fixed and variable costs for each machine is given in Table 5. The two tractors were the most economically impactful machines on the overall harvesting system's costs. In fact, about 85% of the harvesting system's costs in both experimental fields were linked to those of the two tractors (Ebro Model 85 and Ford 4610), while only 15% were related to the towed shredder and the rake.

**Table 5.** Details of the fixed and variable costs for each machine used in both experimental fields.

| | Cost Item | Measure Unit | Facma Comby TR200 | | Ebro Model 85 | | Ford 4610 | | Abimac Girolivo | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | FL | HL | FL | HL | FL | HL | FL | HL |
| Fixed Costs | Reintegration quote | €·yr$^{-1}$ | 1728.63 | 1728.63 | 5355.73 | 5355.73 | 2584.80 | 2584.80 | 1033.66 | 1033.66 |
| | Interests | €·yr$^{-1}$ | 370.71 | 370.71 | 1601.62 | 1601.62 | 772.98 | 772.98 | 231.95 | 231.95 |
| | Shelter | €·yr$^{-1}$ | 17.11 | 17.11 | 15.06 | 15.06 | 13.66 | 13.66 | 4.00 | 4.00 |
| | Insurance | €·yr$^{-1}$ | 52.50 | 52.50 | 200.42 | 200.42 | 96.73 | 96.73 | 32.25 | 32.25 |
| | Miscellaneous expenses | €·yr$^{-1}$ | 69.61 | 69.61 | 215.47 | 215.47 | 110.38 | 110.38 | 36.25 | 36.25 |
| | Total fixed cost per year | €·yr$^{-1}$ | 2168.95 | 2168.95 | 7172.82 | 7172.82 | 3468.16 | 3468.16 | 1301.86 | 1301.86 |
| | Total fixed cost per hour | €·h$^{-1}$ | 4.72 | 4.72 | 15.59 | 15.59 | 7.54 | 7.54 | 2.83 | 2.83 |
| Variable Costs | Maintenance | €·h$^{-1}$ | 1.68 | 1.68 | 1.51 | 1.51 | 0.73 | 0.73 | 1.03 | 1.03 |
| | Fuel | €·h$^{-1}$ | — | — | 7.29 | 8.15 | 1.04 | 1.06 | — | — |
| | Lubricant | €·h$^{-1}$ | — | — | 0.24 | 0.24 | 0.14 | 0.14 | — | — |
| | Manpower | €·h$^{-1}$ | — | — | 11.50 | 11.50 | 11.50 | 11.50 | — | — |
| | Total variable cost per hour | €·h$^{-1}$ | 1.68 | 1.68 | 20.53 | 21.39 | 13.41 | 13.43 | 1.03 | 1.03 |
| | Total cost per year | €·yr$^{-1}$ | 2940.41 | 2940.41 | 16617.50 | 17013.56 | 9635.72 | 9646.28 | 1775.76 | 1775.76 |
| | Total cost per hour | €·h$^{-1}$ | 6.39 | 6.39 | 36.13 | 36.99 | 20.95 | 20.97 | 3.86 | 3.86 |
| | Total cost per hectare | €·ha$^{-1}$ | 4.07 | 8.09 | 23.01 | 46.82 | 34.91 | 23.83 | 6.43 | 4.39 |
| | Total cost per ton | €·$t_{fm}$$^{-1}$ | 1.78 | 1.62 | 10.05 | 9.34 | 15.25 | 4.76 | 2.81 | 0.88 |

A summary of the various costs is also reported in Table 6. Table 6 and Figure 4 show that the systems' costs per unit time (€·h$^{-1}$) were very similar for both FL and HL after considering the raking operation and taking into consideration only the shredder's costs.

**Table 6.** Cost analysis results regarding the FL and HL experimental fields. "Harvesting Operation" refers to the costs of the Facma Comby TR200 and Ebro Model 85 tractors, while "Harvesting + Raking Operations" refers to the overall harvesting system's costs, i.e., the Facma Comby TR200, Ebro Model 85 tractor, Ford 4610 tractor, and Abimac Girolivo rake. FM: fresh matter, DM: dry matter.

| Harvesting Cost | Unit | Harvesting Operation | | Harvesting + Raking Operations | |
|---|---|---|---|---|---|
| | | FL | HL | FL | HL |
| Hourly cost | €·h$^{-1}$ | 42.52 | 43.38 | 67.32 | 68.21 |
| Cost per unit area | €·ha$^{-1}$ | 27.08 | 54.91 | 68.43 | 83.13 |
| Cost per product unit (FM) | €·$t_{fm}$$^{-1}$ | 11.83 | 10.96 | 29.88 | 16.59 |
| Cost per product unit (DM) | €·$t_{dm}$$^{-1}$ | 16.27 | 15.18 | 41.10 | 22.98 |

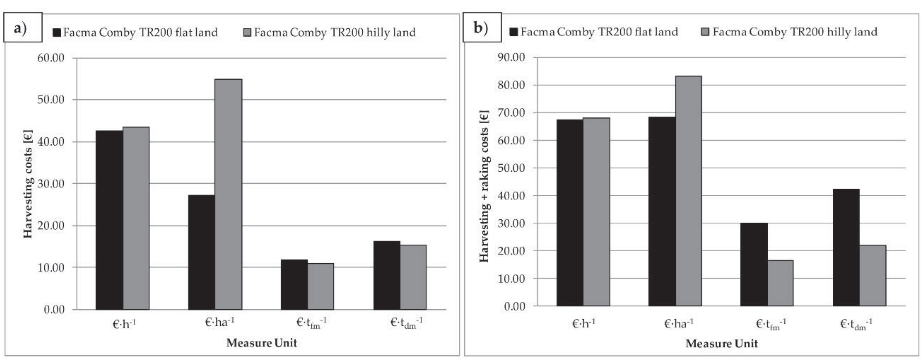


**Figure 4.** (**a**) Cost analysis regarding only the harvesting operation with the Facma Comby TR2000 towed shredder. (**b**) Cost analysis also considering the preliminary raking operation.

Regarding the systems' costs per surface unit area (€·ha$^{-1}$), there were substantial differences mostly when considering only the shredding operation. In particular, the flat slope experimental field incurred a lower cost than the hilly slope due to the lower field capacity of the latter.

Finally, regarding the costs per fresh biomass unit (€·$t_{fm}{}^{-1}$), the analysis showed very similar values for when concerning only the shredding costs. On the other hand, there were important differences between the two experimental fields when considering the overall system's costs (shredding + raking), with HL incurring substantially lower costs than FL. As expected, the trend regarding costs per dry biomass unit (€·$t_{dm}{}^{-1}$) was the same (Table 6).

## 4. Discussion

### *4.1. Machine Performance and Quality of the Work and Woody Comminuted Product*

The shredding and raking field efficiencies for FL and HL were similar. However, the field capacity of the shredding phase for HL was significantly lower than for FL; this was mainly due to the higher amount of biomass available in the hilly field (2.72 $t_{fm}$·$ha^{-1}$ more biomass than in HL), which required more time to be comminuted. It should be highlighted that the field capacity of the machines was influenced by several factors, including the shape of the field, the difficulty in turning, the necessary maintenance in the field, and the time for unloading of the product. However, the material capacity, i.e., the amount of biomass shredded per time unit, was practically the same in both fields (no significant statistical differences); therefore, the performance of the shredder did not change due to its use on the hill.

Consequently, significant differences were found in terms of the working speed, but no differences were observed in the fuel consumed (liter of diesel per hour, and liter per ton of woodchip produced, i.e., L·$h^{-1}$ and L·$t^{-1}$). On the flatland, the machine achieved a speed that was twice that on the hills because the pruning to be chipped was in lower quantities. Although a higher speed usually corresponds to a higher fuel consumption, it was evident that the greater fuel consumption on the hill (L·$ha^{-1}$) (where the machine worked more slowly) was linked not so much to the movement of the machine itself, but rather to the greater amount of pruning to be processed. In fact, by considering the fuel consumption per ton of product harvested (L·$t^{-1}$), as well as the hourly fuel consumption (L·$h^{-1}$), there was no statistically significant difference between the hilly and flat lands.

To explain this phenomenon, it should be added that the test conducted on the hilly land was carried out both uphill (with an increasing effort due to the progressive accumulation of material collected in the container) and downhill (with fuel savings due to utilizing the potential energy of the system and the theoretical zero fuel consumption), which led to a balance of fuel consumption regarding the movement of the tractor–shredder system. Therefore, even if the slope of about 20% measured for the hilly land was starting to be burdensome for the tractor, the overall results showed a slight increase in fuel consumption for the hill (14.2 L·$h^{-1}$ on the hill compared to 12.7 L·$h^{-1}$ on flat land), but this difference was not statistically significant (Table 3).

No statistically significant differences were found between the bulk density of the hog fuel produced on the two different experimental fields. Therefore, it seems that the lower working speed of the machine in the hilly field did not consistently affect this parameter.

Regarding the harvesting losses, which showed values of about 25% for both FL and HL, these were mostly linked to the windrow width, which at some point, became larger than the pick-up system of the shredder machine. This aspect could be improved through the higher compaction of the windrow during the raking phase to reduce the windrow width, or by applying swath brushes on both sides of the shredder pick-up system to facilitate the compaction of the swath at the feeding system of the shredder and thus increasing the harvesting efficiency and reducing the losses. These would improve the compaction of the pruning windrow, reducing the number of branches that escape the collection system.

Regarding the particle size distribution, the hog fuel produced belonged to the particle size class P16.5. The main problem with the obtained product regarding the fuel quality assessment was the consistent amount of oversized chips (15.82%), which could represent a problem for both industrial and domestic plants.

Regarding the physico-chemical properties of the obtained hog fuel, it was possible to make comparisons with the research of Picchi et al. [38], who analyzed hog fuels from different tree species pruning's residues, including olive trees. In particular, the ash content in the present study was very similar to Pichi et al. [38] (4.00% vs. 3.70%), but the HHV showed higher values: 19.53 MJ $kg^{-1}$ vs. 17.51 MJ $kg^{-1}$.

The consistent ash content was probably linked to the collection of soil and rocks, together with biomass within the machine shredding system. Such contamination was unavoidable when raking using mechanical pruning harvesting but could be decreased by adjusting the pick-up system height and by inserting dedicated screens [38]. Especially for olive tree prunings, the presence of leaves that have not fallen from the branches before or during harvesting is another factor that negatively influences the ash content.

By analyzing other previous studies that investigated olive trees' pruning harvesting performed with other machines—namely a 150 kW, self-propelled Favaretto Speedy cut (Favaretto Paolo, Meolo, Veneto, Italy) [8]; a self-propelled SAT-4 (Valoriza Energia-Energy Agency, Villanueva de Algaidas, Andalusia, Spain) [39]; and a tractor-mounted Jordan (Jensen Service GmbH, Maasbüll, Schleswig-Holstein, Germany) powered using a 162 kW tractor [8]—it was found that the Facma Comby TR200 showed a higher effective field capacity on both FL (1.57 ha·$h^{-1}$) and HL (0.79 ha·$h^{-1}$) than both the Favaretto (0.39 ha·$h^{-1}$) and Jordan (0.60 ha·$h^{-1}$); in contrast, the SAT-4 showed a higher value of 3.37 ha·$h^{-1}$.

The Facma Comby TR200 also showed a better performance when compared with the field capacity obtained using a Serrat mod. Olipack T1800 (0.78 ha·$h^{-1}$) (Serrat, Castejón del Puente, Huesca, Spain) and a Berti mod. Picker C180 (0.85 ha·$h^{-1}$) (Berti, Caldiero, Veneto, Italy) towed shredders tested by Velazquez-Martı et al. [40]. Among the few studies available in the literature regarding olive prunings' harvesting using a towed chipper, the results obtained by Assirelli et al. [41] with a Tierre mod. Plano (Tierre Group srl, Curtarolo, Veneto, Italy) should be mentioned, where they recorded a field capacity of 0.85 ha·$h^{-1}$ and a very high material capacity equal to 11 t·$h^{-1}$ [13].

Regarding the material capacity ($t_{fm}$·$h^{-1}$), the Facma Comby TR200 showed better values than the Serrat mod. Olipack T1800 (1.38 t·$h^{-1}$) and Berti mod. Picker C180 (1.26 t·$h^{-1}$) shredding machines recorded by Velazquez-Martı et al. [40], and a Nobili mod. TRP-RT 145 (0.53 t·$h^{-1}$) (Nobili, Molinella, Emilia-Romagna, Italy) shredding machine tested by Recchia et al. [42], both for FL (3.56 $t_{fm}$·$h^{-1}$) and HL (3.75 $t_{fm}$·$h^{-1}$). Furthermore, the chippers Promagri mod. 2000 (1.36 t·$h^{-1}$) (Promagri, Casablanca, Casablanca-Settat, Morocco) and Jounes mod. Atila (0.69 t·$h^{-1}$) (Jonues I Fills Sl, Lleida, Catalonia, Spain), both fed using a pick-up header and discharging into a trailer, tested by Velazquez-Martı et al. [40], as well as a self-propelled Favaretto mod. Speedy cut (0.72 $t_{fm}$·$h^{-1}$) [8], achieved lower productivities than the Facma Combi TR200. In contrast, the SAT-4 and Jordan presented better performances for this variable with 6.01 $t_{fm}$·$h^{-1}$ and 6.7 $t_{fm}$·$h^{-1}$, respectively. Finally, Suardi et al. [43] reported a very high material capacity of 7.26 $t_{fm}$·$h^{-1}$ with a Caravaggi Bio900 stationary chipper.

An overall view of the comparison between the results of this study and other similar studies is given in Table 7. It is important to note that the studies about the working productivity of a machine are strongly linked to the context in which the tests were conducted (biomass amount, wheater conditions, slope, skill of the operators, etc.). Therefore, this table is reported to give an overall view of the productivity of some machinery and systems for pruning harvesting, but it does not represent a way to indicate which machine or system is better than the others.

**Table 7.** Comparisons between the field capacity and the material capacity of the Facma Comby TR200 and other machines for olive pruning harvesting.

| Machine | Reference | Field Capacity ($ha \cdot h^{-1}$) | Material Capacity ($t_{fm} \cdot h^{-1}$) |
|---|---|---|---|
| Facma Comby TR200 FL | This study | 1.57 | 3.56 |
| Facma Comby TR200 HL | This study | 0.79 | 3.75 |
| Favaretto Speedy Cut | [8] | 0.39 | 0.72 |
| SAT-4 | [8] | 3.37 | 6.01 |
| Jordan | [8] | 0.60 | 6.70 |
| Serrat Olipack T1800 | [40] | 0.78 | 1.38 |
| Berti Picker C180 | [40] | 0.85 | 1.26 |
| Promagri 2000 | [40] | n.d. | 1.36 |
| Jounes Atila | [40] | n.d. | 0.69 |
| Tierre Plano | [41] | 0.85 | 11.00 |
| Nobili TRP-RT 145 | [42] | n.d. | 0.53 |
| Caravaggi BIO900 | [43] | 0.60 | 7.26 |

After giving an overall evaluation of the machine, it is possible to say that the Facma Comby TR200 showed good productivity, which was generally higher than other shredders in the market. However, from the obtained results, it is possible to notice the substantial influence of biomass yield on work productivity. In fact, the HL field showed a value that was approximately twice the FL value, thus allowing for a higher material capacity even with a lower field capacity. The same trend was also found in Spinelli and colleagues [8,39].

### 4.2. Cost Analysis

Comparing this paper's results on cost analysis with the previously mentioned studies [8,39], it is possible to notice the interesting economic performance of the Facma Comby TR200. Taking into consideration the costs per fresh biomass unit ($t_{fm}$ $ha^{-1}$), the Facma Comby TR200 on the hilly slope (HL) showed the best economic performance with 16.59 €·$t_{fm}{}^{-1}$. For the flat slope (FL), the Facma Comby TR200 had an economic performance of 29.88 €·$t_{fm}{}^{-1}$; a similar performance was found by Spinelli et al. [39] for a Jordan machine with 22.53 €·$t_{fm}{}^{-1}$ and a SAT-4 with 29.99 €·$t_{fm}{}^{-1}$. Substantially higher costs were found by Spinelli et al. [8] for a Favaretto Speedy Cut (58.70 €·$t_{fm}{}^{-1}$), although it carried out two phases (pruning and harvesting of pruning) in a single phase.

A key aspect to be taken into consideration for properly assessing and evaluating the economic performance of a pruning harvesting system is the economic profitability of these, which can be obtained by subtracting the harvesting costs from the revenue earned at the market price of hog fuel. The main problem in doing this is linked to the difficulties in the determination of the hog fuel price, which is even more complex in Mediterranean areas, e.g., in Greece, since there is not even a market for wood chips and much less one for hog fuel [44].

For this reason, a "revenue-costs" analysis of FL and HL was attempted by referring to Central and South Italy's hog fuel prices. This context is very similar to Greece regarding the spread of olive groves and the problems linked to the pruning's residues value chain. Even in Italy, it is not simple to find information on the hog fuel price; therefore, the authors performed a personal market analysis by interviewing various enterprises and cooperatives involved in the residual biomass value chain. The results of the interviews were very interesting and fundamental for implementing the economic analysis. The first aspect highlighted by the interviews was that the wood chips or hog fuel price, conferred to biomass power plants, is strongly influenced by the contract between the plant and the enterprise that gives the wooden material; therefore, the biomass quality, which is indeed fundamental, is not the only variable to take into consideration. In particular, power plants pay the highest price to big farmers with long-duration conferring contracts but they pay substantially lower prices to little farmers that have no contract and that only bring material to the plant occasionally. In more detail, hog fuel prices range from 25 €·$t^{-1}$ (small producer with no contract with the biomass plant) to 40 €·t$^{-1}$ (big enterprises with long-lasting conferring contracts). These prices are referred to as the landing sites of biomass, but in the case where the producer brings the hog fuel to the plant themselves, the prices are generally 10 €·t$^{-1}$ higher. According to this, to create an efficient value chain for hog fuel from pruning residues, it is important not only the increase the obtained biomass quality, as mentioned above, but also to create cooperatives or consortia among various farmers, allowing them to have better contracts with biomass plants. On the other hand, another possible solution is the development of energetic micro-chains using pruning residues not for selling them to big plants, but for the development of small heating systems for the farm premises.

Considering the complexity of this sector's market, another important and interesting approach is that of Fiusis's power plant (Calimera, Apulia, Italy). This company manages a biomass power plant in the Apulia region (Italy) and also developed a controlled enterprise for pruning harvesting and biomass supply. In detail, the owners of olive groves who want to give pruning residues to Fiusis only have to rake the biomass and then Fiusis handles the biomass harvesting without paying anything to the farmer; the farmer has the advantage of having pruning's residues removed from the field and incurring only raking costs. Such an approach could also be successful in other countries and productive contexts.

Another important aspect to be underlined, which was already reported in the previous paragraph dealing with the work productivity analysis, is the significant influence of biomass yield on machine performance, and consequently, on economic performance.

This aspect is shown in Figure 5. By considering the results of the costs analysis per surface unit area (€·ha$^{-1}$) and a hog fuel price of 25 €·t$^{-1}$, 2.7 $t_{fm}$·ha$^{-1}$ and 3.3 $t_{fm}$·ha$^{-1}$ are needed to obtain economic balance from FL and HL, respectively. Considering instead a hog fuel price of 40 €·t$^{-1}$, 1.7 $t_{fm}$·ha$^{-1}$ and 2.1 $t_{fm}$·ha$^{-1}$ are necessary from FL and HL, respectively.

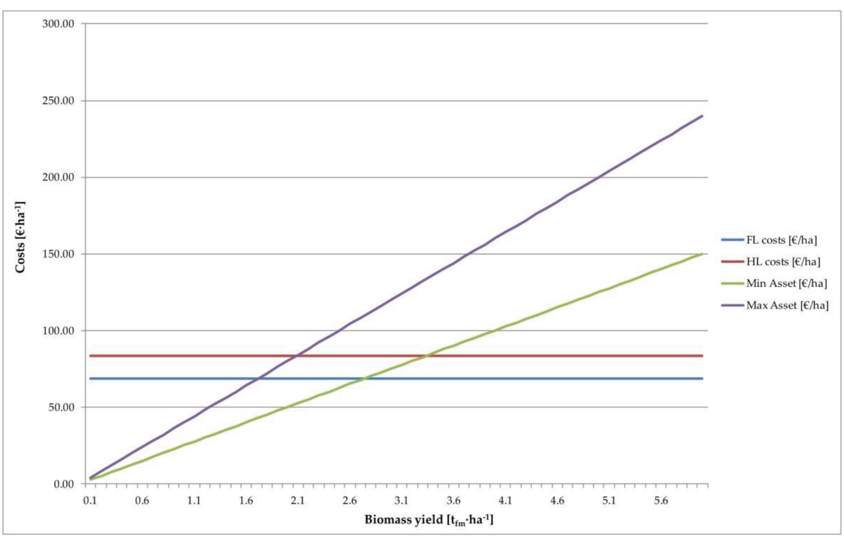


**Figure 5.** Relation between the biomass yield and economic profitability by considering a minimum price for hog fuel of 25 €·t$^{-1}$ (green line) and a maximum one of 40 €·t$^{-1}$ (purple line). The intersections with the blue (FL) and red (HL) lines indicate the minimum biomass yield necessary to achieve an economic balance from pruning harvesting by considering the costs per surface unit (€·ha$^{-1}$) for FL and HL.

Focusing on this paper's results regarding costs per fresh biomass unit (€·$t_{fm}$$^{-1}$) and taking into consideration the minimum price for hog fuel, i.e., 25 €·t$^{-1}$, it is found that only HL was cost-effective with a positive balance of + 8.41 €·$t_{fm}^{-1}$; on the other hand, FL was not cost-effective, showing a negative balance of −4.88 €·$t_{fm}^{-1}$. Considering instead the higher price for hog fuel (40 €·$t^{-1}$), both FL and HL showed positive balances with + 23.41 €·$t_{fm}^{-1}$ and + 10.12 €·$t_{fm}^{-1}$, respectively.

The last aspect to be discussed is about the improvement possibilities of the investigated harvesting system. As previously reported, the first issue is limiting rocks and soil contamination using a correct setting of the pick-up height and through the application of dedicated screens. Moreover, using a smaller tractor to power the Facma Comby TR200 seems to be a better solution, considering that this machine needed only 55 kW of tractor power take-off. The Ebro model 85 used in the tests was consistently oversized and using a smaller tractor, e.g., a 66 kW one, could lead to a lower turning time within the olive grove, thus allowing for a higher field capacity, and also a reduced fuel consumption. This is particularly true for this particular pruning harvesting operation, where the working speed was mostly linked to the towed shredder and not to the tractor itself. Thus a more powerful tractor does not generally lead to a higher working speed but only to a higher fuel consumption and (most likely) to higher turning times.

## 5. Conclusions

In summary, hills with a slope not exceeding 25% seemed to not be an important limit for the Facma Comby TR200 in terms of performance and fuel consumption. In fact, the machine showed good work performances on both flat and hilly slopes, which were often higher than the ones recorded by other authors with other harvesting systems. The worst aspects were represented by biomass losses and the characteristics of the comminuted material, in particular, the unacceptably high ash content. To improve these aspects, some modifications to the shredder's pick-up systems (e.g., swath brushes) seem necessary.

Finally, the economic aspects of this study's results were in line with those reported in the literature. Furthermore, it was concluded that the biomass yield had a significant influence on the machine performance, and consequently, on the economic sustainability of the harvesting phase. To obtain an efficient chain for hog fuel derived from olive groves' pruning, as well as improving the working phase, the development of consortia or a cooperative between the various farmers could be a positive solution, which would allow for obtaining higher prices from biomass plants.

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## Abbreviations:

| | |
|---|---|
| IBLC | Integrated biomass logistics center |
| NUTS | Nomenclature of Territorial Units for Statistics in Greece |
| FL | Flat slope experimental field |
| HL | Hilly slope experimental field |
| TFC | Theoretical field capacity (ha·h$^{-1}$) |
| EFC | Effective field capacity (ha·h$^{-1}$) |
| OT | Operating time (h) |
| MC | Material capacity (t·h$^{-1}$) |
| PSD | Particle size distribution |
| HHV | Higher heating value (MJ· kg$^{-1}$) |
| CRPA | Centro Ricerca per le Produzioni Animali |
| CERTH | The Centre for Research & Technology, Hellas |
| CPERI | Chemical Process Engineering Research Institute |
| FM | Fresh matter |
| DM | Dry matter |
| INASO-PASEGES | Institouto Agrotikis kai Sinetairistikis Oikonomias |
| NUTRIA | NUTRIA S.A., Agios Kostantinos, Fthiotida, Greece |

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# Admixing Chaff with Straw Increased the Residues Collected without Compromising Machinery Efficiencies

**Alessandro Suardi [1], Sergio Saia [1,*], Walter Stefanoni [1], Carina Gunnarsson [2], Martin Sundberg [2] and Luigi Pari [1]**

1 Council for Agricultural Research and Economics (CREA)—Research Centre for Engineering and Agro-Food Processing (CREA-IT), Via della Pascolare, 16 - 00015 Monterotondo Scalo (Rome) Italy; alessandro.suardi@crea.gov.it (A.S.); walter.stefanoni@crea.gov.it (W.S.); luigi.pari@crea.gov.it (L.P.)

2 Research Institutes of Sweden (RISE), Ultunaallén 4, 756 51 Uppsala, Sweden; carina.gunnarsson@ri.se (C.G.); martin.sundberg@ri.se (M.S.)

* Correspondence: sergio.saia@crea.gov.it

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**Abstract:** The collection of residues from staple crop may contribute to meet EU regulations in renewable energy production without harming soil quality. At a global scale, chaff may have great potential to be used as a bioenergy source. However, chaff is not usually collected, and its loss can consist of up to one-fifth of the residual biomass harvestable. In the present work, a spreader able to manage the chaff (either spreading [SPR] on the soil aside to the straw swath or admixed [ADM] with the straw) at varying threshing conditions (with either 1 or 2 threshing rotors [1R and 2R, respectively] in the combine, which affects the mean length of the straw pieces). The fractions of the biomass available in field (grain, chaff, straw, and stubble) were measured, along with the performances of both grain harvesting and baling operations. Admixing chaff allowed for a slightly higher amount of straw fresh weight baled compared to SPR (+336 kg straw ha$^{-1}$), but such result was not evident on a dry weight basis. At the one time, admixing chaff reduced the material capacity of the combine by 12.9%. Using 2R compared to 1R strongly reduced the length of the straw pieces, and increased the bale unit weight; however, it reduced the field efficiency of the grain harvesting operations by 11.9%. On average, the straw loss did not vary by the treatments applied and was 44% of the total residues available (computed excluding the stubble). In conclusion, admixing of chaff with straw is an option to increase the residues collected without compromising grain harvesting and straw baling efficiencies; in addition, it can reduce the energy needs for the bale logistics. According to the present data, improving the chaff collection can allow halving the loss of residues. However, further studies are needed to optimise both the chaff and the straw recoveries.

**Keywords:** bioresource; cereals; commodity; harvest index; staple foods; triticum; wheat

## 1. Introduction

The global cultivation of wheat involves an area of more than 225 Mha for total grain production of 684 Mt y$^{-1}$ [1]. Wheat cropping is a valuable source of biomass residue, mainly as straw, suitable for livestock as bedding, or as raw material for chemical applications, as reported by Scarlat et al. [2]. In addition, the use of vegetable biomass for more environmentally-friendly energy production is strongly supported by the new European policies [3], which encourage the use of crop residues, instead of dedicated crops to reduce the land use by the non-food crops. Since the demand for energy is increasing, the bio sources being currently exploited are unable to meet the new targets set by the EU 2030 framework for climate and energy policies [4,5]. Therefore, the capacity to retrieve as much residual biomass as possible has to be fostered. Chaff, which is the lightest and tiniest fractions resulting from wheat harvesting, could be included in straw collection in order to increase the total amount of biomass collected. According to McCartney et al. [6], chaff accounts, on average, for 17% (*w/w*), compared to grain production. Therefore, considering the 138 Mt and 684 Mt of wheat and spelt harvested yearly in Europe and globally, respectively [1], more than 23 Mt $yr^{-1}$ and 116 Mt $yr^{-1}$ of chaff are potentially available for harvesting in Europe and globally, respectively. Retrieving chaff from cereal crops could also have indirect positive effects on agricultural inputs [7,8]. Indeed, according to Rush [9], under favorable conditions, the presence of chaff in soil may represent a good substrate for saprophytic development, whereas Shirtliffe & Entz [10] highlighted the positive contribution of chaff removal in curbing weed seed availability in the soil. Besides, the additional biomass removed from soils may not lead to impoverishment of the stabile fraction of the soil organic carbon (SOC), since most of it likely derives from the decaying root system, which remains untouched [11]. Indeed, leaving plant residues in soil can reduce the loss of soil sediment and fertility; however, it has been shown that such an effect can be strongly variable [12]. In addition, it was clearly highlighted that a reduction of soil tillage is more likely to reduce the loss of soil organic carbon and soil fertility than maintenance of the soil cover [13].

Despite the chaff potential for various uses, most modern combine harvesters lack of a chaff recovery systems, unless specific equipment is installed [14]. The possible exploitation of agricultural residues for non-food purposes, as wheat chaff, has stimulated machine constructors to develop new systems. Some systems are already on the market and others are in the prototype stage [15]. Regardless of the brand, the common strategy for chaff recovery systems is to catch the chaff at the end of the cleaning shoe system of the combine harvester before it falls to the ground and get lost. Residues collection may not be economically and energetically feasible when crop yields are low [16,17], especially if the transport cost can offset the higher biomass collected when collecting the chaff separately from the straw or transporting it without a baling procedure [18]. The present study aimed to test a strategy to increase the total amount of residual biomass collected by recovering wheat crop chaff by admixing it with straw. This was studied in a two-year experiment using a Rekordverken Combi system installed on a hybrid combine harvester (2017) and a conventional combine harvester (2019). In addition, the overall performance of the machines involved (the grain combine harvester and the baler) in the biomass supply chain were measured. The present experiment was conducted in the framework of the H2020 AGROinLOG project [19], whose aim is to implement and demonstrate the technical and economic feasibility of integration of biomass logistic centres (IBLCs) for food and non-food products into the agro-industry sectors. In particular, there is increasing interest worldwide for more biomass residues available for the production of second generation ethanol. This could be achieved through the use of equipment commonly used in agriculture that does not require large initial investment, such as the spreader tested in this study.

## 2. Materials and Methods

### *2.1. Experimental Design*

A field experiment was conducted in two cropping seasons in Sweden. The first cropping season was in 2017 near Vattholma (Uppsala region, SE) (60°00′54.0″N 17°39′19.1″E); the second cropping season was in 2019 near Alunda (Uppsala region, SE) (60°05′29.7″N 18°07′04.7″E).

The soil of the area under study has a silty clay loam texture. In Vattholma, the soil has pH = 6.2, clay content of 32%, silt content of 66.6%, and 1.8% of soil organic matter. In Alunda, soil has pH = 7.8, clay content of 39%, and 4.9% of soil organic matter.

The elite winter wheat cultivar Julius was sown in early September in both cropping seasons at a rate of 170–180 kg seed/ha. In Alunda, the preceding crop was pea, and pea straw was removed. The winter wheat was treated with fungicide and fertilized with 100 kg MAP/ha (NP 12-23), 140 kg

Axan/ha (NS 27-4), and 30 t of liquid manure ha$^{-1}$ (1.5–2 kg N/t). No additional information is available for Vattholma.

In both cropping seasons, the experiments were arranged as a randomized block design with three replicates. There were two factors in the experiment: chaff mixing (CM) with straw and number or rollers (RN) used in the combine to thresh the grain from the chaff and straw. Chaff mixing with straw consisted of two treatments: either chaff admixed with straw in the combine (ADM) before the residue release by the combine or not i.e., chaff spread on the soil before straw release without mixing with straw in the combine (SPR). Thus, in theory, SPR consisted of a deposition on the soil of the chaff below the straw swath, whereas ADM consisted of a deposition in the soil of a mix of straw + chaff swath. The number of rotors used in the combine to thresh the grain was 1 or 2, indicating 1R or 2R, respectively. The two factors were arranged in an unbalanced design between the cropping seasons: in 2017, the SPR and ADM treatments were applied with only 1R and thus no 2R treatments were present. In 2019, SPR was applied with 2R and ADM was applied with either 1R or 2R. The unbalancing of the complete dataset was carefully taken into account in the statistical analysis (see further).

### 2.2. Equipment Used: Combines, Tractors, and Balers

Two main kind of machines were involved in the wheat harvesting: a combine harvester for collection of the grain and a tractor-baler combination for baling of the residuals (straw and chaff). The combine harvester used in 2017 was a hybrid Fendt 9490, and a New Holland CX5.80 equipped with the Rekordverken Combi System for chaff recovery in 2019. The baling was performed in both cropping seasons by means of a New Holland roll baler 125 Combi driven by a New Holland T6.175 tractors in 2017 and a New Holland T210 tractor in 2019.

### 2.3. Combi System Description

The Combi System developed by Swedish machine manufacturer Rekordverken Sweden AB is installed downstream of the sieving unit of the combine harvester [20]. Regardless of the cleaning shoe system adopted, the Combi System only requires a dedicated opening for the husk discharge. At this point, the fan delivers the chaff to the Combi System which, in turn, channels it either towards the chopping system (then mixed with the straw and in theory baled together), or laterally to the straw swath (spread on the ground, which discard its ability of being baled).

The hybrid combine used in the 2017 had no additional beaters (only 1 beater or rotor) after the separating rotors. For this reason, both SPR and ADM treatments were marked as 1R. In the 2019 test, the combine used was equipped with an additional beater downstream of the cross separator rotor. Such additional beater could be switched off by allowing modulating of the process with one (1R) or two beaters or rollers (2R).

### 2.4. Pre-Harvest Biomass Sampling

Before grain harvesting, sample areas of 1 m$^2$ each were randomly chosen and hand harvested at the ground level to score the potential total yield (grain + chaff + straw + stubble). Sampling areas close to the border were avoided to prevent edge effect. Plants were dissected on field for fresh weight of straw and spikes, then bagged and shipped to the CREA-IT laboratory for spike manual threshing and stubble, spike, chaff, and grain weight assessments. In the laboratory, grain was separated in a stationary thresher (Cicoria mod. Plot 2375) from the rest of the spike (sum of chaff, rachis, lemma, glumes, and palea) and weighed. The rest was weighed as a single by-product and referred to as chaff only. From all culm collected, 30 bunches of 10 randomly selected stems were collected. Relaying on the mean value of hundred stubble heights measured in a transversal transect drawn after the harvest, a cut was performed. The ratio between the weight of the part cut and the total weight of the bunch gave the percentage (*w/w*) of stubble that remained on the ground. The corresponding amount of grain, chaff, straw, and stubble was calculated. In the 2017 cropping season, the straw samples collected were also split in 10-cm pieces and weighed. The distribution of the weight of the straw along the culm was measured.

*2.5. Harvesting and Baling: Machines Performance*

Baling was done one day after grain harvesting. Figure 1 shows the combine harvester working in the SPR and ADM mode.


**Figure 1.** Chaff mixing strategies applied in the present study: the chaff was either spread (SPR, left panel) on the soil laterally to the straw swath by the combine harvester or it was admixed to the straw and released at the same time (ADM, right panel) (Source: CREA).

2.5.1. Time Records

In each experimental plot, the performances of the machinery was evaluated by studying the working times, according to the standard ASAE S496.2 [21]. The working times were measured and used to determine the actual and theoretical amount of area that can be served in the unit time by each machine. These were termed effective field capacity (EFC) [ha $h^{-1}$] and theoretical field capacity (TFC) [ha $h^{-1}$], respectively. The EFC is also computed by dividing the hectares processed by the operative time (OT), i.e., the raw time needed to complete the harvest, including accessory times. These accessory times include turning times, the time needed for maintenance, regulations, refueling, and unloading the hoppers, among others. The TFC is the theoretical maximum field capacity without the accessory times. Lastly, material capacity (MC) was computed as the quantity of grain or wheat residues harvested per time unit [t $h^{-1}$].

2.5.2. Fuel Consumption

Fuel consumption was measured in both the combine harvester and the tractor towing the baler. In the 2017, the fuel consumption was measured using a graduated cylinder to refill the tank at the end of each plot. The volume of the fuel measured per plot was referred per hectare. The refilling procedure was carefully carried out in order to avoid possible biased readings. In the 2019, both machineries were equipped with an onboard computer providing real-time fuel consumption for l $h^{-1}$. The instrument was cleared at the beginning of each plot and the reading was taken at the end of it. All the gathered data were used to define the performance of the machine and the operative costs.

*2.6. Post-Harvesting Analysis*

After straw harvesting, the following parameters were measured: mean bale fresh weight (the last bale on each plot was weighted but not taken into account for this variable), bale density, moisture content of chaff and straw during baling, and harvesting losses due to baling. Each bale was weighed for mean fresh weight and total fresh biomass yield per plot.

2.6.1. Bulk Density

In each plot, all bales were weighed singularl, and three of them were randomly selected and their sizes measured for volume assessment. Bulk density was successively calculated by dividing the mass in kilograms by the volume in cubic meter. The last bale in each plot was not taken into account in the bulk density calculation. In addition, non-completely filled bales (i.e., undersized bales) at the end of each plot were not taken into account in the statistical analyses on bale unit weight and density.

#### 2.6.2. Moisture Content

A sample was taken from one bale in each plot for moisture content determination by using a drill. The resulting moisture content was used to determine the dry matter (DM) yield of each plot. Moisture content was determined using the oven dry method described in the EN ISO 18134-2:2017 standard [22]. Moisture content in the grain, straw, and chaff were determined on three random subsamples.

Additionally, one sample per plot was taken from the swaths directly after combine harvesting. One grain sample was taken during the whole harvesting operation of the nine plots. It was dried at 105 °C for 24 h.

### *2.7. Evaluation of Residue Harvest Losses*

During the test carried out in 2017, biomass losses were evaluated as the average of the residues collected. This was carried out by using a vacuum system in three random transects, each measuring 9.2 m long and 0.5 m wide. The transect collection was performed by splitting the 9.2-m transect in three parts: a central part corresponding to the width of the baler pick-up collector and two lateral parts in which the straw and chaff could not be picked up by the baler. This allowed to compute, for the 2017 test only, two efficiency indexes, taking into account either the total residues (straw + chaff) deposited by the combine (referred as raw efficiency) or the sole residues that the baler was able to pick up (referred to as net efficiency).

In 2019 test, losses were estimated as the difference between theoretical biomass of grains, straw, and chaff collectable before the harvest (see Section 2.4) and the effective amount collected. Losses also included the amount of biomass lost as stubble.

### *2.8. Statistical Analysis*

The experiment in the 2017 cropping season included a comparison between SPR and ADM, both subjected to one transversal threshing. In 2019, treatments included spreading with two rotors, ADM with 2R or ADM with 1R. Notably, the 1R experiment in 2019 was performed by excluding, but not turning off, the second rotor from receiving the straw and chaff. Thus, results on fuel consumption and derived traits also depend on the combine energy needed to move the unused rotor.

The two-years experiment was subjected to a unique general linear mixed model (GLMM) by the Glimmix procedure in the SAS/STAT 9.2 statistical package in which the role of CM (either SPR or ADM), RN (either 1R or 2R), and their interaction was analysed. This procedure can model non-normal data and correct for heteroscedasticity [23]. Restricted maximum likelihood was used to produce unbiased estimates of variance and covariance parameters.

To accommodate for the unbalancing of the experiment, a Kenward-Roger estimation of the denominator degrees of freedom of each error was used and least square means (LSmeans, see below for a definition) of the treatment distributions were computed. When a treatment was considered significant at $p < 0.05$, LSmeans p-differences were computed and corrected by the Tukey-Kramer adjustment at 0.05. See the supplementary material in Saia et al. [24] for both a description of the procedure and the SAS package model applied.

To take into account both the variability of the growing seasons (referred as "year") and position of both the plot in each field and each bale within each plot, the analyses included various random factors depending on the variable measured. For variables relating to single straw bale, random factors included the cropping season, replicate within the cropping season, and the position of the bale in the field. For variables relating to the plot, random factors included the cropping seasonand replicate within cropping season. LSmeans were used instead of the means to compare the treatment effects. Briefly, LSmeans are estimation of a balanced population mean from an unbalanced data population. Thus, they estimate the corresponding mean in a factor level after taking into account both the distribution of the values of the variable within the level (fixed and random factors), and the distribution of the values within the population. In the results sections, data provided were the LSmeans of the treatments and the estimation of its standard error. The raw data means and their standard deviations were provided as supplementary material tables.

## 3. Results

### 3.1. Grain and Straw Yields, Biomass Distribution in the Residues, Straw Traits, and Straw Harvesting Efficiency

On average, the total biomass produced was 16,490 kg DW ha$^{-1}$, with a mean harvest index (i.e., the ratio between grain and total biomass) of 0.49. In contrast to our expectation, grain yield was 10.6% higher in the SPR than ADM plots, on average (Tables 1 and S1).

**Table 1.** Results of the general linear mixed analysis of the wheat biomass fraction and efficiency of the harvesting procedures. During the combine harvesting, the wheat straw was subjected to the chaff mixture (CM): either by admixing the chaff with the straw (ADM) or spreading the chaff in the soil before the straw release (SPR). The procedures were performed by either using 1 or 2 rotors (1R or 2R, respectively). Since no interaction was detectable between factors, only LSmeans data per factor are displayed. See the text for the statistical analysis. Factors at $p < 0.05$ are shown in bold.

| Variable | | *p* Values | | | LSmeans of CM | | LSmeans of RN | |
|---|---|---|---|---|---|---|---|---|
| | | CM | RN | CM × RN | SPR | ADM | 1R | 2R |
| Total Biomass (TB) | kg DW ha$^{-1}$ | 0.709 | *0.110* | 0.677 | 16456 ± 2781 | 16523 ± 2781 | 16262 ± 2781 | 16718 ± 2784 |
| Total Grain yield (GY) | kg grain DW ha$^{-1}$ | ***0.043*** | 0.572 | 0.520 | **8477 ± 1388** | **7665 ± 1388** | 8207 ± 1388 | 7935 ± 1407 |
| Uncut residues (i.e., stubble) | kg uncut straw DW ha$^{-1}$ | ***0.027*** | 0.467 | ***0.028*** | **1617 ± 425** | **1706 ± 425** | 1644 ± 425 | 1679 ± 425 |
| Total Chaff (TC) | kg chaff DW ha$^{-1}$ | 0.058 | 0.685 | 0.453 | 1853 ± 102 | 1676 ± 105 | 1791 ± 105 | 1738 ± 125 |
| Baled straw (BS) | [kg Straw DW ha$^{-1}$] | 0.478 | 0.426 | 0.266 | 3710 ± 1075 | 3829 ± 1076 | 3674 ± 1076 | 3865 ± 1081 |
| Total potential harvestable straw (TPHS) | kg DW ha$^{-1}$ | ***0.023*** | *0.088* | 0.175 | **6362 ± 973** | **7186 ± 974** | 6377 ± 974 | 7171 ± 993 |
| Straw harvest raw efficiency | BS / TPHS | 0.246 | 0.663 | 0.198 | 0.593 ± 0.075 | 0.534 ± 0.076 | 0.580 ± 0.076 | 0.547 ± 0.085 |

Such a difference was marginally significant (with the CM factor showing a $p = 0.043$). Notably, such a difference cannot be attributed to the CM factor and must be considered a natural variation in the field. Nonetheless, it was taken into account in the further analyses. At the same time, the CM strategy strongly affected the total potential harvestable straw (TPHS), with ADM allowing to obtain 13.0% more TPHS compared to the SPR, although such an effect is very likely due to the higher grain yield in this latter treatment compared to ADM.

Straw harvest raw efficiency, i.e., the ratio between the straw baled and total residues (except stubble) available was 56.3%, with no differences among treatments. In general, the treatments applied had a scarce effect on the biomass traits and straw harvest raw efficiency (Table 1) computed on the basis of the TPHS. In 2017, the straw harvest efficiency was computed by both a raw basis, as indicated above, and a net basis. The net harvest straw efficiency was computed by discarding from the analysis the amount of straw that fell outside of the baler collection line. Raw and net efficiencies were found to be strongly correlated (Figure 2).

In contrast, the effect of the CM on the fraction of biomass that was not harvested varied according to the RN (Table 1 and Figure 3). When using 1R, no differences were found between SPR and ADM, whereas using 2 rotors consisted of a slightly higher fraction of non-harvested biomass (i.e., the stubble) in ADM compared to SPR. Notably, such differences did not consist of a difference in the total DW of the straw baled, which however differed for the FW. In particular, ADM showed 4579 kg straw FW ha$^{-1}$ and SPR 4243 kg straw FW ha$^{-1}$ ($p$ of CM = 0.029; $p$ of RN = 0.097; $p$ of the interaction = 0.909).

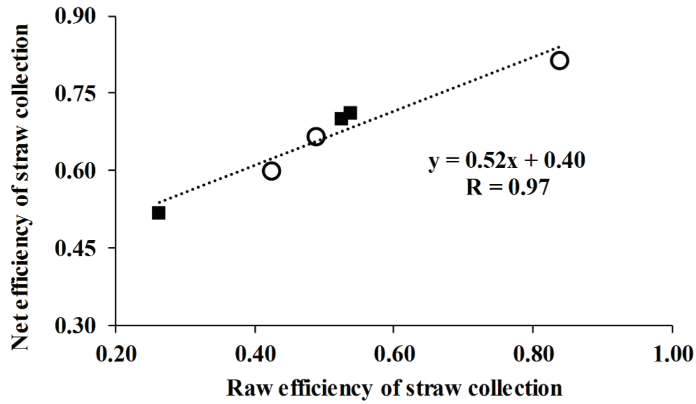


**Figure 2.** Correlation between net and raw straw efficiency collection in the 2017 experiment. Filled squares are for ADM treatments, and open circles for SPR treatments. The correlation coefficient is displayed.

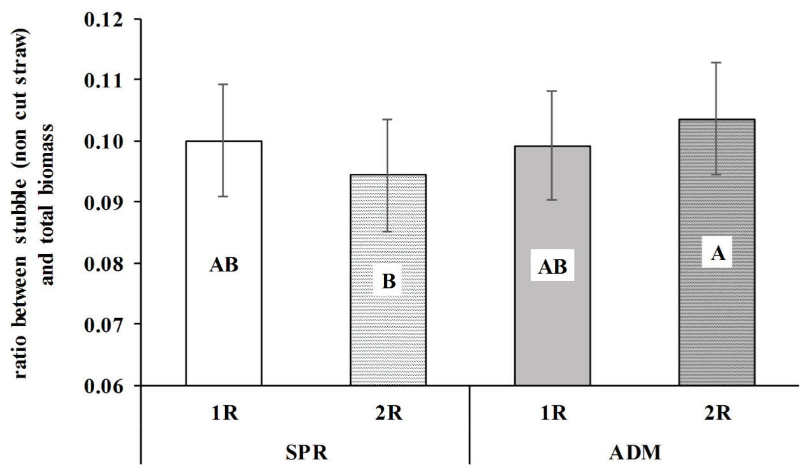


**Figure 3.** Ratio between stubble (i.e., uncut straw) and total biomass on varying the chaff management after grain threshing: either admixing the chaff with the straw (ADM, grey bars) or spreading the chaff in the soil before the straw release (SPR, white bars) and number of rotors for the threshing operation: either 1 (clean bars) or 2 (hatched bars), indicated as 1R or 2R, respectively. Means with a letter in common cannot be considered different according to a conservative Tukey-Kramer test applied to the p differences of the LSmeans.

Biomass distribution along the culm was also measured in 2017 (Figure 4) showing a homogeneous distribution along the first 50 cm of the culm, which is abundantly higher than the cutting height, and a tendency to decline at the 50-cm height.

Rotor number, but not the CM strategy, affected the bale and straw traits (Tables 2 and S2). In particular, 2R allowed for a 5.3% higher bale weight compared to 1R. At the same time, 2R consisted of dramatically shorter straw pieces compared to 1R: 24.1% of length reduction, consisting of 9.0 cm.

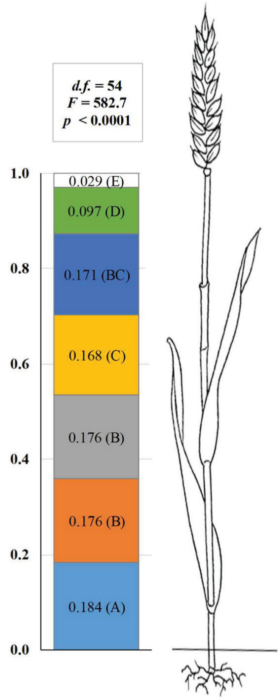


**Figure 4.** Biomass distribution along the total height of the straw (split by 10-cm pieces) in 2017. Each fraction represents a 10-cm piece, except for the upper fraction (white bar) that represents a 2-cm piece. Means with a letter in common cannot be considered different according to a Tukey-Kramer test applied to the *p* differences of the LSmeans. The results of the statistical analysis are shown in the picture.

**Table 2.** Results of the general linear mixed analysis of the single bale traits (mean dry and fresh weight and density) in the complete dataset and length of straw pieces (in 2019, only). During the combine harvesting, the wheat straw was subjected to the chaff mixture (CM): either by admixing the chaff with the straw (ADM) or spreading the chaff in the soil before the straw release (SPR). The procedures were performed by either using 1 or 2 rotors (1R or 2R, respectively). Since no interaction was detectable between factors, only LSmeans data per factors at $p < 0.05$ are displayed. See the text for the statistical analysis. In 2019, arithmetic mean is shown since the dataset was balanced. Factors at $p < 0.05$ are shown in bold, the estimation of the degrees of freedom (d.f.) by the Kenward-Roger procedure and the standard error (S.E.) are shown.

| | **Mean Bale Weight** | | | **Mean Bale Weight** | | | **Bale Density** | | | **Mean Length of Straw Pieces** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *d.f.* | *F* | *p* | *d.f.* | *F* | *p* | *d.f.* | *F* | *P* | *d.f.* | *F* | *p* |
| CM | 10.8 | 1.67 | 0.223 | 10.07 | 0.42 | 0.534 | 9.88 | 0.44 | 0.524 | n.a. | n.a. | n.a. |
| RN | **8.57** | **10.34** | **0.011** | 9.60 | 0.64 | 0.443 | 9.19 | 0.68 | 0.432 | **89** | **60.54** | **<0.0001** |
| CM×RN | 8.25 | 0.02 | 0.896 | 8.29 | 0.01 | 0.919 | 8.24 | 0.01 | 0.920 | n.a. | n.a. | n.a. |
| | ***Least Squares Means (LSmeans)*** | | | | | | | | | ***Means (in 2019, only)*** | | |
| | *Value* | *S.E.* | *N* | | | | | | | *Value* | *S.E.* | *n* * |
| 2R | 187.9 | 2.3 | 37 | | | | | | | 28.40 | 0.75 | 60 |
| 1R | 178.4 | 2.5 | 63 | | | | | | | 37.42 | 0.91 | 60 |

* 10 sub-replicates per replicate.

### 3.2. Efficiency of Combine Grain Harvesting and the Baling Procedures, and Fuel Consumption

Field efficiency (FE) of the grain harvesting procedures was markedly influenced by RN (Tables 3 and S3), with 1R harvested treatments showing an 8% absolute higher field efficiency than the 2R treatment. In contrast, neither the CM nor the RN affected the TFC, EFC, and fuel consumption.

The CM strategy also affected the material capacity of the combine and such an effect was evident, with SPR treatments allowing to collect 14.9% more grain in the same unit time compared to ADM.

On average, TFC and EFC were 3.72 ha $h^{-1}$ and 2.28 ha $h^{-1}$, respectively and the combine required 11.8 l fuel $h^{-1}$.

In contrast to the grain harvesting procedures, the straw baling procedures were not affected by the treatments applied (Tables 3 and S1). In particular, TFC and EFC of the baling operation resulted on average 3.96 ha $h^{-1}$ and 2.01 ha $h^{-1}$, thus consisting of a mean field efficiency of 0.51. No information is available about the fuel needed for the baling procedure.

**Table 3.** Results of the general linear mixed analysis of the grain harvesting and straw baling procedures. During the combine harvesting, the wheat straw was subjected to chaff mixture (CM): either by admixing the chaff with the straw (ADM) or spreading the chaff in the soil before the straw release (SPR). The procedures were performed by either using 1 or 2 rotors (1R or 2R, respectively). Since no interaction was detectable between factors, only LSmeans data per factors are displayed. See the text for the statistical analysis. Factors at $p < 0.05$ are shown in bold.

| | | ***p* Values** | | | **LSmeans of CM** | | **LSmeans of RN** | |
|---|---|---|---|---|---|---|---|---|
| | | **CM** | **RN** | **CM × RN** | **SPR** | **ADM** | **1R** | **2R** |
| ***Data for the grain harvesting procedures*** | | | | | | | | |
| **Theoretical Field Capacity (TFC)** | **[ha $h^{-1}$]** | 0.69 | 0.17 | 0.41 | 3.68 ± 1.66 | 3.76 ± 1.66 | 3.51 ± 1.66 | 3.92 ± 1.67 |
| Effective Field Capacity (EFC) | [ha $h^{-1}$] | 0.71 | 0.66 | 1.00 | 2.29 ± 0.85 | 2.27 ± 0.85 | 2.26 ± 0.85 | 2.30 ± 0.85 |
| Field efficiency (FE) | EFC/TFC | 0.63 | ***0.01*** | 0.24 | 0.63 ± 0.06 | 0.62 ± 0.06 | **0.66 ± 0.06** | **0.58 ± 0.06** |
| Fuel consumpion | [l $ha^{-1}$] | 0.81 | 0.11 | 0.37 | 11.8 ± 2.0 | 11.8 ± 2.0 | 12.1 ± 2.0 | 11.5 ± 2.1 |
| Material Capacity | [t grain $h^{-1}$] | ***0.01*** | 0.34 | 0.11 | **19.6 ± 2.5** | **17.1 ± 2.5** | 18.8 ± 2.5 | 17.8 ± 2.5 |
| ***Data for the baling procedures*** | | | | | | | | |
| Mean ball weight | [kg Straw FW per bale] | 0.78 | 0.36 | 0.35 | 210 ± 17 | 211 ± 17 | 208 ± 17 | 212 ± 17 |
| Bale density | [kg Straw FW $m^{-3}$] | 0.75 | 0.34 | 0.33 | 134 ± 17 | 134 ± 17 | 133 ± 17 | 135 ± 17 |
| Theoretical Field Capacity (TFC) | [ha $h^{-1}$] | 0.38 | 0.76 | 0.64 | 3.86 ± 0.17 | 4.06 ± 0.15 | 3.92 ± 0.15 | 3.99 ± 0.17 |
| Effective Field Capacity (EFC) | [ha $h^{-1}$] | 0.70 | 0.49 | 0.49 | 1.98 ± 0.29 | 2.04 ± 0.29 | 1.92 ± 0.29 | 2.10 ± 0.32 |
| Field efficiency (FE) | EFC/TFC | 0.81 | 0.48 | 0.61 | 0.52 ± 0.07 | 0.51 ± 0.07 | 0.49 ± 0.07 | 0.54 ± 0.08 |
| Material Capacity | [t straw $h^{-1}$] | 0.18 | 0.12 | 0.65 | 8.82 ± 4.32 | 9.50 ± 4.32 | 8.58 ± 4.32 | 9.74 ± 4.33 |

## 4. Discussion

The above ground residual biomass of cereals has a high energy value and can have a high economic value. Nonetheless, it is an untapped by-product that could provide an extra amount of biomass for the production of bio-commodities. From this point of view, its collection should in theory be as high as possible, in order to reduce the fixed energetic costs of collection, as also recently suggested, taking into account that the producing bioenergy from the straw may have lower impacts compared to that from the grain [25] and that combining food and energy systems may allow for a further reduction of the environmental impact and to mitigate the climate-related fluctuations of the agricultural production and commodity value [26].

Concerns have arisen about the straw removal from the soil and its likely negative impact on soil organic carbon (SOC) accumulation. However, it is quite established that SOC accumulation mostly depends on the root carbon rather than above ground carbon [11] and that straw use for bioenergy processes can save various times the $CO_2$ the soil is able to sequester as SOC [27]. In addition, no SOC loss was found depending on the straw removal in various environments in both short- and long-term experiments [7,8].

In this work, a device developed to incorporate the chaff into the swath and thus allow its recovery as baled straw, in contrast to the most common operation of spreading it onto the soil, was tested. This device was tested in combination with a milder process, compared to a harsher threshing operation (i.e., 1R compared to 2R, respectively), which can affect the length of the straw pieces and thus the straw aptness to be baled. Notably, the two operations were performed by taking the whole combine devices turned on. This implies that both the ADM and SPR mode had the chaff-to-straw mixer on, but it did not receive the material when in the SPR mode. Similarly, both 1R and 2R modes had the second rotor turned on, which did not receive material when in the 1R mode.

This implies that differences in the combine performance were likely due to the additional energy required to overcome the friction of the plant biomass being processed into the combine, rather than to the energy required to get the device turned on. Nonetheless, this was enough to produce a difference in the field efficiency (FE) of the system, with the 1R showing higher FE than the 2R. In particular, it was shown that such a friction can be responsible for scarce energy demand by the combine [28–30], but it can still demand more time for the operator to allow the complete threshing of the grain and cutting of the straw. It should be, however, highlighted that field efficiency in this experiment likely differed from a normal cultivation due to the high time needed for turning and stopping compared in the plots, whose size was definitely smaller than that of most fields.

Nonetheless, similar behavior may have occurred when comparing the combine performance in the CM modes, where SPR showed a higher material capacity than ADM. Indeed, ADM consisted of higher amounts of both straw FW baled and TPHS. Therefore, the differences in the material capacity may have been due also to the higher amount of biomass the ADM mode had to process. In SPR, the chaff is spread laterally to the swath, and the chopper is bypassed, which also reduces the wear and energy consumption on the combine. It was excluded that such differences may have been due to a differential regulation by the combine driver of the cutting height since the stubble was slightly heavier (+5.5%) in the ADM compared to the SPR; however, such a difference only corresponds to 0.8–1.1 cm of stubble, that may have been due to a local difference in soil-carrying capacity. In addition, the biomass distribution in the culm was strongly homogeneous below 50 cm height and, above all, this may have not produced a difference in the grain harvested, thus suggesting that local conditions in the ADM plots may have affected the stubble biomass. This confirms the results by Boyden et al. [31] who found that stubble height is not directly and linearly related to the straw baled, despite their stubble height being 50%–100% more than the one in the present study. It was also excluded that difference in the grain harvested could have been due to a higher loss of grain as non-threshed material in the ADM compared to the SPR since no grain was found in the soil after the combine harvesting or into the bales when these were sampled to be analysed. Notably, these differences between SPR and ADM did not consist of a difference in the combine fuel demand.

In contrast to the combine, the treatments applied did not affect baler performance. However, the efficiency of straw removal (i.e., the straw removed per unit total residues available) dramatically differed with the strategy of computation of the efficiency. When taking into account the whole TPHS, including that which fell out of the baler swaths, such an efficiency was 16% lower than when taking into account the only residue fraction in the baler collection swath.

Similar results of the percentage of straw removed were found by other authors [32–34]. In particular, Bergonzoli et al. [34] also found similar effects on machine performance by varying the chaff collection device. A higher percentage of straw removed was found in the present study than others [7,35]. This can explain the lack of difference among treatments. Indeed, in the Lafond et al. [7] experiment, both grain and straw yields were 65% and 75% lower, respectively, when compared to the present experiment, and straw losses ranging from 60% to 78%. In conditions of low yields and high straw losses, little additional straw recovery can determine marked difference in the percentage of straw baled. In addition, SPR and ADM did not differ by mean bale weight, whereas 2R consisted of heavier bales than 1R. Since 2R consisted of definitely shorter straw pieces, this may be an indirect outcome of a better baling procedure. This can explain the higher bale unit DW in the 2R than 1R. Lack of differences in the bale unit weight or density by the chaff management systems could have been due to the scarce amount of chaff compared to the straw, which resulted in 23–29% of the TPHS. Similar or slightly higher results were found by others [7,36].

## 5. Conclusions

In conclusion, alternative management strategies of the chaff and the degree of straw cutting into the combine scarcely affected both grain harvesting and baling procedure performances. Chaff mixing with the straw allowed for slightly higher straw FW yields (+336 kg straw FW ha$^{-1}$), but it may slightly reduce the material capacity of the combine. In contrast, using 1 rotor in the threshing line of the combine can increase combine field efficiency, but it can reduce the bale unit weight, which can have drawbacks in the energy demand of the pipeline of the bale logistics. The strategies applied in the present study consisted of straw losses of 41–47%. If considering that chaff represented 23–29% of the total residues, this implies that an efficient collection of the chaff can allow halving the loss of residues. This could occur without loss in performance of the whole harvesting, baling, and bale handling chain, if considering that chaff management can represent a negligible cost compared to the fixed costs of the whole baling procedure and bale handling [14]. However, further studies are needed to optimise both chaff and the straw recoveries, with special emphasis on the ability to collect it separately from the straw within the combine or better incorporating it into the straw before baling. A main limitation of the present study indeed is the relatively high straw biomass in this field, which may have masked the role of the chaff management, and limited information on the rotor effects.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/1996-1073/13/7/1766/s1, Table S1. Data of the grain, biomass and efficiencies, baling procedures, and grain harvesting procedures in 2017 and 2019 (means ± standard deviations), Table S2. Data of the bale traits in 2017 and 2019 (means ± standard error).

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# Life Cycle Assessment of Giant Miscanthus: Production on Marginal Soil with Various Fertilisation Treatments

**Michał Krzyżaniak [1,*], Mariusz J. Stolarski [1] and Kazimierz Warmiński [2]**

1 Department of Plant Breeding and Seed Production, Centre for Bioeconomy and Renewable Energies, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; mariusz.stolarski@uwm.edu.pl
2 Department of Chemistry, Research Group of Environmental Toxicology, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; kazimierz.warminski@uwm.edu.pl
* Correspondence: michal.krzyzaniak@uwm.edu.pl; Tel.: +48-89-5246146

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**Abstract:** In Poland, unutilised land occupies approximately two million hectares, and it could be partly dedicated to the production of perennial crops. This study aimed to determine the environmental impact of the production of giant miscanthus (*Miscanthus* x *giganteus* J.M. Greef & M. Deuter). The experiment was set up on a low-fertility site. The crop was cultivated on sandy soil, fertilised with digestate, and mineral fertilisers (in the dose of 85 and 170 kg ha$^{-1}$ N), and was compared with giant miscanthus cultivated with no fertilisation (control). The cradle-to-farm gate system boundary was applied. Fertilisers were more detrimental to the environment than the control in all analysed categories. The weakest environmental links in the production of miscanthus in the non-fertilised treatment were fuel consumption and the application of pre-emergent herbicide. In fertilised treatments, fertilisers exerted the greatest environmental impact in all the stages of crop production. The production and use of fertilisers contributed to fossil depletion, human toxicity, and freshwater and terrestrial ecotoxicity. Digestate fertilisers did not lower the impact of biomass production. The current results indicate that the analysed fertiliser rates are not justified in the production of giant miscanthus on nutrient-deficient soils.

**Keywords:** *Miscanthus* x *giganteus*; bioenergy; environmental impact; agricultural production; circular bioeconomy; digestate

## 1. Introduction

Giant miscanthus (*Miscanthus* x *giganteus* J.M.Greef & M.Deuter) is grown in Europe and the world as a source of biomass for bio-based industries. The species has a variety of applications, including in heat and power generation and the production of ethanol and construction materials [1–4]. Giant miscanthus yields are estimated at 10–20 Mg ha$^{-1}$ dry matter (d.m.) per year, but they can range from 2.5 to 60 Mg ha$^{-1}$ year$^{-1}$ d.m., subject to climate and local environmental conditions [5–8].

Giant miscanthus can be cultivated on low-quality soils that are not suitable for growing food or fodder crops [9]. In Europe, marginal land covers around 64 million ha, of which nearly 54 million ha can be used for biomass production to promote sustainable development and protect the environment [10]. In Poland, unutilised agricultural (including arable land, meadow, pasture, orchard, arable land with trees or shrubs) land occupies an estimated area of two million ha and accounts for 14.2% of the total agricultural land [11]. Nearly half of the marginal land is not suitable for the cultivation of food and fodder crops, but it could be sown with crops for biobased products and biofuels. In Poland, low-quality soils are often deficient in organic matter and nutrients, and considerable inputs are required to restore their productive capacity. Agricultural inputs could be reduced using digestates from agricultural biogas plants, which are problematic residues. The European Biogas Association reports that there are more than 18 thousand biogas plants in Europe [12]. The storage, disposal, and management of digestate pose a challenge for the biogas industry. Biogas digestates can be applied directly as fertilisers, but they can also be processed into fertilisers with a high content of carbon, nitrogen, and phosphorus [13–15]. Recycling as a fertiliser is considered to be the most sustainable utilisation of digestate, as it can provide benefits for society in general and the environment in particular, as well as to help the preservation of limited natural resources such as fossil resources of mineral phosphorus [16].

Research into the application of organic by-products for fertilising perennial plants on low-quality soils has been conducted at the University of Warmia and Mazury in Olsztyn for 10 years [17–20]. These efforts involved life cycle assessments of the environmental impact of lignocellulosic plants fertilised with processed digestates. Such assessments (LCA) have been performed for Virginia mallow (*Sida hermaphrodita* Rusby L.), a relatively under-utilised crop whose popularity continues to increase on account of its potential applications in the biofuel and energy sector [21–23]. This article presents a life cycle assessment of giant miscanthus, a plant species which is more widely cultivated than Virginia mallow. In Europe, the area under giant miscanthus is estimated at 40,000 ha, and Great Britain and Germany are the leading producers [24]. Therefore, the aim of this study was to determine the environmental impact associated with giant miscanthus cultivation on sandy soil, fertilised with biogas digestate and mineral fertilisers and compared with a non-fertilised treatment.

## 2. Materials and Methods

### 2.1. Goal, Scope and Functional Units

This attributional LCA aimed to determine the environmental impact of the production of giant miscanthus in treatments fertilised with digestate, in treatments supplied with mineral fertilisers and in non-fertilised treatment. The Attributional LCA modelling describes the environmentally relevant physical flows to and from a life cycle and its subsystems [25]. The cradle-to-farm gate system boundary was applied, and the functional units were 1 Mg of dry biomass and 1 GJ of energy from fresh biomass.

The system boundaries (Figure 1) covered the co-production of digestate in a biogas plant, conversion of digestate into fertilisers, mineral fertilisers, and equipment production.

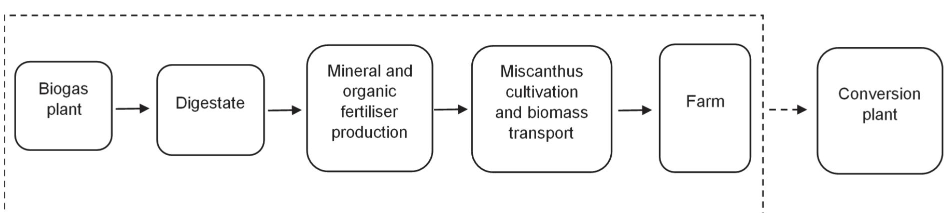


**Figure 1.** System boundaries for the cultivation, harvest, and transport of miscanthus.

### 2.2. Modelling and Data Sources

A life cycle inventory (LCI) was based on the results of field trials conducted in 2013-2015 at the UWM farm in Leginy. The trials were set up on a low-fertility site on sandy soil and contained 2.65% of organic matter. The contents of N-total, $P_2O_5$, $K_2O$ in the soil were 0.08%, 129, and 104 mg $kg^{-1}$, respectively, and the soil pH was 5.3. More details on the site are described in Stolarski et al. [19]. The field operations performed for the plantation establishment and operation are presented in Table 1.

The study involved five treatments: wet digestate (WD), dry digestate (DD), torrefied digestate (TD), mineral fertilisation (MF), and non-fertilised treatment (base scenario/control—C). Digestate fertilisers were applied at 85 and 170 kg ha$^{-1}$ N, as described by [26]. Mineral N fertiliser was applied as ammonium nitrate at the same nitrogen rates; phosphorus and potassium fertilisers were applied at 30 kg ha$^{-1}$ $P_2O_5$ and 60 kg ha$^{-1}$ $K_2O$, as triple superphosphate and potassium salt. It was assumed that the miscanthus plantation lifetime was 15 years. It was assumed that the miscanthus biomass yield in the plantation lifetime would be equal to the average yield of this crop for the first three years of field experiments [19] multiplied by 15 years of operating the plantation. Energy yields were calculated from the product of fresh miscanthus biomass and its lower heating value (Table 2). The digestate used for fertiliser production was composed of 50% pig manure and 50% cattle manure. The conversion of digestate to fertilisers was described in Krzyżaniak et al. [26].

**Table 1.** Field operations.

| Operation | Diesel Oil (kg ha$^{-1}$) | Materials | Comments |
|---|---|---|---|
| Establishment and Closure of Plantation-Operations Performed Once per Plantation Lifetime | | | |
| Spraying | 2.04 | Glyphosate—Roundup 360 SL. 5 dm$^3$ ha$^{-1}$ | |
| Disking | 8.98 | | |
| Ploughing | 29.30 | | 5–ridge plough, ploughing depth—30 cm |
| Harrowing (x2) | 11.20 | | 2 operations |
| Planting | 14.06 | rhizomes 10,000 ha$^{-1}$ | 4-row planting machine, suitable for seedlings, rhizomes, or locally produced tubers |
| Mechanical weed control (3x) | 21.09 | | 3 operations |
| Plantation closure | 44.65 | | Ploughing liquidating Miscanthus plantation after 15 years of its use (5–ridge plough. ploughing depth—30 cm) |
| Operations Performed Annually | | | |
| Application of wet digestate | 12.86–25.94 | | Fertiliser inputs differed subject to fertilisation rate |
| Application of dry and torrefied digestate | 7.03–14.06 | | Fertiliser inputs differed subject to fertilisation rate |
| Application of mineral NPK fertiliser | 7.02 | | The lower and higher fertilisation rates were applied at the same time |
| Soil mixing with fertilisers | 12.65 | | |
| Harvest | 11.25–73.84 | | Subject to yield; average harvester capacity: 10 Mg h$^{-1}$ |
| Biomass transport | 37.2–57.7 (tkm)* | | Subject to yield |

* units in tonne-kilometre (tkm)

**Table 2.** Organic carbon (OC) contribution of digestates, dry biomass yield, and net energy yield during 15 years of miscanthus cultivation.

| Fertilisation | N Rate (kg ha$^{-1}$ N) | OC in Digestate (kg ha$^{-1}$ C) | Biomass Yield (Mg ha$^{-1}$ d.m.) | Net Energy Yield (GJ ha$^{-1}$) |
|---|---|---|---|---|
| Wet digestate (WD) | 85 | 750 | 33.3c | 528 |
| | 170 | 1499 | 36.2 bc | 576 |
| Dried digestate (DD) | 85 | 2515 | 40.8 abc | 657 |
| | 170 | 5030 | 53.0 abc | 855 |
| Torrefied digestate (TD) | 85 | 2786 | 47.0 abc | 753 |
| | 170 | 5572 | 62.1 ab | 1005 |
| Mineral fertilisers (MF) | 85 | 0 | 55.1 abc | 867 |
| | 170 | 0 | 64.1 a | 1014 |
| Control (C) | 0 | 0 | 54.9 abc | 878 |

a, b, c letters mean that yields are statistically different (Tukey's test at $p < 0.05$)

Greenhouse gases (GHG) emissions were determined with the use of the methods described by [26]. In brief, GHG emissions associated with soil carbon sequestration and $N_2O$ emissions were calculated with the below Equation (1):

$$E_{GHG} = -\frac{44}{12} \times SCS + GWP_{N_2O} \times \left(E_{direct\ N_2O} + E_{indirect\ N_2O}\right) \quad (1)$$

where: $E_{GHG}$—greenhouse gas emissions [kg $ha^{-1}$ $CO_2$ eq.], $SCS$—soil carbon sequestration [kg $ha^{-1}$ C], $GWP_{N2O}$—global warming potential of $N_2O$, $E_{direct\ N2O}$ + $E_{indirect\ N2O}$—direct and indirect emissions of $N_2O$ [kg $ha^{-1}$ $N_2O$], 44/12—$CO_2$/C molar ratio.

The GHG emission balance was determined on the assumption that $CH_4$ emissions equal zero because giant miscanthus was grown on non-waterlogged mineral soil. The nitrification and denitrification of nitrogen compounds in soil was the main source of $N_2O$ emissions (direct emissions). The production of $N_2O$ from the atmospheric deposition of $NH_3$ and $NO_x$ volatilised from soils, N leaching, and runoff (indirect emissions), was also taken into account [27]. Soil carbon sequestration was adopted at 9.7% of the net C input [28]. The net C input was calculated from the difference between the amount of organic matter (OM) available to giant miscanthus (digestate and crop residues) and spring barley (cultivated in a conventional tillage system) with straw incorporated into the soil (as reference) [29,30]. The number of crop residues introduced to soil was calculated in the C-TOOL model [31]. The procedure of selecting parameters for the C-TOOL model was described by Krzyżaniak et al. [26]. The amount of OM introduced to soil with digestate was calculated based on the applied digestate rate and the carbon content of digestate determined with the CHS 500 elemental analyser (ELTRA GmbH, Germany).

The emissions of ammonia ($NH_3$), nitrogen oxides ($NO_x$), non-methane volatile organic compounds (NMVOC), and particulate matter PM10, nitrate, and phosphate leaching were calculated according to the methods described in the authors' previous work [26].

### 2.3. Life Cycle Impact Assessment (LCIA)

A life cycle impact assessment of giant miscanthus was carried out using the ReCiPe Midpoint (H) method. This method is the successor of two popular methods, Ecoindicator 99 and CML-IA. The objective of the method is to transform the Life Cycle Inventory data into a limited number of indicator scores. ReCiPe can be used with two levels of indicators: midpoint (as in the authors' studies) and endpoint categories. Eight of eighteen impact categories were selected based on other studies on perennial crops [26,32,33]: climate change, human toxicity, particulate matter formation, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, and fossil depletion. Impact categories were normalised (Europe ReciPe H/H) and recalculated per European citizen. The population of the EU28 was set at 464 million people.

## 3. Results and Discussion

### 3.1. Miscanthus Production without Fertilisation (Base Scenario)

The production of giant miscanthus in the base scenario was associated with net emissions of 33.83 kg $CO_2$ equivalents (eq.) per tonne of dry biomass (Table 3) (including the capture of 2.19 kg $CO_2$ eq.). Biomass harvest transport and plantation closure contributed most to the climate change category (Figure 2). The impact on human toxicity was 3.80 kg $Mg^{-1}$ d.m.1,4-DB eq., and the main contributors were glyphosate use, biomass transport, and harvest (Table 3, Figure 2). Particulate matter formation reached 0.60 kg $Mg^{-1}$ d.m. PM10 eq. Field emissions (mostly particulate matter from the soil) were mainly responsible for PM10 release. Fuel combustion associated with the operation of harvesting machines was the second-largest source of PM10 emissions. In the terrestrial acidification, emissions were determined at 0.31 kg $Mg^{-1}$ d.m. $SO_2$ eq. and fuel combustion accounted for 64.7% of emissions in this category. Other contributors were plantation closure and biomass transport. Total emissions in the freshwater eutrophication category reached 0.0034 kg P eq. per tonne of dry biomass (Table 3). The pre-emergent herbicide had the main impact, followed by biomass transport and biomass harvest. In the terrestrial ecotoxicity, the highest emissions (0.006 kg $Mg^{-1}$ d.m. 1,4-DB eq. in total) were found for the production and use of pre-emergent herbicide, followed by fuel use for harvest. In the freshwater ecotoxicity category, total 1,4-DB emissions were determined at 0.169 kg $Mg^{-1}$ d.m., where pre-emergent herbicide and biomass transport were the main contributors. Fossil depletion was determined at 12.42 kg $Mg^{-1}$ d.m. oil equivalents, and it was associated mainly with harvest (Table 3, Figure 2). Fuel consumption contributed the most to fossil depletion during harvest and other field operations.

The results indicate that the use of pre-emergent herbicide and fuel consumption were the main contributors to all but one impact categories in the base scenario (C). Field operations contributed most to particulate matter formation.

### *3.2. Production of Giant Miscanthus with Fertilisation*

GHG emissions associated with miscanthus production in the base scenario were determined at 33.8 kg $Mg^{-1}$ d.m. The energy inputs per 1 GJ of produced biomass reached 2.1 kg $CO_2$ eq. (Figure 3). A notable increase in biomass yield was observed in treatments TD 170 and MF 170 (13% and 17%, respectively) relative to control (Table 2). In treatment MF 85, fertilisation increased miscanthus yield by only 0.4%. In the remaining treatments, biomass yields were 3–39% lower than for control. As a result, agricultural inputs did not induce a significant increase in yields but led to high GHG emissions per unit of biomass and energy (Figure 3). The environmental impact in the climate change category increased in every fertilisation treatment. The lowest increase (30%) in GHG emissions relative to control was noted in treatment TD 170. Greenhouse gas emissions were very high for both fertiliser rates in treatments WD and MF. The contribution of these treatments to climate change was 13- to 20-fold higher relative to the base scenario. Greenhouse gas emissions were lower for miscanthus produced without fertilisers than for Virginia mallow produced without fertilisers (95.9 kg $Mg^{-1}$ d.m. $CO_2$ eq.) [26]. The above can be attributed to higher soil carbon sequestration in the miscanthus plantation, whereas in the production of Virginia mallow, the highest GHG emissions were associated with the depletion of soil organic matter. In the study of treatments, WD and MF were also associated with high emissions of greenhouse gases, but these emissions were lower in treatments TD and DD than in control, which can be attributed to higher yields and higher soil carbon sequestration [26]. In a study by Brandão et al. [34], GHG emission of giant miscanthus production was 707 kg $ha^{-1}$ $CO_2$ eq. The analysis was performed for high yield values, which led to high carbon sequestration and emissions of 27.6 kg $Mg^{-1}$ d.m. $CO_2$ eq. In an Irish study [35], the emissions from the production of miscanthus pellets in treatments with mineral and organic fertilisers were determined at 20.23 and 15.50 kg $GJ^{-1}$ $CO_2$ eq., respectively, when biomass was transported over a distance of 50 km. GHG emissions reached 5.98 and 1.25 kg $GJ^{-1}$ $CO_2$ eq., respectively, when biomass was not pelleted. Therefore, fertilisation with biosolids contributed far less to climate change. Other studies showed that perennial plants have higher soil carbon sequestration potential than annual plants, and their production in a biobased economy could minimise the adverse consequences of climate change [36].

Particulate matter formation was higher in all fertilisation treatments than for the control (Figure 4). Mineral fertilisation increased emissions 2–2.5-fold, whereas digestates increased its 3.7–6.2-fold. Field emissions contributed most to PM10 formation in all fertilisation treatments (61–84%). Particulate matter formation in miscanthus production with digestate and mineral fertilisers was 10–200% higher than in the production of Virginia mallow in the corresponding treatments [26].

**Table 3.** Environmental impact of miscanthus production without fertilisation (base scenario) per 1 Mg of biomass dry matter.

| Impact Category | Unit | Total | Chemical Weed Control | Disking | Winter Ploughing | Harrowing | Planting | Mechanical Weeding | Harvest | Transport | Plantation Closure | Field Emissions |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Climate Change | kg CO2 eq. | 33.8 | 1.09 | 0.61 | 1.99 | 0.76 | 0.96 | 1.43 | 21.8 | 4.31 | 3.04 | −2.19 |
| Particulate Matter Formation | kg PM10 eq. | 0.60 | 0.002 | 0.003 | 0.009 | 0.004 | 0.004 | 0.007 | 0.10 | 0.01 | 0.01 | 0.44 |
| Terrestrial Acidification | kg $SO_2$ eq. | 0.31 | 0.005 | 0.006 | 0.018 | 0.007 | 0.009 | 0.013 | 0.201 | 0.02 | 0.03 | 0 |
| Freshwater Eutrophication | kg P eq. | 0.003 | 0.002 | 0.00001 | 0.00005 | 0.00002 | 0.00002 | 0.00003 | 0.0005 | 0.001 | 0.0001 | 0 |
| Human Toxicity | kg 1,4-DB eq. | 3.80 | 1.36 | 0.02 | 0.06 | 0.03 | 0.028 | 0.06 | 0.83 | 1.31 | 0.12 | 0 |
| Terrestrial Ecotoxicity | | 0.006 | 0.002 | 0.00005 | 0.0003 | 0.00006 | 0.0002 | 0.0001 | 0.002 | 0.0007 | 0.0003 | 0 |
| Freshwater Ecotoxicity | | 0.17 | 0.12 | 0.0005 | 0.002 | 0.0006 | 0.0008 | 0.001 | 0.02 | 0.03 | 0.002 | 0 |
| Fossil Depletion | kg oil eq. | 12.42 | 0.41 | 0.21 | 0.69 | 0.26 | 0.33 | 0.50 | 7.55 | 1.43 | 1.05 | 0 |

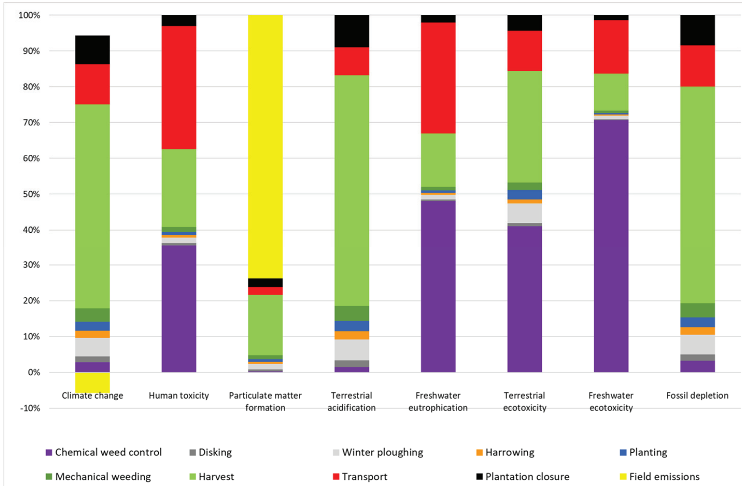


**Figure 2.** Contribution of miscanthus production processes in selected impact categories in the base scenario (control).

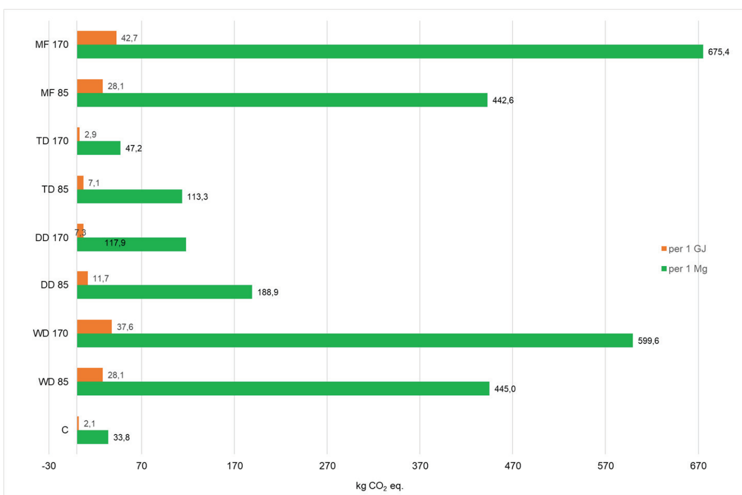


**Figure 3.** Greenhouse gases emission for miscanthus production in different fertilisation treatments.

Particulate matter emitted by agricultural facilities, soil, and farming operations is classified as pollution. The type, properties, and moisture content of soil as well as wind speed, significantly influence PM10 emissions associated with tillage and wind erosion. Dry, mechanically tilled soils with sparse vegetation cover have the highest dust-generating potential [37–39]. An increase in dust emissions was observed during tillage on biochar amended soils [40]. For this reason, no-till systems and perennial crops are more environmentally-friendly than annual crops produced in conventional systems [37]. Particulate matter emitted by agricultural soils contains far fewer toxic compounds (heavy metals, persistent organic pollutants) than that produced by fuel combustion, traffic, and industrial operations [41,42]. Agricultural operations also lead to the production of particulate matter from the combustion of diesel oil. These particulates penetrate the respiratory tract of humans and animals and are deposited in the pulmonary region of the lungs and exert adverse health effects [43].

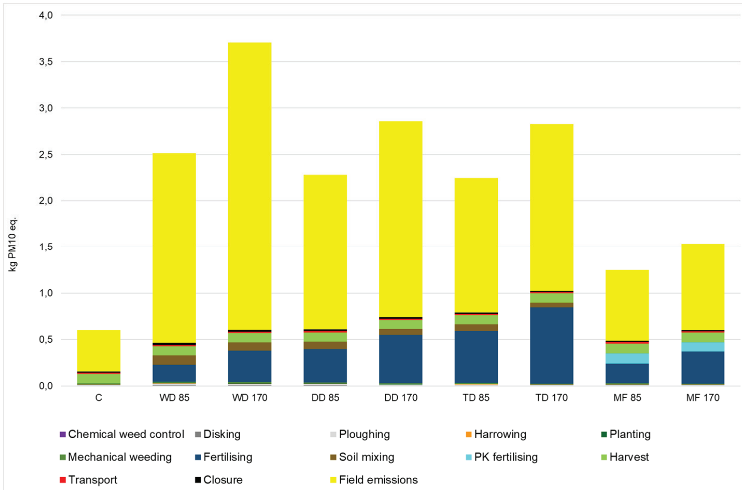


**Figure 4.** Particulate matter formation per 1 Mg dry matter (d.m.) of miscanthus in different fertilisation treatments.

Environmental impact of terrestrial acidification was lower in mineral fertilisation treatment than in all digestate treatments (Figure 5). Both digestate rates (85 and 170 kg N $ha^{-1}$) showed approximately 30-fold higher and 40- to 54-fold higher impact, respectively, relative to control. These emissions can be attributed to nitrogen leaching from the applied fertilisers (52–91% contribution). In other studies, acidification potential was determined at 0.59 kg $Mg^{-1}$ d.m. $SO_2$ eq. for SRC willows [44], 0.91 kg $Mg^{-1}$ d.m. $SO_2$ eq. for maize [45], and 1.10–1.32 kg $Mg^{-1}$ d.m. $SO_2$ eq. for wheat with mineral fertilisation [33]. In the present study, the acidifying effect of digestate was considerably higher than in other experiments, which can be attributed mainly to higher crop yields (up to 10-times higher) in the other cited studies. In the current experiment, higher fertilisation rates did not increase yields compared with the control (except MF170 and TD 170 variants), and excess nitrogen was released as $NH_3$ and $NO_x$, compounds that contribute to acidification.

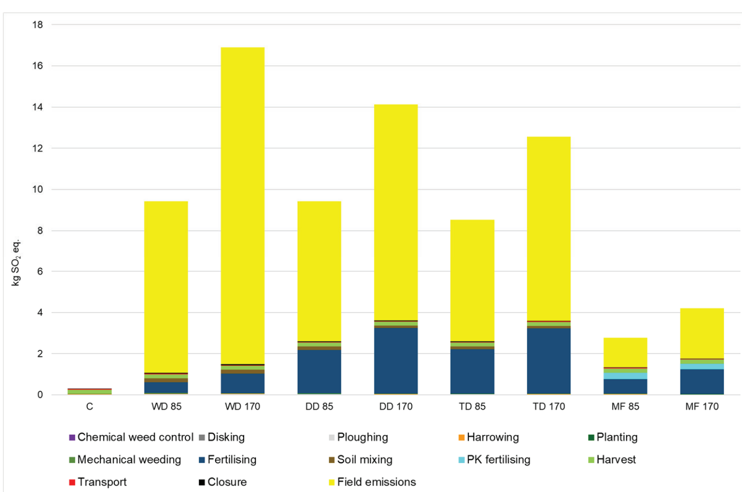


**Figure 5.** Terrestrial acidification per 1 Mg d.m. of miscanthus in different fertilisation treatments.

A significant portion of N and P applied to the soil with fertiliser and manure reaches freshwater systems and is transported by rivers to coastal areas, thus contributing to the eutrophication of groundwater, rivers, lakes, coastal, and marine ecosystems [46]. Fertilisation treatments contributed to this effect as well. The impact of WD 85 and WD 170 was 40–72 times higher than in the control, and N, and P leaching had the highest impact (86–94%) in this category (Figure 6). In contrast, in MF 170 and MF 85, the main contributor to freshwater eutrophication was triple superphosphate production (66–72%). Fertilised treatments emitted 9% (TD 170) to 203% (WD 170) more P equivalents.

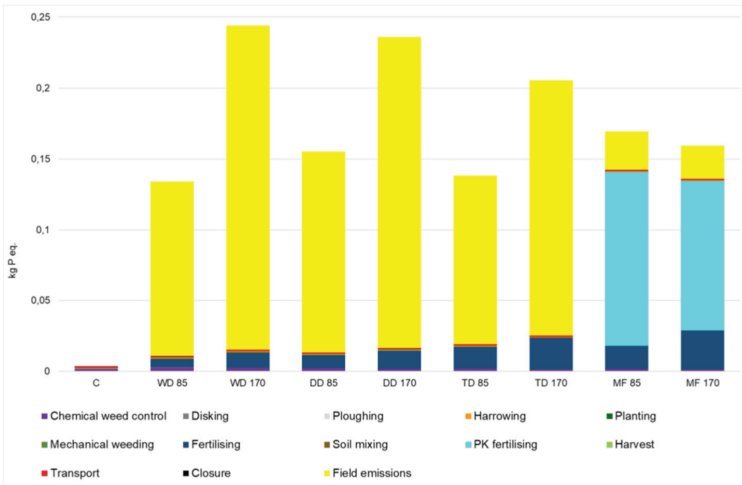


**Figure 6.** Freshwater eutrophication per 1 Mg d.m. of miscanthus in different fertilisation treatments.

In the authors' previous study of Virginia mallow, fertilisers (particularly various forms of digestate) also contributed to freshwater eutrophication [26]. Murphy et al. [35] found that the replacement of synthetic fertiliser with biosolids increased acidification potential by 290–400% and eutrophication potential by 258–300%. In a study by Stolarski et al. [19], higher fertilisation rates did not promote the growth of giant miscanthus, and higher yields were noted in the third year of the experiment in a plot without organic fertilisation. The authors also reported that fertilisation was practically unnecessary in the first year of the experiment. According to other researchers, nutrients released by decomposing leaves are re-circulated into the soil, and nitrogen is relocated to the rhizomes in winter, which is why giant miscanthus requires very little or no fertilisation. In this study, fertilisation did not compensate for low biomass yields on nutrient-deficient soils, which led to low nutrient availability, nutrient leaching, and considerable freshwater eutrophication.

Every fertilisation treatment had a higher environmental impact on human toxicity than the control. Both fertilisation rates in treatments WD and DD were the least detrimental to the environment relative to control (Figure 7). The associated emissions were approximately 4–6 times higher than in the control. The greatest contributors were the production of equipment in treatment WD and digestate drying in treatment DD. The impact of treatment MF was 12–16 times higher than C, and the production of nitrogen and phosphorus mineral fertilisers were the greatest contributors. Treatment TD was most detrimental to the environment, with a negative impact 24 and 35 times higher than in C. The emissions in TD 85 and TD 170 were determined at 90.7 and 132.6 kg $Mg^{-1}$ d.m. 1,4-DB eq., respectively.

In the terrestrial ecotoxicity category, the emissions in TD 85 and TD 170 were 86 and 129 times higher, respectively, than in the control (Figure 8). In those variants, wood was used as fuel for digestate torrefaction. It was also assumed that wood ash (contaminated with heavy metals) was used to fertilise agricultural land, which significantly contributed to terrestrial ecotoxicity. The emissions in WD and

DD were 2–3 times higher than in C, and the greatest contributors were the production and use of diesel oil for fertilisation, followed by the application of glyphosate in weed control. The impact of mineral fertilisers on terrestrial ecotoxicity was four and five times higher (MF 85 and MF 170, respectively) relative to the control. In these treatments, N fertilisation (mainly ammonium nitrate production) was responsible for 51–66% of the impact.

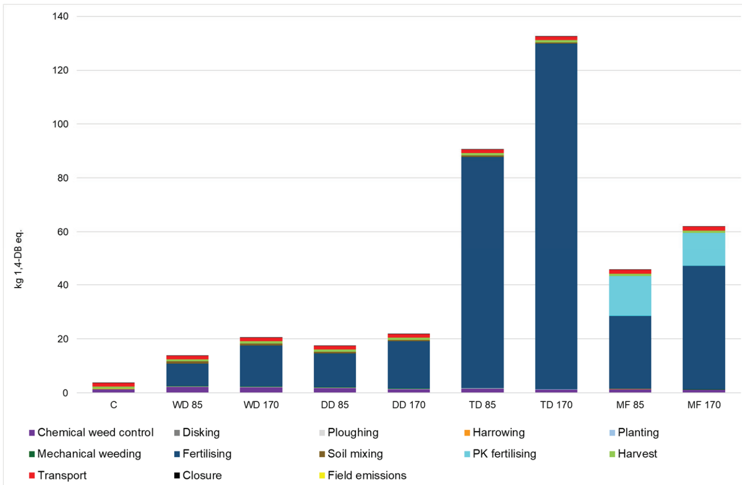


**Figure 7.** Human toxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.

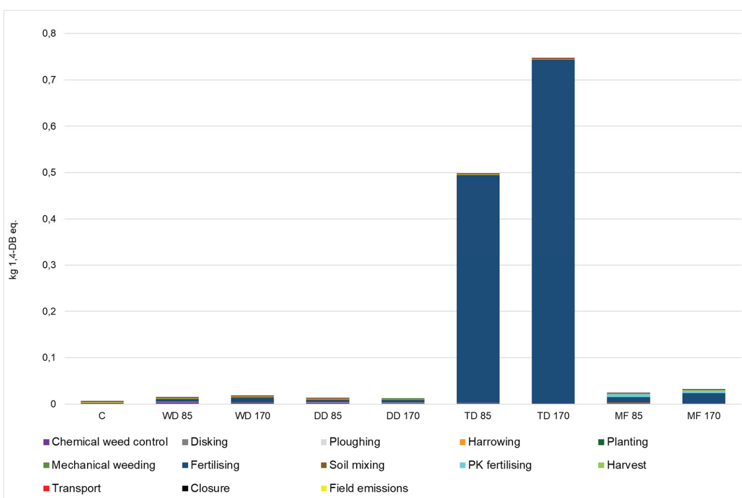


**Figure 8.** Terrestrial ecotoxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.

The freshwater ecotoxicity impact associated with the production of giant miscanthus in treatments with digestate utilisation was 2.5–4.7 higher than in the control (Figure 9). The adverse effects of digestate increased in a linear manner with an increase in fertilisation rate as well as digestate drying and torrefaction. Treatments MF 85 and MF 170 were five and six times more detrimental to the environment, respectively, relative to the control. Ammonium nitrate and triple superphosphate production (in N fertilising and PK fertilising processes (Figure 9) were the main contributors in this impact category (80–85%) followed by chemical weed control.

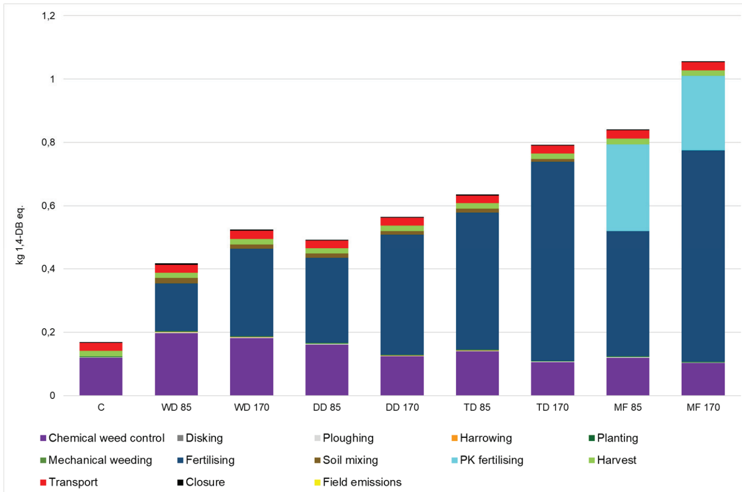


**Figure 9.** Freshwater ecotoxicity per 1 Mg d.m. of miscanthus in different fertilisation treatments.

Similar results were noted for Virginia mallow in all toxicity categories, but the environmental impact of giant miscanthus production per 1 Mg of dry biomass was higher than for Virginia mallow. This was particularly visible in treatments WD 170, DD 85, and DD 170, whose environmental impact in all three toxicity categories was 60–90% higher [26]. The human and terrestrial toxicity of poplar supplied with mineral fertilisers was lower or similar to that noted in the authors' study in the base scenario and treatments WD and DD [47]. However, the effects of treatments TD and MF on human and terrestrial toxicity were significantly higher than in the referenced experiment.

All fertilisation treatments contributed more to fossil depletion than the control (Figure 10). In the group of digestate treatments, WD 170 exerted the most adverse impact. Treatment WD was characterised by the lowest yield, which also contributed to its adverse environmental effect per tonne of dry biomass. The influence of TD and DD on fossil depletion was approximately three times higher than the base scenario. In all stages of miscanthus production, fertilisation contributed most to fossil depletion and ranged from 41% (WD) to 84% (TD). Diesel use during harvest was also an important contributor. In a life cycle assessment of two oilseed crops (camelina and flax), fertiliser production also exerted the greatest effect on fossil depletion [48]. In the authors' previous study, diesel consumption was the greatest energy input in the production of giant miscanthus [19]. Similar results were noted in this study and the authors' previous study on Virginia mallow. In addition, high fossil depletion occurred in the production of mineral fertilizers. However, in the production of digestate fertilizer (drying), heat from biogas production was used, thanks to which fewer fossil resources were used per one tonne of miscanthus dry matter [26].

The normalisation results of the LCIA per tonne of giant miscanthus dry biomass per European citizen are presented in Figure 11. The impact category with the highest normalised score was freshwater eutrophication. Treatment WD 170, followed by treatments DD 170 and TD 170, was characterised by the most adverse environmental impact. Digestates also significantly contributed to terrestrial acidification. Variants MF 85 and MF 170 contributed less to terrestrial acidification than to freshwater eutrophication. In the particulate matter formation category, digestate treatments also exerted a more adverse impact than mineral fertilisers. The average normalised score was lower in the human toxicity category than in the particulate matter formation category, but treatments TD 86 and TD 170 were characterised by similar high scores.

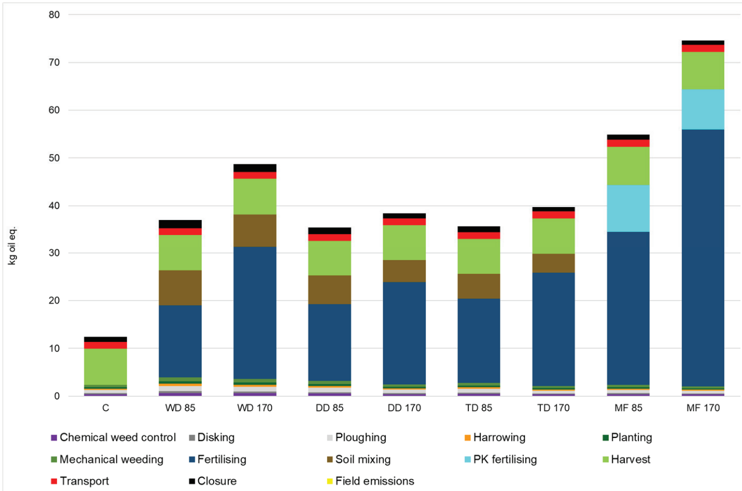


**Figure 10.** Fossil depletion per 1 Mg d.m. of miscanthus in different fertilisation treatments.

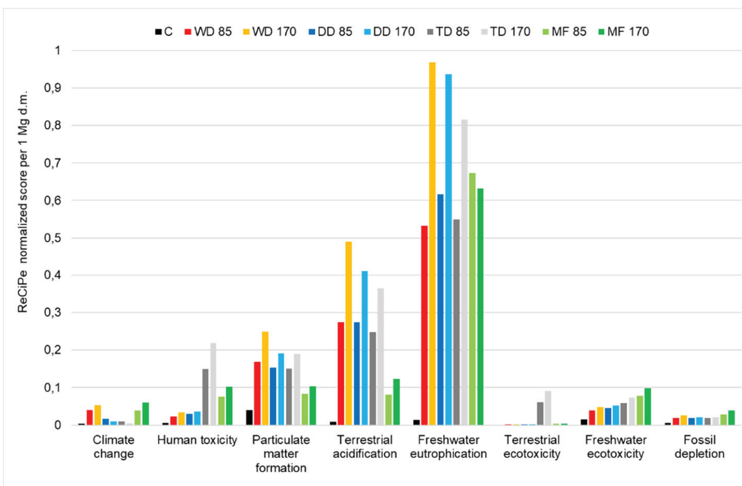


**Figure 11.** Normalisation scores for giant miscanthus production with the ReCiPe method (hierarchical version with European normalisation).

Low scores in fossil depletion and climate change categories are very important considerations in a circular economy and the renewable energy sector because they point to low consumption of diesel oil and fossil fuels as well as low GHG emissions. A similar sequence of normalised scores was noted in the authors' study of Virginia mallow. The production of Virginia mallow had the greatest influence on freshwater eutrophication than other impact categories. However, due to higher yields, the normalised score (environmental impact) for Virginia mallow was up to 52% lower in comparison with giant miscanthus [26]. In an LCA of poplars supplied with mineral fertilisers and lignin (a residual product in the process of paper production) as a soil amendment, the normalised score was also highest in the freshwater eutrophication category [47].

## 4. Conclusions

The study found that the environmental impact of miscanthus fertilisation in all impact categories was higher in comparison with the base scenario (no fertilisation). In the base scenario, the highest energy inputs were associated with the consumption of diesel and the application of pre-emergent herbicide for weed control. The environmental impact of non-fertilised treatment could be reduced by deploying less energy-intensive machines and improving the logistic chain.

In fertilised treatments, the production and application of fertilisers were the weakest links in the biomass production process. Fertiliser production and fuel consumption were the weakest links in fossil depletion, human toxicity, freshwater, and terrestrial ecotoxicity categories. In particulate matter formation, freshwater eutrophication, and terrestrial acidification categories, field emissions contributed most to total emissions. These findings were confirmed by normalised scores, which demonstrated that fertilisation had the greatest impact on freshwater eutrophication and terrestrial acidification. The climate change score was relatively low in all fertilisation treatments.

It can be concluded that the application of fertilisers in the production of giant miscanthus on sandy soil did not increase yields and did not reduce environmental impact per tonne of biomass. The results of this study indicate that fertilisation is not justified in giant miscanthus plantations established on poor soils. Lower fertilisation levels could be applied, but further research is needed to determine the most effective rates. The presented results apply only to giant miscanthus grown under the described conditions in a temperate climate, and more favourable outcomes could be expected on higher-quality soils and in a warmer climate, which is generally preferred by giant miscanthus. Therefore, further field trials are required to confirm and expand on the presented findings.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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# Storage of Fine Woodchips from a Medium Rotation Coppice Eucalyptus Plantation in Central Italy

**Luigi Pari [1], Simone Bergonzoli [2,*], Paola Cetera [1], Paolo Mattei [1], Vincenzo Alfano [1], Negar Rezaei [1], Alessandro Suardi [1], Giuseppe Toscano [3] and Antonio Scarfone [1]**

1 Council for Agricultural Research and Economics—Research Centre for Engineering and Agro-Food Processing (CREA-IT), Via della Pascolare, 16, Monterotondo, 00015 Roma, Italy; luigi.pari@crea.gov.it (L.P.); paola.cetera@crea.gov.it (P.C.); paolo.mattei@crea.gov.it (P.M.); vincenzo.alfano@crea.gov.it (V.A.); negar.rezaei@crea.gov.it (N.R.); alessandro.suardi@crea.gov.it (A.S.); antonio.scarfone@crea.gov.it (A.S.)

2 Council for Agricultural Research and Economics—Research Centre for Engineering and Agro-Food Processing (CREA-IT), Via Milano 43, Treviglio, 24047 Bergamo, Italy

3 Department of Agricultural, Food and Environmental Sciences, Marche Polytechnic University, Via Brecce Bianche, 60131 Ancona, Italy; g.toscano@univpm.it

* Correspondence: simone.bergonzoli@crea.gov.it; Tel.: +39-0363-49603

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**Abstract:** *Eucalyptus* spp. has received attention from the research and industrial field as a biomass crop because of its fast growth and high productivity. The features of this species match with the increasing demand for wood for energy production. Commonly, the wood used for energy production is converted in chips, a material susceptible to microbial degradation and energy losses if not properly stored before conversion. This study aims at investigating two outdoor storage systems of Eucalyptus wood chips (covered vs. uncovered), assessing the variation in moisture content, dry matter losses and fuel characteristics. The class size of the material was P16, which was obtained using a commercial chipper appositely searched to conduct the study. The results highlighted how the different storage methods were influenced by the climatic condition: the woody biomass covered showed the best performances in terms of dry matter losses achieving 2.7% losses vs. The 8.5% of the uncovered systems. However, fuel characteristics displayed minor changes that affected the final energy balance ($\Delta En$ = −0.2% in covered; $\Delta En$ = −6.17% in uncovered). Particle size varied in both methods with respect to the start conditions, but the variation was not enough to determine a class change, which remained P16 even after storage.

**Keywords:** eucalyptus; woody biomass; storage of fine wood chips; moisture content; calorific value; ash content; dry matter loss

## 1. Introduction

Short and medium rotation coppice (SRC and MRC) are fast-growing tree plantations that generally produce high quantities of woody biomass in productive cycles of 2 years (SRC) and 5–6 years (MRC) [1]. According to species and site-fertility, the stump regenerates after cutting, and the production cycle can be repeated until the coppice is no longer productive. The woody biomass obtained from the plantations can be used as a renewable energy source [2] through different thermo-chemical conversion processes [3]. In Mediterranean environment, Eucalyptus plantations are having a success thanks to the use of fast growing inter-specific clones [4], suitable for employment in SRC and MRC. The most cultivated European countries are Spain and Portugal, with an amount of cropped area above 600,000 ha [5]. In Italy, the cultivated surface is approximately 70,000 ha, of which 20,000 are utilized for bioenergy production in Sicily and Sardinia [6]; the rest are cultivations addressed to soil protection or as windbreak, rarely utilized as firewood. Despite a still-limited distribution, there is a growing interest in cultivating eucalyptus in Italy, especially for MRC plantations, which can obtain trunks suitable for firewood production, a product having a higher economic value with respect to wood chips [7].

SRC and MRC are also gaining interest because international policies promote the production of forest woody biomass as a renewable energy source (European Energy 2020 strategy—Directive 2009/28/EC) [8]. It was observed that plantations provide also environmental advantages, working as a mechanism to promote local biodiversity during the growing period [9].

However, doubts about harvest and storage systems still remain, raising barriers to the feasibility of these crops and marketability of the products, limiting their distribution. In the last decade, some important achievements have been reached in the mechanization sector through innovation in technology [10], but a clear demand for more research is needed to address the problem of storage systems [11]. Certainly, the conservation of the material and the relative costs are important issues that need attention.

Wood is generally stored in whole tree sections or in form of chips. Storing whole tree sections is considered a suitable solution to avoid energy losses [12]; this is because the surface of the wood exposed to potential microbial activity is very low with respect to other forms utilized for wood storage, such as the chips [3]. On the other hand, the handling of tree trunks is more expensive with respect to the direct chipping of the material, mainly for transport and other logistic aspects; for this reason, the mobile chipping in harvesting site is considered the most practical and feasible solution in the woody biomass-for-energy chain [13].

Unfortunately, wood chips are susceptible to microbial degradation and during storage high loss of dry matter can occur if the material is stored in the wrong conditions. The loss of dry matter implies a high loss of energy, that in some cases can be very high, as demonstrated by Pari et al. [14]. Other risks of managing wood chips include the spontaneous combustion of chip piles due to particular thermo-chemical reactions and potential human health hazards caused by airborne fungal spores [15]. Many studies have been performed to identify suitable storage methods able to address these problems [16]. Despite the storage time and conditions, many of these issues are related to the quality of the chips, especially the particle size, which influences the air circulation inside the pile. When air circulation is not enough, the dehydration process of the woody biomass slows down and determines the persistence of moisture, which in turn facilitates the microbial degradation and the heat development processes [17]. However, at present there is a growing interest in the market of "microchip", i.e., a wood chip of homogeneous size (about 7 mm target length) with high commercial value that can exploited in conventional pellet stoves and boilers upon minor modifications to the feeding apparatus and a new setting of the combustion system [18]. Specifically, a microchip must possess also other physic-chemical characteristics such as Ash content $A \leq 1\%$, Moisture content $MC \leq 10\%$, Bulk density $BD$ $150 < x < 250$ kg/m$^3$, lower heating value $Q_{LHV} \geq 16$ MJ/kg, and the presence of fine fractions $FF \leq 1\%$ according to current standards (ISO 17225-1:2014) [19]. The production of microchip obviously implies additional passages with respect to the production of traditional chips such as the screening and the forced drying to obtain a product that is homogeneous in size, with a low fine fraction and moisture content.

The information right now on the storage behavior of P16 size class wood chips, a product that possess the prerogative to became microchip, but that, at the same time, could experience high degradations during storage for the limited air circulation occurring inside the pile, is still very limited. Previous studies are mainly focused on the storage of woody biomass belonging to P45 size class and very few studies exist on Eucalyptus chip storage. Considering that, this study proposes the evaluation of the storage dynamics performance of P16 wood chips obtained from a eucalyptus MRC plantation in Mediterranean environment by using a storage method (chip pile) and two treatments (covered and uncovered pile). The aim is to fill the knowledge gap on P16 Eucalyptus storage by using an already studied and spread storage method.

The current research on wood chip storage refers mainly to materials typically used in biomass power plants of medium and large scale, i.e., wood chips with an approximate mean length of 3 mm, belonging to the size class of P45. This specific size class is required because power plants components are generally standardized and the presence of smaller or larger material may create problems during the system functioning; such problems may include the clogging of the feeding apparatus of the boiler, the presence of unburned material in the ash collector, and inefficient combustion. For this reasons, small size wood chips were not of relevant interest until a few years ago.

Nowadays, the demand for microchips for domestic uses has increased, and deeper attention should be payed to products having the potential to be employed for such uses. The present study proposes an evaluation of the storage performance of P16 size class wood chips, a material with a mean length of 7 mm, potentially converted into microchips upon further processing. Considering that, the study proposes the evaluation of the storage dynamics performance of P16 wood chips obtained from a eucalyptus MRC plantation in a Mediterranean environment by using a storage method (chip pile) and two treatments (covered and uncovered pile). The aim is to fill the knowledge gap on P16 Eucalyptus storage by using an already studied and spread storage method.

## 2. Materials and Methods

The study was conducted between April and October 2018 at a Research Centre for Engineering and Agro-Food Processing (CREA-IT) in Monterotondo, near Rome, Central Italy (42°10′19″ N latitude, 12°62′66″ E longitude). The wood chips utilized derived from a five-year-old Eucalyptus plantation at the first productive cycle (Figure 1) Production data and further plantation characteristics are provided in Pari et al. [20]. The tree felling was performed in early April and plants were chipped immediately after using a Farmi Forest CH260. This chipper was appositely selected because in previous studies it demonstrated the ability to produce small size chips. In a work proposed by Spinelli et al. [21], nine commercial chippers were compared for chip size distribution; the study displayed that Farmi Forest CH260 was the only machine producing P16 chips (more than 60% of the chips size between 16 and 3 mm), which is the main prerogative of microchips [21]. The cutting configuration of commercial chippers can be also re-adjusted to produce finer woodchips, as verified in other studies [22].

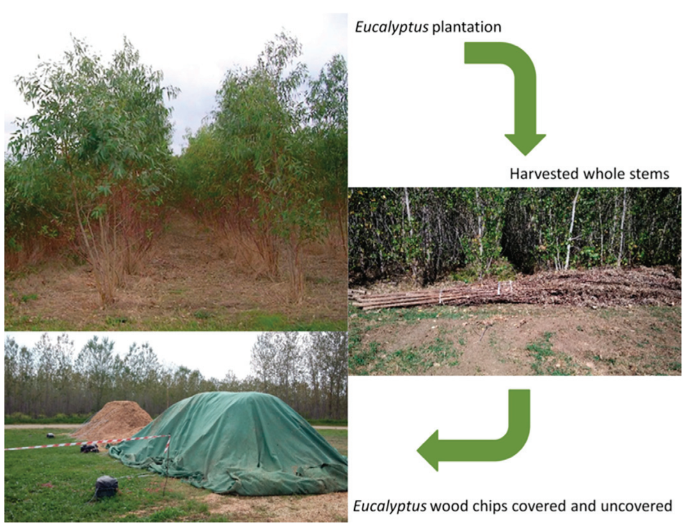


**Figure 1.** Experimental phases from field to storage site.

## 2.1. Climatic Parameters

The storage of Eucalyptus wood chips was carried out outdoors with two different storage systems (covered vs. uncovered); the material was exposed to the same weather conditions and the climatic parameters such as temperature, precipitation, wind speed and wind direction were recorded during the entire storage period (6 months). These parameters were recorded using a weather cab (Davis Instruments, 3465 Diablo Avenue, Hayward, CA 94545-2778 U.S.A) "DAVIS VANTAGE PRO 2" placed in the proximity of the storage site and connected to wireless net.

## 2.2. Storage Conditions

Around 34.6 tonnes of comminuted woody biomass (approximately 100 $m^3$) has been stored in two piles, 8 m long, 4 m wide and 3 m tall. The material was stored for 6 months in a flat site close to the plantation. To isolate the chips from the soil and avoid contamination, a polyvinyl chloride (PVC) sheet was laid on the ground, working as storage floor. The shape and the orientation of the two piles were maintained as similar as possible, to ensure that climatic factors had the same influence on both treatments. One of the piles was covered using a Toptex textile tissue, i.e., a material able to allow transpiration and avoid the penetration of precipitations. Each pile consisted of three sections (replicates), each one including six sampling points (TC1, TC2, TC3, TC4, TC5, TC6); in total, 18 sampling points per pile were utilized (Figure 2); a similar scheme was utilized in previous studies [15]. Internal temperature during storage was monitored by placing one pT-100 thermocouple in each sampling point. The probes were connected to a computerized data monitoring cab, connected to the web and remotely controlled.

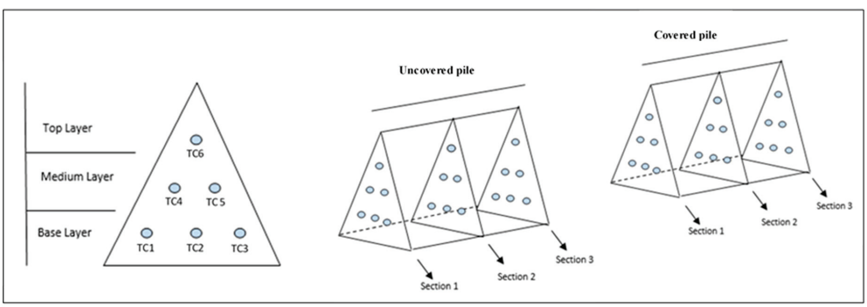


**Figure 2.** On the left side, the single transversal section of the scheme utilized to set the experiment; on the right side, the full scheme of the experiment with three sections (replicates) in both treatments.

## 2.3. Physical Characteristics

Near each thermocouple, a plastic net filled with about 1 kg chips (pre-weighed) was placed in order to monitor dry matter losses. After storage, the bags were removed from the piles and weighed before and after drying in a ventilated oven set at 105 ± 2 °C. The calculation of the dry matter losses was performed using the following equation (Equation (1)).

$$DML\ (\%) = \left[1 - \left(\frac{DW_2}{DW_1}\right)\right] \times 100 \tag{1}$$

*DML*: Dry matter losses (%);
$DW_1$: Dry weight prior storage (kg);
$DW_2$: Dry weight after storage (kg).

Moisture content of the chips was determined according to standard ISO 18134-1:2015 [23] at the beginning of storage, taking 10 random samples (500 g each) from the fresh material; at the end of the experiments, the operation was repeated using 10 random samples (500 g each) taken during pile opening. For calculation of moisture content, the following equation (Equation (2)) has been used.

$$MC\ (\%) = \frac{W_{fb} - W_{db}}{W_{db}} \times 100 \quad (2)$$

$W_{fb}$ = Weight of the sample on fresh basis (g);
$W_{db}$ = Weight of the sample on dry basis (g).

In addition, the particle size distribution of the comminuted woody biomass was analyzed according to UNI EN 15149:2010 [24] before and after the storage in piles considering three samples of 8 L volume each.

### 2.4. Chemical and Energetic Properties

The parameters studied were the following: ash content (*A*), chemical composition (C, H, N, Cl, S), Higher and Lower Heating Values (*HHV* and *LHV*). These parameters were determined according to the respective European standards: ISO 18122:2015 *"Determination of ash content"* [25], UNI EN 15104:2011 *"Determination of total content of carbon, hydrogen and nitrogen content instrumental method"* [26], ISO 16994:2016 Solid biofuels—determination of total content of sulfur and chlorine [27] and UNI EN 14918:2010 *"Determination of Calorific Value"* [28], respectively.

During storage, the dry matter losses and the change in some fuel quality parameters (heating value) can determine variations in the final energetic balance. In fact, as dry matter losses determine energy losses, variation in the heating value can mitigate or worsen the final energy balance. For this reason, an evaluation of the Δ energy, (i.e., the energy available before and after biomass storage) was performed using the following equation (Equation (3)), as reported in previous studies [15].

$$\Delta En.\% = \left\{\left[\left(1 - \frac{Dry\ Matter\ Losses}{100}\right) \times final\ LHV\right] - initial\ LHV\right\}\frac{100}{initial\ LHV} \quad (3)$$

*Final LHV* = Lower Heating Value after storage;
*Initial LHV* = Lower Heating Value before storage.

### 2.5. Statistical Analysis

For the statistical analysis of the data obtained from the two treatments, the open source statistical package PAST v.3.26 [29] was used in order to check the statistical significance. After checking the data for normality, the software was used to perform T-test or ANOVA, between the means. Considering that the experimental plan was based on only two treatments, the two Paired samples T-test was used when studying the differences only among the treatments (i.e., dry matter losses) while ANOVA was used for the analysis between treatments and pre-storage conditions (i.e., particle size, moisture content).

## 3. Results and Discussions

### 3.1. Climatic Data

During the storage period, the main weather parameters were daily recorded. The amount of precipitation was mainly concentrated in May 2018, followed by an anomalous drought period until the end of the experiment, as confirmed by the referring institution on regional climatic data (Servizio Integrato Agrometeorologico della Regione Lazio (SIARL)) [30]. The air humidity followed the same trend of precipitation, with the highest value recorded in May (83%), and a strong reduction until July (59%). After a fluctuation between August and September, as in the case of precipitation, the value of air humidity at the end of the experiment was 67%. The temperature ranged between 17 and 25 °C (average min and max, respectively), recording the warmer month in July 2018 (Figure 3).

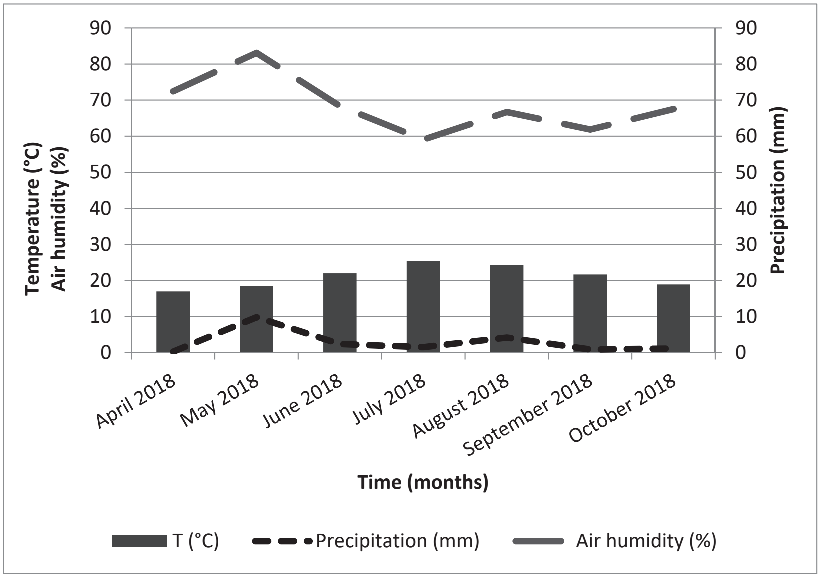


**Figure 3.** Trend of main climatic parameters: temperature (°C), precipitation (mm) and air humidity (%) recorded during the storage of Eucalyptus from April to October 2018.

The climate can greatly influence the storage performance of the biomass, and precipitation is a very important parameter to be considered, since it determines the increase in air humidity and the re-wetting of the material. The presence of moisture facilitates the microbial degradation activity, especially in the uncovered piles, contributing to dry matter losses. In this regard, the high drought occurred in summer 2018 had probably positively affected the storage performance of this biomass. The results obtained in this study should be therefore interpreted taking into account this general consideration.

### *3.2. Particle Size Distribution*

The particle size analysis shows that the chipper Farmi (Farmi forest corporation, Ahmolantie 674510 Iisalmi) CH260 produced a chip falling in the class of “P16”, i.e., the class in which more than 60% of the sample weight is characterized by a chip size between 3.15 and 16 mm according to ISO 17225-1 2014 [19]. The storage did not cause a class variation, so the “P16” was maintained also after the storage in both even if the several-sample test ANOVA confirmed the presence of significant differences among values of same size class between the treatments (data not shown). The coarse fraction above 31 mm was absent, while the fine fraction was among values of 20% and 25% before and after storage (in both treatments), determining the classification of the product as “F25”. It should be noted that a small increase in fine fractions was observed in both treatments after storage; from an initial 20.17% of fine fraction in the fresh material, this became, respectively, 22.15% and 23.19% in covered and uncovered chip piles after storage. On the contrary, the size class between 3.15 and 8 mm displayed an opposite trend; form an initial 59.7%, this fraction became 57.31% in covered chips and 56.96% in uncovered chips (Figure 4). Even if the size classification of the product was not affected by storage, the minimal but significant size variation should be attributable to the degradation process of microorganisms. As previous studies confirmed, the small size of the chips determined problems of air circulation in the piles [22], which in turn determine the persistence of moisture in the stored material. This is also confirmed by the final moisture content of the two treatments (31% covered vs. 40%

uncovered). The slowed air-drying allowed microorganisms to continue their activity, and this was also confirmed by the temperature monitored inside the piles, which displayed a more similar trend (with higher temperatures) in the uncovered pile, i.e., more degraded treatment according to dry matter analysis. Another interesting observation that indicates degradation activity is the quantification of the fine fractions, which increased in both treatments after storage, which was slightly higher in the uncovered pile.

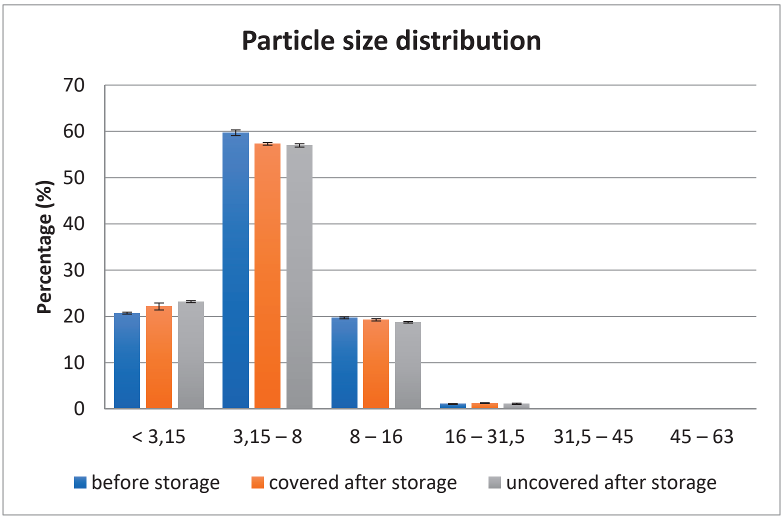


**Figure 4.** Particle size distribution of the chips before and after storage.

Such a small size of chip can have great influence on the storage dynamics, because the air circulation inside the pile is very limited.

*3.3. Moisture Content and Internal Heat Development*

At the end of storage, the moisture content of uncovered P16 wood chips was higher than 9% with respect to the chips of the covered pile (Table 1). The several-sample test ANOVA confirmed the presence of significant differences ($p < 0.05$) among fresh chips and post-storage chips and among the material of the two treatments (covered vs. uncovered). In this case, it therefore confirmed the efficacy of the Toptex for small size chips. Despite the initial *MC* values, the fresh woody biomass samples showed a reduced standard deviation (SD ± 0.13), and the moisture of the final samples deviated remarkably in both covered and uncovered piles (from the mean values the SD was ±8.45 in covered pile and ±4.88 in uncovered pile). The moisture behavior inside the wood chip piles of coniferous biomass was recently studied by Wästerlund et al. [31]. In this work, it is explained that the moisture inside the open-air stored pile is not distributed homogenously during storage because of physical dynamics that influence the water movement. For instance, the internal heat development promoted by microbial activity determines the movement of moist air from the internal to the external part of the pile. The precipitation and the air humidity can also influence the moisture of chips, especially in the external layer; indeed, when the chips are handled with a tractor bucket the product is mixed and some regions can be moister than others. Therefore, these high deviations can be explained, as our sampling was performed during pile opening with a tractor bucket, determining a mixing of the pile layers during sample collection; it should be noted that this methodology was followed to resemble the normal conditions that occur in power plant when chips are loaded in the feeding system of the boiler.

**Table 1.** Moisture content (*MC*) of Eucalyptus covered and uncovered woody biomass pile, expressed in percentage (%), where: $MC_i$, initial moisture content and $MC_f$, final moisture content, that is at the end the storage. *MC* values with different letters indicate mean values significantly different ($p < 0.05$) according to the several-sample ANOVA test.

| Type of Storage | Replicas | $MC_i$ (%) | $MC_f$ (%) |
|---|---|---|---|
| Covered | 10 | 50 ± 0.13 [a] | 31 ± 8.45 [b] |
| Uncovered | 10 | | 40 ± 4.88 [c] |

It should be noted that, considering the novelty of the research, comparison with the results found in other studies was based on different species and class size, as reported in the literature.

Effectively, the internal heat development recorded during storage in the two piles may reflect the moisture content deviations between both treatments (Figure 5; Figure 6). The uncovered pile in fact maintained a trend of temperatures higher and constant in all measurement points with respect to the covered piles, indicating a steady fermentation process with respect to the covered treatment. The more rapid heat dissipation occurring in the lower external part of the covered pile (T1 and T3) is a confirmation of the microbial breakdown in this treatment; it should be mainly associated with the vicinity of the material to the ground and to the external environment. Probably, these regions of the pile have lost moisture more rapidly with respect to the others, causing the microbial activity to stop faster. The uncovered pile, on the contrary, has probably suffered the effect of the moist air of the night, which maintained the conditions necessary to keep the fermentation process alive.

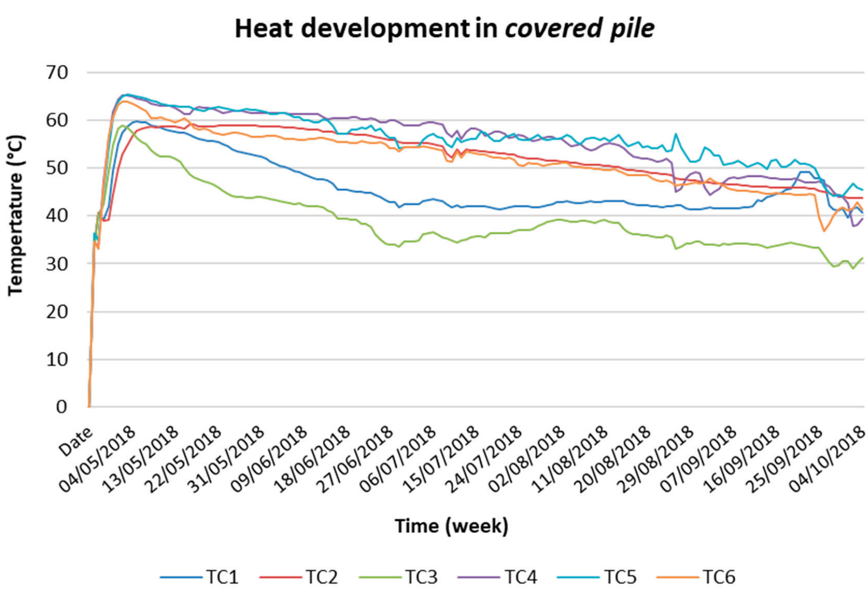


**Figure 5.** Heat development in covered pile. The numbered letters (TC1, TC2, etc.) indicate the thermocouple location according to the scheme shown in Figure 2.

In general, the difficulties to dissipate heat in both piles should probably be associated with the lack of ventilation [32], which is also due to the small chip size; this has favored the persistence of moisture, and therefore the microbial vitality. The gradual decrease in temperature in some parts of the covered piles that can observed during the time in both treatments is a reflection of the gradual reduction in the fermentation processes, meaning that growing substrate and water availability were decreasing, as verified in other studies [15].

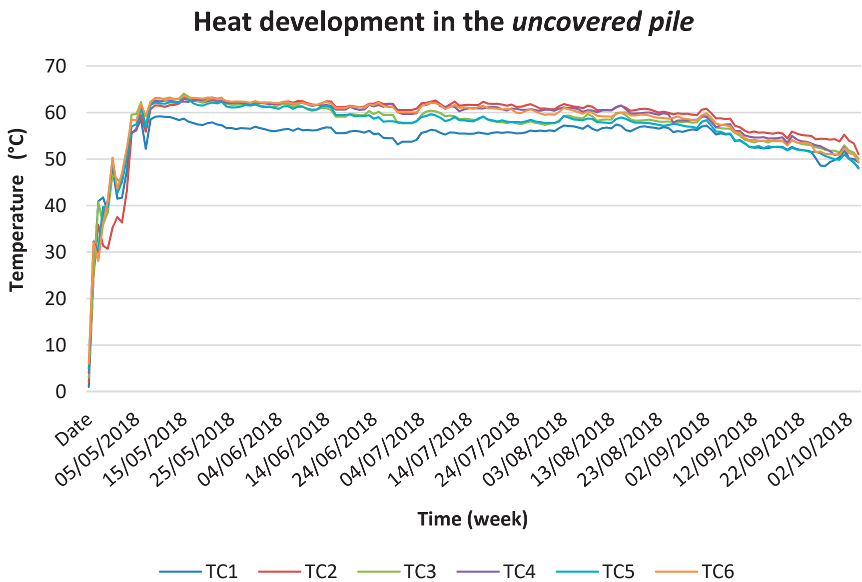


**Figure 6.** Heat development in uncovered pile. The numbered letters (TC1, TC2, etc.) indicate the thermocouple location according to the scheme shown in Figure 2.

### *3.4. Dry Matter Loss*

Table 2 shows the dry matter losses that occurred during the six-month (April–October 2018) storage in the two piles. Higher losses were observed in uncovered pile. The two paired sample T-tests (equal sample sizes, same variance) performed on the data confirmed the presence of significant differences among treatments ($p < 0.05$). Even in this case, the efficacy of the Toptex was confirmed, as covered wood chips experienced only 2.7% of losses in six months. On the other hand, even if limited, the climatic factors affected the storage performance of uncovered chips. Probably, the precipitations that occurred during storage facilitated the permanence of moisture in the uncovered pile, creating and maintaining the ideal conditions for microorganism to grow and degrade organic matter.

**Table 2.** Value of dry matter loss (*DML*) of different type of storage of P16 Eucalyptus woodchips, expressed as percentage (%). *DML* value with different letters indicate mean values significantly different ($p < 0.05$) according to the T-test.

| Storage | *DML* (%) |
|---|---|
| Covered | $2.7 \pm 1.7^{a}$ |
| Uncovered | $8.5 \pm 4.7^{b}$ |

### *3.5. Fuel Characteristics*

In Table 3, some parameters are predicted, such as A, C, H, N, Cl, S, *HHV* and *LHV* of the fresh woody biomass for the two treatments at the end of the trial. The results obtained after the test are characterized by an increase in the heating values in both treatments. This phenomenon was also verified in other studies and could be explained by the degradation of the most susceptible wood fractions to microbial degradation, i.e., cellulose and hemicellulose [32]. From an energetic point of view, these fractions are less powerful, because their heating value is much lower with respect to that of lignin; therefore, a reduction in these compounds in woody material (with the lignin remaining not degraded) determines an increase in the energetic performance of lignocellulosic biomass. Chemical elements (C, H, N, Cl, S) did not show remarkable differences from the fresh material, while ash content slightly increased in both treatments with respect to the start conditions. Regarding this, Lenz et al. [33] found the evidence of a direct relation between the increase in ash content and the total DML. The observation and the trends are also confirmed in this study. On the other hand, another factor that may have affected the increase in ash content is the increasing percentage of fine fractions (<3 mm) at the end of storage. In fact, the same behavior was verified in previous studies by Pari et al. [14].

**Table 3.** Ash content, elementary compounds and fuel quality parameters of P16 woodchips.

| Parameter | Unit | Fresh Biomass | After Storage Uncovered Chips | After Storage Covered Chips |
|---|---|---|---|---|
| Ash | % | 3.0 | 3.4 | 3.2 |
| Carbon | % | 47.8 | 47.4 | 48.0 |
| Hydrogen | % | 5.8 | 5.5 | 5.6 |
| Nitrogen | % | 0.32 | 0.50 | 0.30 |
| Chloride | % | 0.10 | 0.13 | 0.11 |
| Sulfur | % | 0.03 | 0.02 | 0.01 |
| **Heating Value** | | | | |
| Higher heating value | kJ/kg | 19.035 | 19.440 | 19.439 |
| Lower heating value | kJ/kg | 17.773 | 18.228 | 18.225 |

Regarding the energy variations due to storage, in covered biomass the increase in the heating value has almost compensated the dry matter losses that occurred, indicating a final energy balance equal to −0.2%. On the contrary, in uncovered biomass, the heating value increase was not enough to balance the dry matter losses and the final energy content was −6.17% (Figure 7). According to other studies, the increase in the heating value is attributable to the degradation of cellulose and hemicellulose, i.e., the less energetic and more degradable fractions of lingo-cellulosic biomass. Their reduction can favor a relative accumulation of lignin that is reflected in the increase in the heating value after storage [33].

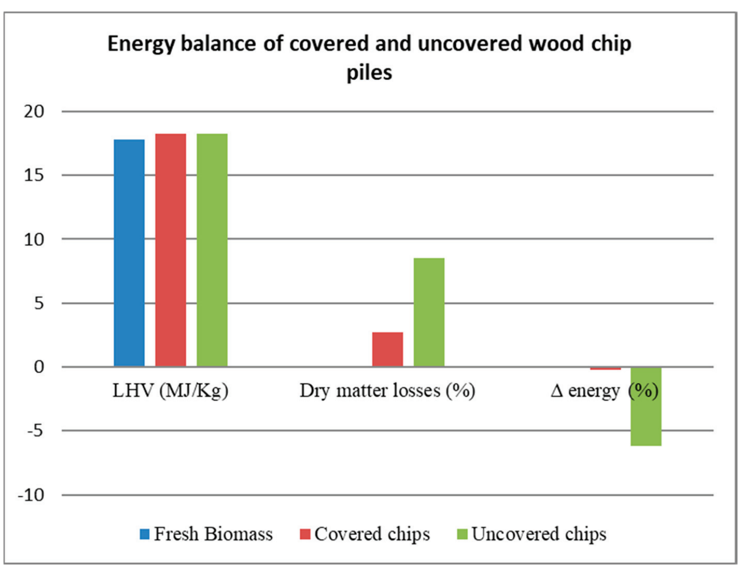


**Figure 7.** Variations in energy content according to storage systems.

## 4. Conclusions

The study highlights how it is possible to store P16 woodchips from an MRC Eucalyptus plantation located in central Italy. The results open new rooms of investigation and market opportunities on this class size of Eucalyptus biomass since, to date, according to author experience, no studies have been carried out on this topic. Two types of storage system (covered vs. uncovered) were adopted, and several parameters were monitored for six months in order to ensure a complete study of the dynamics involved. The covered system highlighted the best results regarding dry matter losses and moisture content and energy balance. Although the advantages of using a covering systems are not new, the main interesting finding of this study is the demonstrated storability of small chips, which, despite a limited air circulation achieved, only a 2.7% loss of dry matter and 0.2% loss of energy content using the Toptex covering system. Considering the potential destination of this product (microchip production upon sieving and forced drying), this finding opens the opportunity to improve the logistics in forestry operations, suggesting that handling methods should be based on direct chipping of woody biomass immediately after being cut, also for the microchip chain.

Due to a lack of information in the literature, future research should focus on the economic evaluation of the feasibility of the micro-wood chip supply chain, analyzing how storage could affect the final production costs. In addition, it will be critical to compare the economic sustainability of micro energy supply chains based on both long and short wood chips in order to define the best logistics for this type of solid biofuel.

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# Medium Rotation *Eucalyptus* Plant: A Comparison of Storage Systems

**Luigi Pari [1], Negar Rezaie [1,*], Alessandro Suardi [1,*], Paola Cetera [1], Antonio Scarfone [1] and Simone Bergonzoli [2]**

1 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria, Centro per l'Ingegneria e le Trasformazioni Agroalimentari (CREA-IT), Via della Pascolare, 16, Monterotondo, 00015 Rome, Italy; luigi.pari@crea.gov.it (L.P.); paola.cetera@crea.gov.it (P.C.); antonio.scarfone@crea.gov.it (A.S.)
2 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria, Centro per l'Ingegneria e le Trasformazioni Agroalimentari (CREA-IT), Via Milano, 43, Treviglio, 24047 Bergamo, Italy; simone.bergonzoli@crea.gov.it
* Correspondence: negar.rezaei@crea.gov.it (N.R.); alessandro.suardi@crea.gov.it (A.S.)

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**Abstract:** *Eucalyptus* spp. are among the most suitable species for biomass production, even for the firewood derived from medium-rotation coppice (MRC). The general problem of wood is that it cannot be utilized immediately because of the high moisture content, which in the combustion process would reduce remarkably the yield of energy. In this context, outdoor storage of whole stems without branches (WS), outdoor storage of whole stems with branches (WSB), open shed storage of firewood logs in mesh bags (OSF), and outdoor firewood logs in mesh bags (ODF) of *Eucalyptus* spp woody biomass were compared in term of moisture and dry matter loss to evaluate the most convenient form of storing biomass deriving from a medium-rotation coppice. During the storage period, ODF showed higher moisture values than OSF, WSB, and WS, underlining that moisture reduction is related to local climatic conditions, pile size and permeability (compaction). However, at the end of the storage period, the four options reached a similar moisture to the commercial one of fuel wood (around 15%). WSB showed the highest loss of dry matter (18%), which can be ascribed to the drying and falling process of the leaves. In conclusion, the qualitative and quantitative characteristics of the biomass were similar after the different storage systems, producing firewood suitable for new market opportunities.

**Keywords:** *Eucalyptus*; tree whole stem; firewood logs; storage system; moisture content; dry matter loss

## 1. Introduction

Renewable biomasses play a crucial role in mitigating climate change as a substitute for fossil fuels [1,2]. Plantations on agricultural land give an opportunity for producing biomass sustainably and improving farm income [3]. Fast-growing trees are one of the most promising alternatives for the production of biomass when planted in short-rotation coppice [4,5]. However, this system can be divided into very-short-, short- and medium-rotation systems depending on density of plantation and cycle length [6]. In recent years, there has been growing interest in extending the rotation age to a five-year cycle (medium-rotation coppice). This is due to an actual advantage of medium-rotation coppice (MRC) in terms of yield maximization (high quantity of biomass at low plant density), a great improvement of the product quality (reduced bark/fiber ratio) and less dependence on adverse seasons [7,8]. *Eucalyptus* spp. are among the most suitable species for biomass production, because of their rapid adaptability to different climatic conditions, even Mediterranean ones, and easy use in plant breeding programs [9]. Worldwide, commercial plantations of these species, 20 million ha, are the main source of lignocellulosic biomass for cellulose pulp and the production of energy [10]. Plantations are mainly located in temperate areas, but they can be found in climates with a dry season, such as that of the Italian peninsula. In the Mediterranean environment, *Eucalyptus* spp. plantations are largely cultivated in Spain and Portugal, with an amount of cropped area above 600,000 ha [11]. The cultivated surface in Italy is much lower, corresponding to about 70,000 ha; among these, the cultivation for energy productions is limited to 20,000 ha and is mainly concentrated in Sicily and Sardinia [12].

In general, the surface of energy plantations in Italy is not enough to cover the demand for biomass for energy production, and, in the last ten years, Italy has become one of the world's largest importers of woody biomass for energy use [11].

However, despite a limited distribution, there is a growing interest in cultivating *Eucalyptus* in Italy, especially in MRC plantations, which allow obtaining trunks suitable for firewood production, a product having higher economic value relative to wood chips [13].

The biomass of *Eucalyptus* presents good quality characteristics for being utilized as firewood, with similar characteristics to classical firewood species (for example, oak and beech) (Table 1), unlike other tree species identifiable in MRC plantations, such as poplar, where the wood burns very fast without producing embers [13].

**Table 1.** Fuel quality parameters of different species.

| Species. | Unit | Heating Value | References |
|---|---|---|---|
| Birch | MJ $Kg^{-1}$ | 18 | [14] |
| Spruce | MJ $Kg^{-1}$ | 18.6 | [14] |
| Beech | MJ $Kg^{-1}$ | 19.8 | [15] |
| Maple | MJ $Kg^{-1}$ | 18.5 | [14] |
| Oak | MJ $Kg^{-1}$ | 19.17 | [16] |
| Poplar | MJ $Kg^{-1}$ | 18.5 | [17] |
| Willow | MJ $Kg^{-1}$ | 18.4 | [17] |
| Eucalipts | MJ $Kg^{-1}$ | 19.44 | [18] |

However, beside the harvesting phase, the general problem of wood is that it cannot be utilized immediately because of the high moisture content, which in the combustion process would reduce remarkably the yield of energy. This is because part of the energy is spent to evaporate the water present in the biomass to permit combustion [19]. However, using boilers with flue gas condensation reduce energy loss even for moist biomass [20].

The moisture content is therefore an important property when considering the energetic potential of any biomass, because it has the greatest influence on the energetic variation of the material [21,22]. Hence, between harvesting and utilization, the wood must be stored to reduce the moisture content and optimize the energy yield when it is burned. On the other hand, storage is a factor that can also negatively affect the wood characteristics. Key mechanisms responsible for the major changes in woody biomass during storage are: (i) living cell respiration, (ii) biological degradation, and (iii) thermo-chemical oxidative reactions. All three mechanisms involve mass-to-energy conversion and dry matter losses. Living cell respiration is a short-term effect that lasts only several weeks, while starch and sugar are readily available and adequate temperature and oxygen levels are present. Biological degradation is caused by a large variety of organisms, from bacteria to wood-degrading fungi, which can also produce toxic compounds [23] and function best under specific moisture, temperature and oxygen conditions. Finally, thermo-chemical oxidative reactions can contribute to excessive dry matter loss once elevated temperatures have been attained in biomass as a consequence of the first two mechanisms [24].

All these processes can alter the biomass characteristics and determine dry matter loss. For this reason, it is important to identify suitable storage forms and solutions to facilitate the drying process of wood, limiting its degradation. Normally, the biomass harvested from MRC of *Eucalyptus* is chipped and then stored until utilization. The comminution of the biomass after harvesting requires large areas for the storage of biomass in piles, and is subjected to degradation phenomena. On the contrary, it is possible to harvest the biomass and to store it as whole stem on the field edge; at the end of the storage time, it is still possible to chip the biomass or to produce firewood depending on market demand. In this context, the objective of the study was to measure the qualitative and the quantitative parameters (humidity after storage and losses of dry matter) of whole stem and firewood logs storage, to evaluate the most convenient form of storing biomass deriving from a medium-rotation *Eucalyptus* (MRC) plant as alternative to biomass comminution. At present, only a few experiences of *Eucalyptus* storage as whole stem logs have been recorded in Europe and no experience of firewood is recorded, even if recent studies [25] have reported the availability of *Eucalyptus* as firewood, highlighting market opportunities for this biomass form. For this reason, this study fills a knowledge gap in wood storage research for these two forms of *Eucalyptus* biomass.

## 2. Materials and Methods

### *2.1. Studying Site*

The research was conducted between February and September 2018 (8 months) at the experimental fields of CREA-IT (Council for Agricultural Research and Economics-Research Centre for Engineering and Agro-Food Processing) in Monterotondo (Rome, Italy—42°10′19″ N latitude, 12°62′66″ E longitude), characterized by a Mediterranean climate (Figure 1). The plants, harvested in February 2018, used for the study were obtained from a medium-rotation (5 years old) *Eucalyptus* plantation present at the CREA-IT experimental fields. The planting layout was 3 m × 2 m, with a total plant density of 1600 plants per hectare. The stand was grown on a flat area of about 1 ha, characterized by alluvial soil with a silty clay soil texture [26]. Two different storage systems were investigated: wood stem and firewood logs in mesh bags. Each storage system was tested under two different conditions: wood stems with and without branches and firewood logs in mesh bags outdoors and indoors.

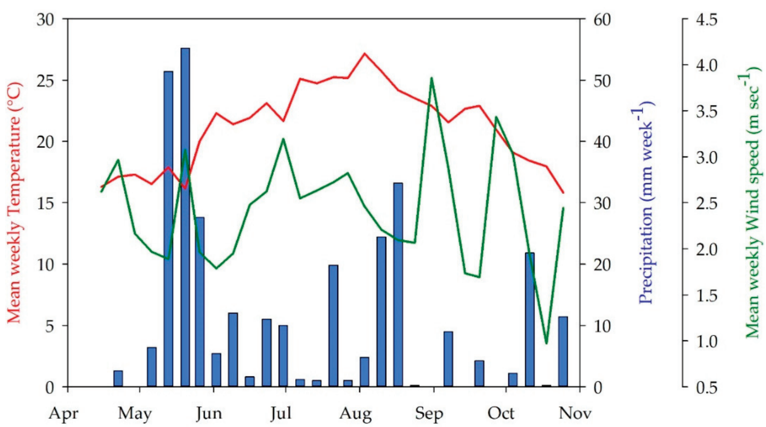


**Figure 1.** Weather data of the storage period. The red line represents the mean weekly temperature; blue bars are the cumulative weekly precipitation; the green line is the mean weekly wind speed.

### *2.2. Storage Systems*

The four storage treatments of eucalyptus woody biomass examined in this research are:

- Outdoor storage of whole stems without branches (WS).
- Outdoor storage of whole stems with Branches (WSB).
- Open shed storage of firewood logs in mesh bags (OSF).
- Outdoor firewood logs in mesh bags (ODF).

### 2.2.1. Outdoor Storage of *Eucalyptus* Whole Stems with (WSB) and without (WS) Branches

Immediately after the plants' harvesting, the storage trial took place outdoors using 3.5 t of *Eucalyptus* plants, felled using a chainsaw and transported to the field edge with a tractor fork. Details of the harvesting operations, including fuel consumption, oil lubricant consumption, timing and number of workers employed were recorded with respect to felling, limbing and logging/stacking operations (Table 2). Half of the plants were de-branched and piled in two heaps (WS—Figure 2). Another two heaps were made with the remaining plants, which were left with branches and leaves (WSB—Figure 3). At felling date, each pile of trees was weighed using a dynamometer (model CS 1000N, PCE Italia Srl, Lucca, Italy—range of measurement 1000 kg and sensitivity 0.2 kg). The weight of each pile was measured every 30 days till the end of the storage period to calculate the mass variation due to losses of dry mass and moisture content reduction. In this regard, concurrently with the day of weighing, 10 samples of wood stem for each pile were randomly selected, according to the methodology proposed by Laurila and Lauhanen (2010) [27], to determine the moisture content following the international standard ISO 18134-1 [28]. The determination of the total moisture content of a test sample of solid biofuels was done by drying in an oven. The moisture content of solid biofuels is always reported based on the total mass of the test sample (dry basis). For calculation of moisture content, the following equation was used:

$$MC\ (\%) = \frac{W_{fb} - W_{db}}{W_{db}} \times 100 \qquad (1)$$

where $W_{fb}$ is the weight of the sample on fresh basis (g) and $W_{db}$ is the weight of the sample on dry basis (g).

**Table 2.** Description of the operation time and consumption during the harvesting of *Eucalyptus* spp. plants in MRC.

| Operation. | Unit | Felling | Limbing | Logging and Stacking |
|---|---|---|---|---|
| **Tools** | | **Chainsaw** | **Chainsaw** | **Tractor with Fork** |
| Time | [sec tree$^{-1}$] | 18 | 58 | 14 |
| Fuel consumption | [KJ Kg$^{-1}$] | 2.06 | 7.51 | 0.03 |
| Oil lubricant consumption | [ml tree$^{-1}$] | 1.6 | 5.6 | |
| Worker | [*n*] | 1 | 1 | 3 |

**Figure 2.** *Eucalyptus* whole-stem storage without branches (WS).

**Figure 3.** *Eucalyptus* whole-stem storage with branches (WSB).

Only wood stem was considered in this study in order to evaluate the effect of the leaves on wood drying by comparing the moisture content variation of plants with or without branches.

#### 2.2.2. Firewood Logs in Meshed Bags: Outdoor (ODF) and Open Shed (OSF) Storages

After plant felling, 20 plants were cut using a circular saw (Rosselli, mod. Grizzly 700R) driven by the PTO of a 66-kW tractor. Around 1.2 t of firewood, of 30 cm length, was packed into 52 meshed plastic bags; half of this was stored outdoors and the other half was stored in an open shed (Figure 4). Each meshed bag was weighed using a dynamometer (model CS 1000N, PCE Italia S.r.l., Lucca, Italy—range of measurement 1000 kg and sensitivity 0.2 kg) at the beginning of the storage, every 30 days, and at the end of the storage period, in order to calculate the mass variation due to losses of dry mass and moisture content reduction. In this regard, concurrently with the day of weighing, three samples of firewood logs per treatment were randomly selected to determine the moisture content according to the international standard ISO 18134-1 [28] (for more details, see Section 2.2.1).


(**a**) (**b**)

**Figure 4.** Open shed (**a**—OSF) and outdoor (**b**—ODF) storage of firewood logs in mesh bags.

### 2.3. Climatic Data

The woody biomass stored outside (WS, WSB and ODF) was exposed to the same weather conditions, and the climatic parameters, such as temperature, precipitation, wind speed and wind direction were recorded during the entire storage period (8 months) using a weather cab (Davis, model Vantage Pro 2, CA, USA) placed in the proximity of the storage site and connected to a wireless net.

### 2.4. Statistical Analysis

Repeated measurement analyses of variance using dates and storage methods as factors were used for analyzing the moisture data obtained from the treatments. Pairwise multiple comparison was conducted with the Holm–Sidak method. The differences among the storage methods in dry matter loss were analyzed using ANOVA and Tukey post hoc test. Analysis were performed using PAST [29].

## 3. Results

### 3.1. Climatic Data

During the storage period, the total rainfall recorded was 665.8 mm. The mean temperature during the whole storage period was 17.97 °C, and the mean monthly rainfall was 73.98 mm. Maximum and minimum temperature were registered, respectively, in July (38.4 °C) and February (−8.7 °C), while the maximum amount of precipitation was recorded in March (179.4 mm) and the minimum in September (13.2 mm). The evolution of weather is shown in Figure 1.

### 3.2. Harvested Plants Characteristic

At time of harvest, after five years of cultivation, the mean height of the plants was 9.5 ± 1.31 m and the mean diameter was 10.07 ± 1.94 cm. The total weight of the plants was 70.12 ± 11.11 kg on average, the stem representing 56.64 ± 4.11% of the total plant. The moisture content was 50.56 ± 1.96%.

### 3.3. Moisture Dynamic and Dry Matter Loss

The four storage methods showed a similar moisture variation pattern (Figure 5). Among the storage methods, we found significant differences between ODF and OSF ($t = 6.187$, $p$-value $< 0.01$), and uncovered log and whole stem ($t = 4.668$, $p$-value $= 0.01$). Considering the time, at the beginning we observed a significant decrease in samples' moisture until July, then moisture reduction was not significant. In April, a significant difference was found between ODF and OSF ($t = 5.107$, $p$-value $< 0.001$). In July, significant differences were found between ODF and WSB ($t = 2.955$, $p$-value $= 0.03$). At the end of the experiment, the moisture was different only between debranched stems and OSF ($t = 3.029$, $p$-value $= 0.03$). In Autumn, an increase in moisture content of 4.33% and 1.3% was observed in WS and in the WSB piles, respectively.

Significant differences were found between the dry matter loss ($F = 10.758$, $p$-value $< 0.001$), with the highest loss observed for the whole stem storage (Figure 6).

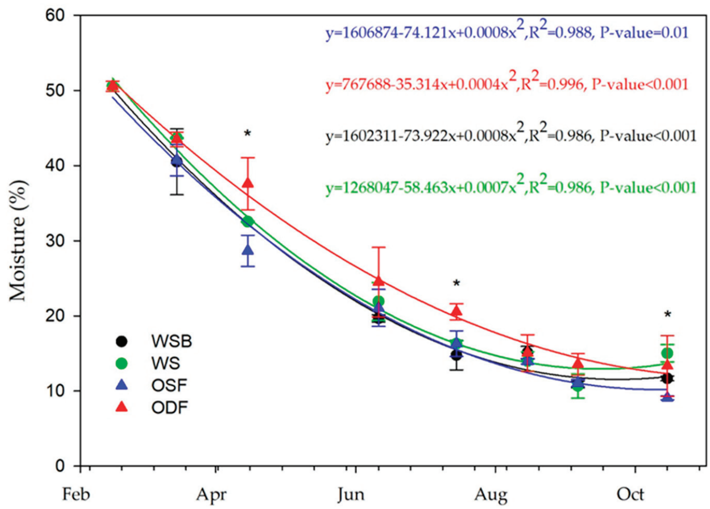


**Figure 5.** Moisture dynamic during the storage period. WS is the outdoor storage of whole stems without branches; WSB is the outdoor storage of whole stems with branches; OSF is the open shed storage of firewood logs in mesh bags; ODF is outdoor firewood logs in mesh bags (ODF). Differences between the storage methods in sampling date are indicated with *. Bar error represents standard deviation.

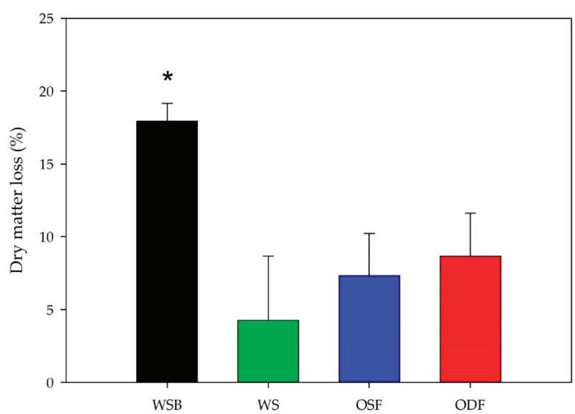


**Figure 6.** Dry matter loss for each storage method. WS is the outdoor storage of whole stems without branches; WSB is the outdoor storage of whole stems with Branches; OSF is the open shed storage of firewood logs in mesh bags; ODF is outdoor firewood logs in mesh bags (ODF). Differences between the storage method in sampling date are indicated with * ($p$-value < 0.05). Bar error represents standard deviation.

## 4. Discussion

*Eucalyptus* biomass can satisfy, considering its high growth potential and relative hardness [10], the growing firewood demand [11]. Hence, it is crucial to provide the best storage system for placing products on the market which can compete with classical fuel wood (oak, beech). Indeed, storage is fundamental to reach commercial moisture and reduce dry matter loss. Moisture reduction is a crucial objective for storing biomass for direct energy generation. In wet biomass, energy produced by combustion is used to evaporate water from the material, thus reducing the usable energy available or the fuel's net heating value. During the storage period, ODF showed higher moisture values than

OSF. Considering that even whole (WSB) and debranched (WS) stems were stored outside, this result underlines that moisture reduction in stored biomass is related to local climatic conditions, material composition, form of biomass, pile size and permeability (compaction), and the activities that affect the internal temperature of the pile [24]. However, at the end of the storage period, the four options reached a similar moisture to the commercial one of the fuel wood (around 15%). Considering that, from July, moisture remained stable, the storage time until the end of September would have avoided the autumnal precipitation, which caused, for the debranched stems, an increase of 4.4% in the moisture. Hence, in similar climatic conditions, it is more convenient to store until the end of summer, to avoid a moisture increase due to autumn precipitation. Indeed, the seasons of harvest and storage affect the final moisture content of harvest residues. Especially for biomass stored outdoors, the seasoning is crucial. Various studies of biomass storage have shown that the lowest moisture content was reached around the end of summer. On the contrary, prolonging outdoor storage until winter leads to an increase in biomass moisture content [30,31]. The comparison of the WSB and WS moisture dynamics suggested that leaves did not affect transpiration. The most significant loss of moisture resulting from transpirational drying occurs within 36 h of felling [32]. At the end of the storage period, the four systems reached the same moisture value. All the storage systems analysed in the manuscript reached lower moisture values than 31% and 40% of wood chips stored in covered and uncovered piles, respectively [18]. Dry matter loss can be affected by biological degradation [24] and in turn affect the energetic potential of the biomass. The dry matter loss of the log systems showed values around 1% of dry matter loss per month, with a very similar mass loss estimated for pulp chips stored outdoors in North America [33], as well as for the 1% of birch chips stored under cover in Norway [34] for different climatic conditions and characteristics of the biomass. Regarding dry matter losses, no differences were found among firewood storage systems, while differences were found between whole plant storage systems. Results suggest that no impact on the dry matter losses is given by the type of firewood storage, but the debranching of the whole stem is a crucial aspect. The dry matter losses of the four storage systems reported in this study are comparable with those of woodchip storage in similar conditions [18]. Results achieved with debranched stems are in line with those obtained in other studies, such as in the storage experience of whole young trees of downy birch performed in Sweden [35]. On the other hand, the high losses identified in WSB piles should be ascribed to the drying and total falling process of the leaves, as the initial amount of leaf biomass of eucalyptus trees was very high (about 44% of the tree was branches and leaves). Moreover, it is important to underline that in the WS storage system all the potential energy of branches was lost. However, these organs are richer in bark than stems, hence producing more ash after combustion.

## 5. Conclusions

*Eucalyptus* biomass is a species of particular interest, especially for MRC. Storage alternatives to piles of wood chips were investigated to limit biomass degradation and find easier handling strategies without affecting the storage time and the quality of the biomass.

The research has studied the variation in moisture and dry matter loss resulting from the storage of bagged logs and whole plants from a MRC *Eucalyptus* plantation in Central Italy. In particular, two type of storage system were adopted for each biomass product: open shed (OSF) and outdoor (ODF) storage of firewood logs in mesh bags and outdoor debranched (WS) and whole stem (WSB) plants. For this reason, this study represents a novelty due to the usage of alternative fast growing species, such as *Eucalyptus*, for fire wood. Consequently, we analyzed innovative storage systems suitable for the firewood market.

At the end of the 8 months' storage (September 2018), the dry matter losses were lower than 10%, except for WSB treatment (17%), and all the treatments resulted in similar moisture content (around 15%). The trend of the dry matter losses was similar to other studies focused on the storage of wood chips in piles.

In conclusion, producing firewood directly at harvesting time opens new market opportunities, considering the qualitative and quantitative characteristics of the biomass after storage. The storage of whole plants, in the presence of sufficient space at the edge of the field (given the greater volumes generated by the presence of branches) can represent an interesting alternative to WS due to the lack of the limbing phase, and economic savings would result. Moreover, at the end of storage period (which in Mediterranean climates according to the data could be in July), the presence of branches that would normally be lost would represent an additional quantity of biomass available to produce wood chips or firewood. Further studies should investigate the economic feasibility of such MRF storage systems by comparing them with more traditional wood chip storage methods.

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# A GIS Approach to Locate a Small Size Biomass Plant Powered by Olive Pruning and to Estimate Supply Chain Costs

**Francesco Latterini [1], Walter Stefanoni [1,*], Alessandro Suardi [1], Vincenzo Alfano [1], Simone Bergonzoli [2], Nadia Palmieri [1] and Luigi Pari [1]**

1 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, Italy; francesco.latterini@crea.gov.it (F.L.); alessandro.suardi@crea.gov.it (A.S.); vincenzo.alfano@crea.gov.it (V.A.); nadia.palmieri@crea.gov.it (N.P.); luigi.pari@crea.gov.it (L.P.)

2 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano 43, 24047 Treviglio, Italy; simone.bergonzoli@crea.gov.it

* Correspondence: walter.stefanoni@crea.gov.it; Tel.: +39-06-90675248

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**Abstract:** The valorization of agricultural residues plays a fundamental role in renewable energy production. Particularly, the management of olive orchards in Lazio region generates a considerable amount of biomass that is currently unexploited, but it could represent a valid source of solid biofuel for energy production in the Lazio region (Italy). Using a Geographic Information System (GIS) approach entirely based on open source software, five suitable areas (A, B, C, D and E) have been selected as eligible for hosting and feeding a 1 MWe power plant. Harvesting and transportation costs were also calculated. The harvesting operation costs were EUR 96.79 $Mg_{fm}^{-1}$ in A, while they ranged from EUR 49.83 $Mg_{fm}^{-1}$ (E) up to EUR 56.51 $Mg_{fm}^{-1}$ (D) for the other sub-areas. Sub-area A showed also higher transport costs, EUR 21.55 $Mg_{fm}^{-1}$ while the same value ranged from EUR 14.75 $Mg_{fm}^{-1}$ (E) to EUR 16.59 $Mg_{fm}^{-1}$ (B) in the other sub-areas. However harvesting costs resulted higher than those reported in the literature, mainly due to the low pruning yield per surface unit, an aspect which is directly related to the olive grove's management in the region where annual pruning is the usual practice. Future developments of the present study should encompass the social and environmental aspects of residual biomass supply chains herein proposed.

**Keywords:** renewable energy; pruning; harvesting; slope; suitable areas; Central Italy; Corine Land Cover

## 1. Introduction

Since the worldwide population is expected to increase up to 9 billion people by 2050 [1], the demand for food and energy will increase accordingly, generating competition for land use and energy sources. In fact, the cultivation of energy crops is gaining more and more interest around the world as a possible surrogate of crude oil products that could represent a competition for food land use.

In 2017, the domestic electricity production in Italy accounted for the 87% of inland demand [2] but only one third of it was produced from renewable sources such as hydroelectric (11%), wind (6%), and solar (8%) power plants [3].

Biomass and waste resources accounted only for the 6% of the total national production of electricity. Since most of the production of the remaining share of electricity relies on imported fossil fuels, fostering the exploitation of domestic agriculture residues for energy production could help to reduce the national dependence on other countries for energy source and reduce the greenhouse effects too. Moreover, reducing energy production from fossil fuels is the key topic of the European Renewable Energy Directive (RED II, directive 2018/2001/EU) which seeks to address the problem by encouraging the agricultural residues exploitation.

Producing renewable energy from agricultural residues has indeed a double advantage, i.e., to turn biomass which actually has a disposal cost into an economic resource for farmers, without requiring additional land and competing with the food industry [4–7].

European, national and regional laws particularly encourage small size biomass power plants (≤1 MWe) powered by local biomass [8–10] like the Fiusis power plant situated in the south of Italy (Fiusis s.r.l, Calimera, Apulia). Fiusis represents a successful and unique case in Europe of short supply chain of local olive tree pruning used for electricity production [11]. It relays on an innovative logistic chain of the biomass suppling that is not bought from external enterprises as generally happens for conventional power plants. Instead, a Fiusis subsidiary harvest firm called "Ligna" is responsible for collecting the biomass produced during the pruning stage for feeding the power plant [11].

As in Apulia, olive growing is among the most important crops in the Lazio region (Central Italy), where 81,231 ha are engaged in such farming [12]. Here, tree pruning is generally carried out yearly (seldom every 2 years) generating a considerable amount of residue ranging from 1 to 5 $Mg_{fm}$ $ha^{-1}$ [13]. Although the potential of such biomass has already been stated, pruning residues are still considered as a problem instead of a valid resource for energy production [14–16]. Thus, replicating Fiusis' approach in another Italian region like Lazio, where olive cropping is extensive, can produce positive effects on the economy as well as on the environment at both local and national scale.

Indeed, very few studies focused on the development of a biomass plant powered by agricultural residues in the Lazio region and no one has considered olive pruning in particular [17].

Certainly, the degree of the sustainability of a given biomass plant depends on several factors, such as: a regular and consistent biomass availability, well-designed logistics of feedstock supply, and optimal use of the resources [18–21]. Particularly, the location of the power plant is critical [22] and the Geographic Information System (GIS) is one of the most powerful and widely accepted tools for planning in agriculture and forestry sectors [23–26]. In fact, GIS permits us to combine both spatial and non-spatial factors such as the extractable biomass from forests and orchards, cost indicators and particular restrictions applied on a given area [27–29] to assess land suitability for the location of the biomass plant [30–32] and support the decision-making phase of the whole supply chains [19,33,34].

However, many of them relied on expensive commercial software which are also highly demanding in terms of computer performance. Moreover, few works included the harvesting operation analysis in the calculation of the supply chain costs [19].

Hence, this study aimed to provide the suitable locations of prospective small size power plants in the Lazio region (Figure 1) using olive pruning exclusively as feedstock, following the Fiusis model, applying a "user-friendly" GIS approach, which implies the usage of open-source software and medium sized hardware. Although the accuracy of open-source GIS software has already been stated [35], only a few works have relied on it for agriculture or forestry applications [36–38].

In details the first step consisted in the identification of the areas within regional territory which showed feasible characteristics for the implementation of a theoretical biomass plant. The second step is the localization of theoretical small size power plants according to the Regional Plan for Energy ("Piano Energetico Regionale" P.E.R. Lazio) [10]. Finally, the last step involved the estimation of the cost for harvesting, handling, loading and transportation of the biomass, taking the Fiusis and Ligna models as examples, i.e., the same plant enterprise which performs also the biomass collection operation.

Relying on realistic data, this study represents an innovative approach for dealing with agricultural residues management and sustainable energy production, providing agronomists, investors and policy makers with a handy and open access tool for drawing future strategies in the Lazio region.


**Figure 1.** Lazio region localization.

*Recent GIS Applications in Spatial Allocation of Biomass Power Plants in Europe*

Several previous studies have identified GIS as a suitable and versatile tool to perform the spatial analysis needed for the location of a biomass power plant and of the related biomass supply chain [23,39,40]. Through this technology, it is indeed possible to capture, store, analyze, display and manipulate spatial data [41], also integrating them with non-spatial quantitative or qualitative data [23]. Considering this, much attention has been paid to such tools by scientific research in the renewable energy sector, with a particular focus on energy from biomass. Indeed, GIS, along with other methods such as Multi Criteria Decision Analysis, is able to face and solve different issues such as land availability and suitability, supply chain costs, and environmental impacts quantification and limitation [42].

Concerning the use of GIS in Europe during the last six years (2015–2020), many successful applications have been reported regarding the management of biomass for energy purposes.

Biomass availability from agriculture residues in Central Europe was analyzed by Haase et al. identifying cereal straw as a very interesting feedstock for energy production in those areas [43]. Similar findings were reported by Comber et al., who analyzed the possibility of exploitation of straw, along with cattle slurry and food waste, for the development of anaerobic digestion plants in United Kingdom, also integrating supply locations that minimize distances to demand sites in the simulation model [44]. Similarly, in Denmark, the economic and social aspects of the development of a biogas supply chain were analyzed by Franco et al. [45].

In Mediterranean areas, biomass availability for biogas production has been studied in Sicily (Italy), reporting that the region could produce 211,000 Mg year$^{-1}$ of biomass, which can be converted into 15,373,000 m$^3$ of biogas and 30,000 Mg of soil amendment, generating 23.1 GWh of electricity [46,47]. Su Jeong and Ramírez-Gómez instead applied an MCDA analysis to optimize the location of biomass facilities in Spain concerning both forestry and agriculture biomass [20], whilst López-Rodríguez et al. performed similar studies in Southern-West Europe focusing only on forestry biomass [25].

Finally, concerning pruning availability and exploitation for bioenergy production, an interesting study by Delivand et al. was performed in Apulia (Italy). The authors focused on the development of a supply chain for both cereal straw, vineyard pruning and olive one identifying the optimal location of theoretical biomass plants, also estimating supply chain costs and Green House gases (GHG) emissions [19].

## 2. Materials and Methods

### *2.1. Software and Hardware Used for the Study*

The software used during the study was the open source Quantum GIS ver. 3.10 [48]. A personal computer with processor Intel Core i5 2.20 GHz, a graphics processing unit (GPU) NVIDIA GeForge310, and 6.0 Gb RAM was used for the study. The minimum system and hardware requirements are: Core i3 2.7 Ghz Processor, 1 Gb Graphic card, 2 Gb Memory RAM, and Windows 7-10 OS [49].

### *2.2. Average Pruning Biomass and Harvesting Scenarios*

An average pruning yield for Central Italy of 2.18 $Mg_{fm}ha^{-1}y^{-1}$ and moisture content of 41%, were considered for the study [14,50]. Regarding the harvesting operations, data influencing both the supply chain costs and the amount of available biomass were taken into account.

In particular, the performance of the harvesting systems used by the Ligna firm were considered in this study according to the results obtained during the European project AGROinLOG [51]; thus identifying two harvesting systems which correspond to three different harvesting scenarios.

The first system consists in pruning harvesting with a towed shredder. This system also requires a preliminary raking operation [52]. In detail, pruning residues are raked and then comminuted by the shredder which unload the hog fuel at a landing site out of the field. Here, a lifter loads on the truck for the transport to the plant. According to the Fiusis and Ligna models, the timeframe between biomass collection and loading-transport varies generally between 15 to 30 days. Considering such a short timeframe and referring to the Fiusis example (on field storage costs covered by the farmer) no intermediate storage costs are considered in the estimation of supply chain costs. The towed shredder system can work on slopes up to 25% and, with such a system, average collection loss reaches 25%. The first harvesting scenario (SF) consisted of a shredder working on flat slopes (up to 5%) and the second with the towed shredder working on slopes up to 25% (SS). This harvesting system showed different harvesting costs per surface unit, depending on flat or hilly slopes applications [52].

In the second harvesting system, the biomass is comminuted using a stationary chipper. In this system, the pruning residues are bunched close to the chipper by a tractor with fork. Then, a hydraulic loader feeds the chipper which, in turn, unloads the comminuted material on the ground. Then a lifter collects and load it on a truck for transport [11]. This represent the third harvesting scenario (SC) which consists of the use of the stationary chipper and it is considered for a slope ranging from 25 to 30%. This scenario presents substantially higher costs per surface unit if compared to the other two but, on the other hand, it does not produce significant biomass loss during the harvesting [11].

Slopes higher than 30% were not considered as suitable for mechanical harvesting of pruning residues. A summary of the main parameters of the various harvesting scenarios used in this study are reported in Table 1. It is important to underline that in the following paragraphs of the present paper, the term "harvesting" refers to biomass collection, handling and loading on the truck.

**Table 1.** Main characteristics of the harvesting scenarios.

| Slope Range (%) | Harvesting Scenario | Machineries and Operations | | Harvesting Costs per Surface Unit (EUR $ha^{-1}$) | Harvesting Loss (%) | References |
|---|---|---|---|---|---|---|
| 0–5% | SF | *Raking* pruning rake + 44kW tractor | *Shredding, handling and loading* towed shredder + 96 kW tractor + 90 kW lifter | 72.90 | 25 | [11,52] |
| 5–25% | SS | *Raking* pruning rake + 44kW tractor | *Shredding, handling and loading* towed shredder + 96 kW tractor + 90 kW lifter | 87.60 | 25 | [11,52] |
| 25–30% | CS | *Bunching* 66 kW tractor | *Comminuting, handling and loading* stationary chipper + hydraulic loader + 126 kW tractor + 90 kW lifter | 230.38 | 0 | [11] |

## 2.3. Identification of Suitable Areas

GIS data were geo-referenced in ED50UTM33 coordinate.

The first step of the GIS procedure was the identification of the suitable zones for the biomass supply chain implementation. Starting from the size of the supply basin of Fiusis (about 10 km radius), the map of Lazio region (vector file) was firstly subdivided into "sub-areas" of approximately 400 $km^2$ each.

Subsequently, starting from a 20 m pixel DTM (Digital Terrain Model) [53], a slope map of Lazio region was developed (map's name: Lazio_Slope) and then reclassified assigning value "1" to slope up to 30% and "0" to higher slopes (map's name: Lazio_Slope_Reclassified). In parallel, the regional Corine Land Cover Map (year 2016) was used to extract regional olive groves map [54]. The overlay between the reclassified slope map and the olive groves map led to the development of the harvestable olive grove map, according to the three harvesting scenarios reported in Table 1. This last map was successively converted in vector format and overlaid with the sub-areas map in order to identify the harvestable olive grove surface in each sub area. The sampling of the previously created Lazio Slope map allowed us to know the slope of the various harvestable olive groves in each sub area and so the applicable harvesting scenario. Moreover, it was also possible to estimate the pruning amount in each sub area considering 2.18 $Mg_{fm}$ $ha^{-1}$ for CS olive groves, considering no harvesting loss, and 1.64 $Mg_{fm}$ $ha^{-1}$ for SF and SS ones, thus considering 25% harvesting losses, as reported in Table 1.

Relying on that information, it was possible to identify the suitable areas according to the following criterion: a suitable sub area is the area where the harvestable amount of pruning biomass every year is at least 8000 $Mg_{fm}$. This threshold of 8000 $Mg_{fm}$ is taken from data from Fiusis, which is annually powered by this amount of biomass [55].

## 2.4. Theoretical Small Size Biomass Plants Localization

The second step consisted in the localization of one small size biomass plant (≤1 MWe) powered only by olive pruning in each sub area.

First of all, a "Constraints" layer was built by merging into a single vector file all those zones having environmental (both Protected Natural Areas and Natura 2000 zones), landscape or hydrogeological constraints [32]. In these areas, the biomass plant was considered not allowed. It is important to underline that in Italy, there is no regulation which clearly forbids the localization of a biomass plants in constrained areas, neither at the national nor at the regional level. Nevertheless, authors maintained a precautionary approach in order to guarantee as less impact as possible on both environment and landscape. Thus, the areas affected by such constraints were excluded. Consequently, a "Restrictors" layer was created [32], thereby showing the suitable areas for the location of the biomass plant. These areas are the ones with slopes lower than 15%, with distance to road network lower than 300 m and distance to electric power lines lower than 500 m. The vector difference between "Restrictors" and "Constraints" identified the possible areas for the plant localization.

Finally, photointerpretation of Google satellite images, along with the Corine Land Cover map of the region, allowed to spot on the map, the location of a single power plant unit per single sub area, carefully excluding the non-industrial areas as suggested by the P.E.R. Lazio [10].

A view of some of the layers used in the GIS procedure is given in Figure 2.

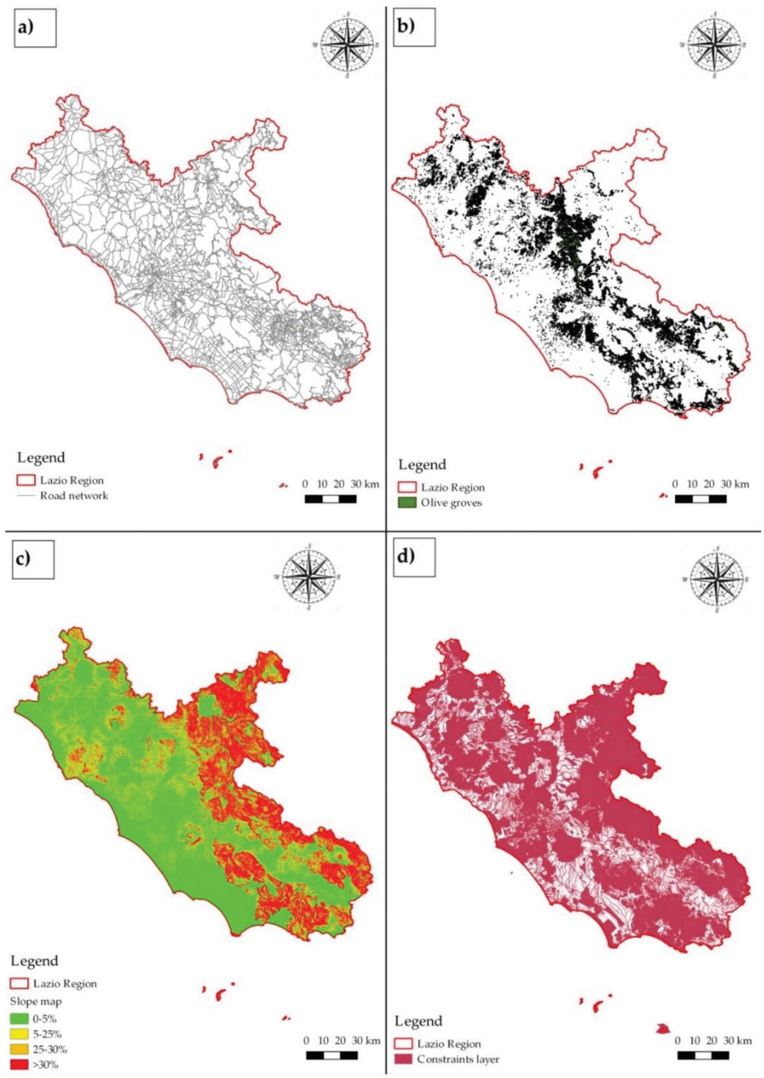


**Figure 2.** (**a**) regional road network; (**b**) olive groves map; (**c**) slope map; (**d**) Constraints layer.

*2.5. Estimation of Supply Chain Costs*

Firstly, it is necessary to explain that the Fiusis model is based on a short supply chain with a very short period of intermediate storage of the biomass. In particular, comminuted biomass storage takes place in the field for a period which generally ranges from 15 to 30 days and this material is brought to the plant when it is needed. In this way, storage costs, which are low compared to the other operations of the supply chain [56], are covered by the farmers who accept Fiusis to collect their pruning; so, in this simulation storage costs are not taken into consideration because they do not represent a cost item for the biomass plant.

Concerning the last part of the GIS procedure, a 10 hectares grid was overlapped to each suitable sub area. Each cell of the grid represented one "plot". The intersection between the grid and the harvestable olive groves map allowed us to know the harvestable olive groves surface in each plot. Therefore, in each plot the information regarding olive groves surface, slope (so applied harvesting scenario) and pruning yield was provided. Applying the costs per surface unit showed in Table 1 for the various harvesting scenarios it was possible to assess, also, the harvesting costs for each plot.

Successively, the estimation of transport costs, assuming the hypothesis of using an 18-ton truck to carry out such operation, was performed. Transport cost per biomass and distance unit was considered equal to EUR 1.175 $Mg_{fm}^{-1}$ $km^{-1}$ [11].

In the next step, the data of each plot were assigned to the plot's centroid. Simultaneously, the road network shapefile was cleared out by deleting paths, footways and residential roads, and a maximum travel speed was assigned to each road according to Italian roads' speed limits, i.e., 50 km $h^{-1}$ for urban roads, 70 km $h^{-1}$ for main roads and 80 km $h^{-1}$ for motorways [36].

Subsequently, the fastest pathway from each plot's centroid to the biomass plant was calculated for each suitable sub area trough "Network analysis" tool [57]. Thus, transport costs estimation was performed by multiplying the obtained travel distance for the plot's pruning yield and the previously reported transport cost of EUR 1.175 $Mg_{fm}^{-1}$ $km^{-1}$. The information regarding the supply chain costs for each plot was obtained by adding harvesting and transport costs. A summary of the overall procedure is given in Figure 3.

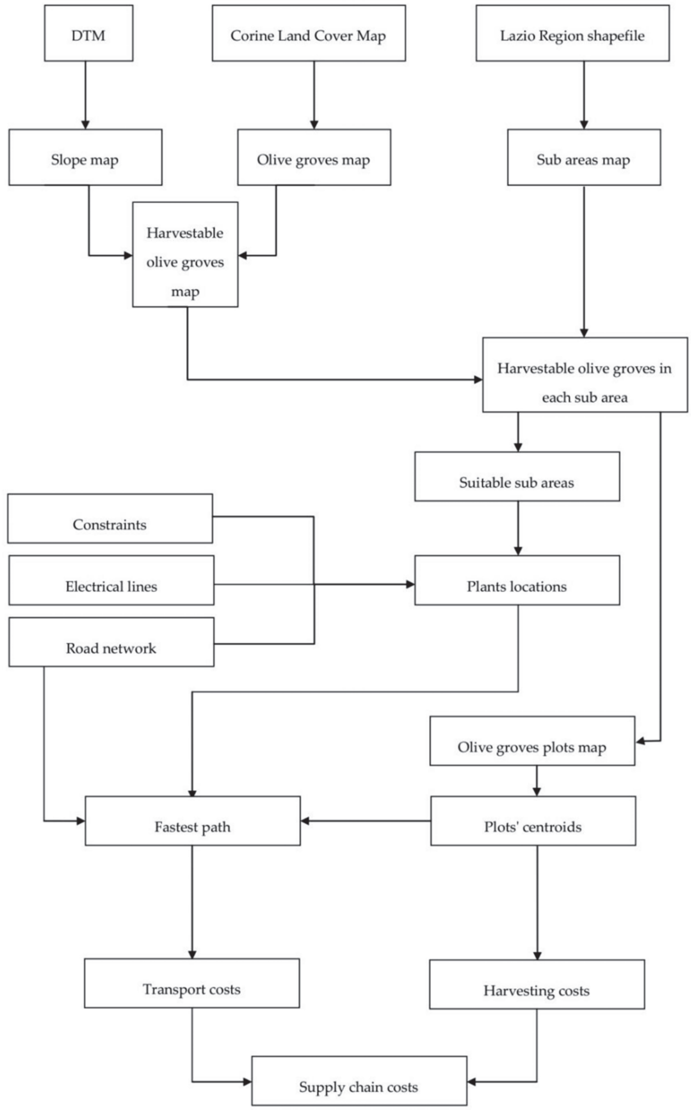


**Figure 3.** Graphical block diagram of the GIS procedure.

## 3. Results

### 3.1. Identification of Suitable Sub-Areas and the Respective Main Characteristics

According to the previously reported definition, i.e., a sub area of about 400 $km^2$, in which there are at least 8000 $Mg_{fm}$ of harvestable pruning residues, five sub-areas were identified as suitable for the implementation of a pruning supply chain capable to fuel a 1 MWe biomass plant (Figure 4). Figure 4 also shows the location of existing biomass power plants with sizes higher than 0.5 MWe reported in the region, as well as the position of the GIS-planned power plant for each suitable sub-area.

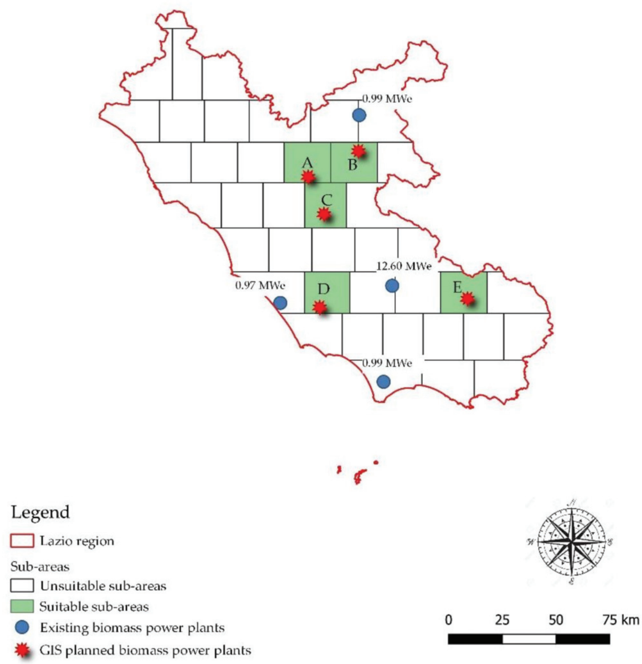


**Figure 4.** Sub-areas identified as suitable for the implementation of the pruning supply chain, existing biomass power plants in the region (blue dots), and location of the theoretical plant for each sub-area (red stars).

Total harvestable olive groves surface and yearly harvestable pruning availability in each suitable sub-area are given in Table 2. B and C areas showed a pruning yield values twice as high as 8000 $Mg_{fm}$ required as minimum productivity for feeding the power plant. Meanwhile, pruning availability in areas A, D and E is similar to the previous value set as threshold.

**Table 2.** Harvestable pruning yield and harvestable olive groves surface for each suitable sub-area.

| Sub-Area | Yearly Harvestable Pruning Availability (Mgfm·year$^{-1}$) | Total Olive Groves Surface (ha) |
|---|---|---|
| A | 11,162.18 | 5396.01 |
| B | 17,246.13 | 10,448.09 |
| C | 19,838.51 | 12,062.10 |
| D | 9664.76 | 5753.62 |
| E | 8979.98 | 5483.13 |

Focusing on the harvesting scenarios depicted in Figure 5, it is evident that the SS system can be applied extensively in B, C, D and E, while in A there is a substantial predominance of the CS harvesting system. Instead, SF provides limited contribution with the highest share (13.53%) reported only in C.

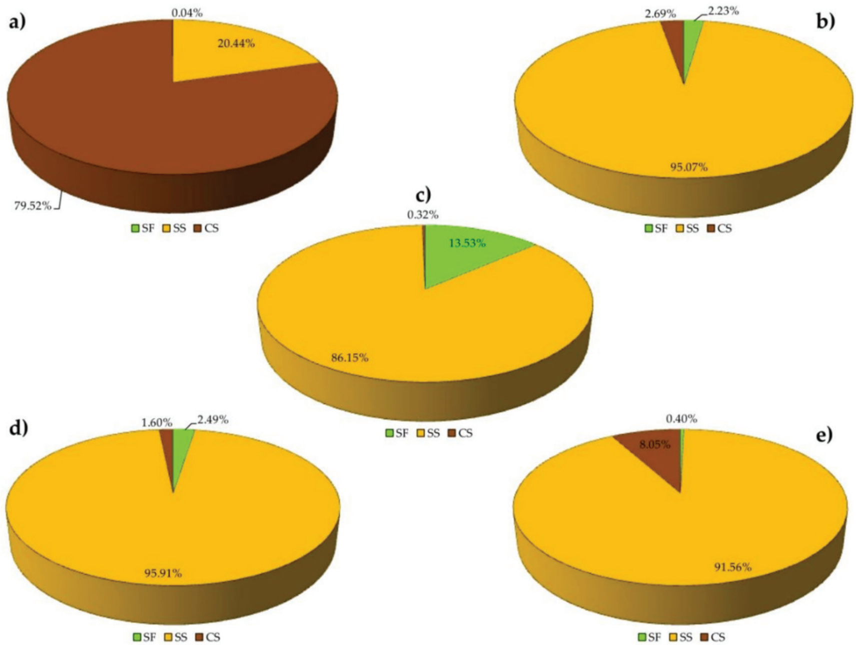


**Figure 5.** Harvesting scenarios percentage in each suitable sub-area. (**a**) A sub-area; (**b**) B sub-area; (**c**) C sub-area; (**d**) D sub Area; (**e**) E sub-area.

### 3.2. Estimation of Supply Chain Costs

The comparison of the supply chain costs among the various suitable sub-areas is given in Figure 6. Noticeably, there is a substantial difference between area A and the others. Particularly, sub-area A showed harvesting costs substantially higher in comparison to the others sub areas and higher transport cost as well.

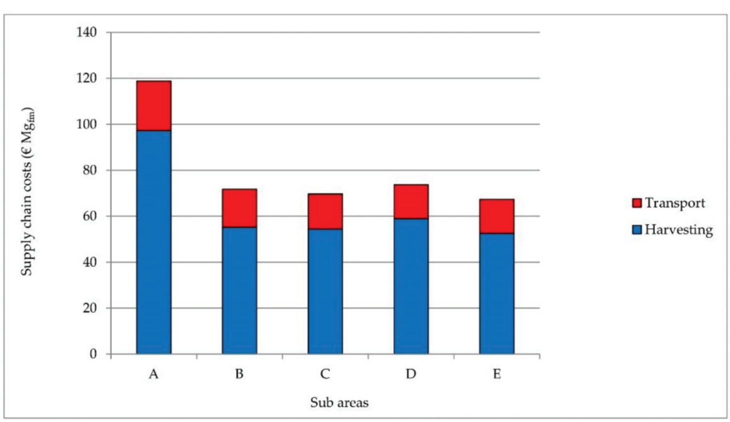


**Figure 6.** Supply chain costs for each suitable sub-area (harvesting, handling, loading and transport costs).

The harvesting, handling and loading operations costs were EUR 97.23 $Mg_{fm}^{-1}$ in A, while they ranged from EUR 52.55 $Mg_{fm}^{-1}$ (E) to EUR 58.95 $Mg_{fm}^{-1}$ (D) for the other sub-areas. Indeed, the large use of CS harvesting system in A led to a substantial increase in the harvesting costs.

Sub-area A also showed higher transport costs, EUR 21.55 $Mg_{fm}^{-1}$ while the same value ranged from EUR 14.75 $Mg_{fm}^{-1}$ (E) to EUR 16.59 $Mg_{fm}^{-1}$ (B) in the other sub-areas. Such difference depends on the transport distance, which in A resulted as being longer. In particular, the average transport distance for A was 22.46 km, while it ranged from 12.98 km (E) to 15.85 km (B) among the other sub-areas.

## 4. Discussions

The analysis of the obtained results permitted to better refine the identification of the most suitable zones, in Lazio region, for the theoretical pruning supply chain implementation. For instance, sub-area A showed higher costs for both transport and harvesting. Particularly, the latter phase is far more responsible for the remarkable increase in the costs, dimming the possibility to include it within a practical and feasible plan for the development of a proper supply chain. In fact, the topography of the territory requires an extensive use of the most expensive harvesting scenario, i.e., CS, with the consequent increase in the harvesting costs. Moreover, the hilly-mountainous morphology of this sub-area exhibited poor reliability of the road network, this determined the increase in the length of the distance to drive and consequently, the transportation costs as well.

The B, C, D and E sub-areas instead showed very similar costs per biomass unit for both harvesting and for transport. However, there is an important consideration to be had. In fact, as reported in Table 2, the D and E sub-areas showed an average pruning yield just slightly higher than the 8000 $Mg_{fm}$ which represented the threshold value for being considered as a suitable sub-area. So, in order to ensure the sufficient supply of biomass for feeding the power plant, all olive groves' owners in the sub-area are supposed to provide their contribution to the supply chain. Practically, this is not always true. For instance, Fiusis acknowledged that it can gather approximately 30% of the total annual biomass available in its supply basin [55], as not all farmers contribute to the supply of biomass. Hence, the overall estimated supply chain costs in B and C resulted as more trustable in the view of future development of the pruning supply chain. While D and E seem more suitable for a further smaller biomass plant.

Interestingly, B and C sub-areas lays adjacent, actually offering the possibility to be considered as a unitary source of biomass for feeding a bigger biomass plant. However, the European and National policies along with the specific Regional Directives strongly encourage smaller biomass plants. Such an approach seeks to make the local population benefit from the transformation of a burden, such olive pruning management, into energy. Therefore, in order to be in compliance with all the guidelines dictated by the regulations at the different levels drawn by environment and energy policy making, the development of two distinct biomass plants is the most preferable option.

Before trying to make a comparison with previous studies' results, it is important to underline that there are few examples in the literature with which to make a comparison with the present study, because, as reported by Palmieri et al. [55], Fiusis represents a very particular power plant in the European context.

Focusing on supply chain costs, comparing the results of this simulation with a similar study [19] and applicative examples, it is possible to notice how the present work showed substantially higher values. Excluding the A sub-area, which, as already reported above, showed very high costs, the result of the simulation reported for the other four sub-areas' supply chain costs was in the order of EUR 65.00–70.00 $Mg_{fm}^{-1}$. Delivand et al. [19], in a simulation of olive pruning supply chain costs in Southern Italy, reported a range of EUR 36.00–39.00 $Mg_{fm}^{-1}$, so considerably lower values. Similarly, the price of EUR 38.69 $Mg_{fm}^{-1}$ was reported by Suardi et al. in the Fiusis case $Mg_{fm}$ [11].

Such aspects could represent an obstacle for the development of a pruning supply chain in the Lazio region. The higher cost obtained is due to the different management system applied in olive groves which affects negatively the pruning yield per surface unit. In fact, in the Apulia region, the pruning operation is usually carried out every three years [55] and the pruning yield is usually in the range of 4–7 $Mg_{fm}$ $ha^{-1}$ $year^{-1}$ [11,58], thus substantially higher than in the Lazio context. Therefore, when the costs per unit of biomass in the Lazio supply chain are calculated, higher values are unavoidable since the harvesting costs per surface unit are considered as fixed. Obviously, collecting the biomass in a hardly accessible field is more costly than accomplishing the same task on flat lands, but a certain amount of cost increase has to be tolerated. Certainly, if a real biomass power plant is to be built, more specific tests are encouraged in order to better discriminate the maximum slope acceptable, and a cost-benefit analysis must be performed. So far, a possible solution to reduce the supply chain costs in the B and C sub-areas is to avoid collecting olive grove pruning in fields with slopes higher than 25%, thus excluding the most expensive harvesting scenario (CS). Moreover, it is important to consider that the efficiency of the machinery is not constant, but may change according to the tractor driver, the quality of the biomass collected and the ground conditions. Thus, all the regulations of the machine should be performed carefully, as, for instance, the regulation of the pick-up system and the optimization of the raking operation [58,59] could significantly decrease the biomass loss and, consequently, the supply chain costs. In particular, considering no biomass losses for SS and SF harvesting scenarios and excluding olive groves with slopes higher than 25% from the supply chain, the overall costs would decrease to EUR 49.83 ${Mg_{fm}}^{-1}$ and EUR 52.54 ${Mg_{fm}}^{-1}$ for B and C, respectively. Despite their being higher than those reported for the Fiusis supply chain [11], or in similar studies in another context [19], they are close to the price of wood chips obtained from forest maintenance operations (i.e., EUR 50 ${Mg_{fm}}^{-1}$ referred to the purchase of a full cargo truck, VAT excluded, without transport) [60]. Moreover, another aspect to be highlighted is the fact that pruning mulching, which is the common practice adopted for residue management in Lazio, costs EUR 140.00 $ha^{-1}$, which is actually covered by the farmer and corresponds to EUR 64.00 ${Mg_{fm}}^{-1}$ considering the average olive pruning yield in the study area [61]. So, another possibility to reduce the cost of the supply chain for the biomass plant is to look for a deal with the various farmers, who could pay a certain amount of money to the biomass plant per biomass unit—obviously substantially lower than the actual price for mulching—in order to collect the pruning residues.

To summarize, the result of this preliminary simulation of a theoretical olive pruning supply chain in the Lazio region, able to feed a ≤1 MWe biomass plant, showed that this zone of Central Italy presents interesting areas for this aim. However, the supply chain costs estimation reported higher values than similar applicative examples and simulations. Thus, the real feasibility of the biomass supply chain implementation in that zone has to be further investigated. Particularly, additional aspects related to all three pillars of sustainability (economy, environment and society), also integrating Life Cycle Assessment (LCA) [62] or Sustainability Impact Assessment (SIA) [63,64] approaches, have to be taken into account. The valorization of agriculture residues, from an energetic point of view, does not lead only to economic or environmental positive externalities but also to social ones [65–67]. In fact, a Fiusis-like power plant is an opportunity for creating new jobs directly and indirectly, if all the collateral activities are taken into account. Besides, it is very important to not underestimate the positive contribution of such new activities, acting as valid tools for fighting the phenomenon of the abandonment of rural areas in Italy [68].

Another important aspect of the present paper is the applied GIS procedure, which is fully developed with open source GIS software and with medium performing computer. This GIS approach is more "user-friendly" than the ones found in literature, providing all the stakeholders, for example agronomists or public servants, with a handy tool for drawing future strategies for bio-fuel supply chain development. This procedure is, in fact, applicable not only to pruning biomass but also to other agricultural residues or dedicated energy crops.

Obviously, it represents a first approach to the implementation of a real supply chain, and further steps are certainly needed in order to switch from preliminary study to operative planning.

## 5. Conclusions

The exploitation of the residual biomass produced by olive pruning management could significantly contribute to achieving the challenging environmental goals set by the European policy for the next decades. However, in order to guarantee the beneficial effects of applying such strategy, the whole supply chain has to be managed properly for the successful running of the power plant. In fact, transportation costs and feedstock availability have been limiting factors for the development of similar supply chains in the past, and GIS can help to provide reliable data for preliminary planning.

The present study aims to provide stake holders and policy makers with a handy tool for assessing, at least at the very first step of the decision making, the possibility and the location of a biomass power plant at regional scale in the Centre of Italy. An open source GIS was used in order to discriminate, by the field's slope, the harvestable area in the Lazio region capable of providing the minimum biomass required for running the power plant all year round. Environmental, landscape and hydrogeological constraints were taken into account when defying the suitable area for locating the power plant, thus five macro areas were selected. Costs for harvesting and transportation were also included, providing reliable base data to draw the attention of investors and policy makers.

This represents a preliminary analysis, and deeper investigation is needed in the subsequent steps of the planning process. The future development of the present study could focus on the possibility of integrate the present procedure with indicators about environmental and social externalities of residual biomass supply chains.

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## Abbreviations

| | |
|---|---|
| GIS | Geographic Information System |
| $Mg_{fm}$ | Fresh matter ton |
| SF | Shredder on flat slope |
| SS | Shredder on hilly slope |
| CS | Chipper on hilly slope |
| DTM | Digital terrain Model |
| SIA | Sustainability Impact Assessment |
| LCA | Life Cycle Assessment |
| MCDA | Multi Criteria Decision Analysis |
| GHG | Green House Gases |

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Article

# Willow Biomass as Energy Feedstock: The Effect of Habitat, Genotype and Harvest Rotation on Thermophysical Properties and Elemental Composition

**Mariusz Jerzy Stolarski [1,*], Michał Krzyżaniak [1], Kazimierz Warmiński [2], Dariusz Załuski [1] and Ewelina Olba-Zięty [1]**

1 Centre for Bioeconomy and Renewable Energies, Department of Plant Breeding and Seed Production, Faculty of Environmental Management and Agriculture, University of Warmia and Mazury, Plac Łódzki 3, 10-724 Olsztyn, Poland; michal.krzyzaniak@uwm.edu.pl (M.K.); dariusz.zaluski@uwm.edu.pl (D.Z.); e.olba-ziety@uwm.edu.pl (E.O.-Z.)

2 Centre for Bioeconomy and Renewable Energies, Department of Chemistry, Faculty of Environmental Management and Agriculture, University of Warmia and Mazury, Prawocheńskiego 17, 10-720 Olsztyn, Poland; kazimierz.warminski@uwm.edu.pl

* Correspondence: mariusz.stolarski@uwm.edu.pl; Tel.: +48-89-5234838

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**Abstract:** Willow biomass is used as a bioenergy source in various conversion technologies. It is noteworthy that apart from the beneficial environmental impact of a willow plantation, the biomass quality is also very important as it has an impact on the effectiveness of its use and emissions produced in various bioenergy technologies. Therefore, this study analysed the thermophysical properties and elemental composition of 15 genotypes of willow biomass from two plantations situated in the north of Poland, harvested in two consecutive three-year rotations. The differences in the moisture content, ash content and the lower heating value were mainly determined by the genotype, i.e., by genetic factors. In contrast, the content of carbon, nitrogen, sulphur and hydrogen was determined by the location (environmental factors), but also by the genotype, and by a combination of these factors. The following were the mean levels of the willow biomass characteristics, regardless of the location, genotype and harvest rotation: 48.9% moisture content, 1.26% d.m. ash content, 19.4% d.m. fixed carbon, 79.4% d.m. volatile matter, 19.53 MJ kg$^{-1}$ d.m. higher heating value, 8.20 MJ kg$^{-1}$ lower heating value, 52.90% d.m. carbon, 6.23% d.m. hydrogen, 0.032% d.m. sulphur, 0.42% d.m. nitrogen. The present research has shown that the selection of the willow genotype is important for the quality of biomass as energy feedstock. However, plantation location, as well as successive harvest rotations, can have a significant impact on the biomass elemental composition.

**Keywords:** short rotation coppice; Salix; genotype × site interaction; ash content; lower heating value; nitrogen content; sulphur content

## 1. Introduction

Due to increasing levels of $CO_2$ in the atmosphere resulting from anthropogenic activities, and many European Union (EU) countries striving to increase their energy independence, there is growing interest in the use of renewable energy sources (RES), which are successfully replacing fossil fuels [1–5]. Although the use of each RES type is important, the portion of each RES in energy production is different in each country and depends on the geographic latitude, size and demographic structure of a country. In general, bioenergy, especially solid biomass, is of the greatest importance in EU countries [6]. Bioenergy also plays a particularly important role in Poland, as it accounted for nearly 85% of energy production from RES in 2018, with solid biofuels accounting for over 69% [7]. Due to a large forest area in Poland (over 9 million ha, which accounts for approx. 30% of the country area) and the amount of wood acquired annually (over 40 million $m^3$) [8], wood processing industry waste and post-felling biomass, i.e., branches and twigs left over after tree felling, is the dominating source of woody biomass. Plantations of woody crops grown as short rotation coppice (SRC) are another source of woody biomass and include mainly willow and poplar [9–13]. The area of poplar and willow cultivation in the SRC system in Poland is estimated at approx. 16.8 thousand ha [14]. Therefore, assuming a mean yield of 8.5 Mg $ha^{-1}$ $year^{-1}$ d.m., this kind of plantation can potentially give ca. 142,800 Mg $year^{-1}$ d.m.

The perennial nature of SRC crops and low demand for nutrients with limited agricultural procedures were shown to have a positive impact on the GHG balance and carbon accumulation in soil [15–18]. Moreover, a life cycle assessment of willow and poplar biomass production has shown that yield is a very important factor affecting the GHG balance, and that fertilisation can have negative effects [19]. It is noteworthy that apart from the beneficial environmental impact of an SRC plantation and the yield, the biomass quality is also very important as it has an impact on the effectiveness of its use and emissions produced in various bioenergy technologies. Woody biomass, including willow and poplar, is successfully used as an energy feedstock in the combustion of chips, pellet and briquette [20–23]. Increasing attention has been attracted recently by the cascade use of lignocellulosic biomass. This concept involves the acquisition of valuable bioactive substances and post-extraction biomass is used for energy production. Moreover, woody biomass is being studied for the production of second-generation transport biofuels [24,25]. However, if these technologies of lignocellulosic biomass conversion continue to develop commercially, they will require a continuous supply of raw material of consistent quality.

Lignocellulosic biomass quality depends on several factors, especially the type of plant and biomass. In general, woody biomass obtained from SRC (willow, poplar, black locust) is characterised by a higher content of lignin and greater higher heating value (HHV) as well as a lower content of hemicellulose, ash and chlorine compared to grasses and herbaceous crops [26,27]. Therefore, woody biomass is usually regarded as good material for thermal conversion. On the other hand, ash and other mineral biomass components may pose a problem for thermal and thermochemical conversion technologies as they cause corrosion and the formation of slag and sediments. Furthermore, the ash present in biomass can decrease the effectiveness of its pre-treatment in biochemical conversion processes. Therefore, the biomass quality characteristics and understanding the source of variability are of great importance [28]. This is particularly important in the case of willow because of the large number and diversity of species, cultivars and clones. Significant differences in bark and ash content were found in initial breeding experiments on many willow genotypes of many species in the USA [29,30]. Later studies also revealed great differences between 18 willow genotypes with respect to polysaccharides and ash and considerable genotype interactions with the environment for some characteristics [11]. Therefore, both genetic factors and environmental and agrotechnical conditions have a significant effect on the composition and quality of biomass [28,31–34]. Research in Poland on willow production, biomass quality and its use for energy purposes also accelerated at the beginning of this century [10,35]. Willow has become one of the perennial crops grown in Poland for energy or industrial purposes in two cultivation systems, mainly as SRC and Eko-Salix, which differ primarily in the method of setting up and managing the plantation and the duration of a harvest rotation [10]. However, studies on the topic have usually concerned only a few clones, locations and harvest rotations, whereas the present research covers a dozen promising, preselected willow cultivars and clones, which are suitable for cultivation as SRC under the climatic conditions of Poland as well as in central Europe. Therefore, the main aim of the current study was to evaluate the thermophysical properties and elemental composition of the biomass of 15 willow genotypes (including 7 cultivars and 8 clones) as energy feedstock, harvested at two different sites in two consecutive three-year harvest rotations. These data were subsequently used for the quantitative determination of the relative contribution of genetic and site-related factors, and their interactions in explaining the variability of biomass characteristics. Moreover, the study aimed to determine the effect of genetic and site-related diversity on willow biomass quality.

## 2. Materials and Methods

### 2.1. The Field Experiments

The study was based on two field experiments at the University of Warmia and Mazury in Olsztyn (UWM), conducted in the north of Poland in 2013–2018. The first experiment was conducted in the village of Bałdy in the Warmińsko-Mazurskie Voivodship (53°35′48″ N, 20°36′12″ E) on mud-muck soil developed on calcareous gyttia in loamy subsoil. This experiment was set up in 2008 and the plants were harvested in 2008–2012 in one-year harvest rotations. Subsequently, beginning with 2013, the plants were harvested twice in two consecutive three-year rotations: 1st rotation, plant growing years 2013–2015; 2nd rotation, plant growing years 2016–2018; The second plant experiment was located in the village of Obory, the Pomeranian Voivodship (53°43′34″ N, 18°53′55″ E), on complete humic heavy alluvial soil, formed from silty clay. This experiment was set up in 2009 and plants were harvested in 2009–2012 in one-year harvest rotations. Subsequently, beginning with 2013, the plants were harvested twice in two consecutive three-year rotations, like in Bałdy. Both experiments were conducted on good, fertile soils. However, they were approx. 150 km apart, so the climatic conditions were different. The annual average temperature during the experiment at Obory (9.0 °C) was higher by approx. 0.7 °C compared to the temperature at Bałdy. The total annual precipitation at Bałdy (six-year average – 598 mm) was higher by approx. 20% than at Obory. The rainfall at Bałdy during the study period ranged from 484 to 803 mm, with that at Obory ranging from 454 to 640 mm, in 2014 and 2017, respectively. Moreover, the groundwater level at both sites was suitable for willow cultivation since it ranged from ca. 80 cm to ca. 190 cm depending on the season and rainfall.

Fifteen willow genotypes of nine different species and interspecies hybrids were grown at both locations. These included seven cultivars of *Salix viminalis* (Start, Sprint, Turbo, Tur, Kortur, Oltur, Żubr) bred at the UWM, which are registered in the Polish entity which maintains the cultivar register, the Research Centre for Cultivar Testing in Słupia Wielka, and eight clones of other species from the UWM collection: *S. acutifolia* (clone number – UWM 093), *S. alba* (UWM 095), *S. dasyclados* (UWM 155), *S. fragilis* (UWM 195), *S. pentandra* (UWM 035), *S. triandra* (UWM 198), *S. viminalis* × *S. amygdalina* (UWM 054), *S. viminalis* × *S. purpurea* (UWM 033). Those 15 different willow clones were chosen which seemed interesting and prospective at the time of setting up the experiments. However, in order to verify it, similar studies at various sites were necessary, as presented in this paper.

The same mineral fertilisation was applied at both sites before the next harvest rotation started (April 2013 and 2016). Nitrogen (N) was applied as ammonium nitrate at a rate of 90 kg $ha^{-1}$. Phosphorus (P) was applied as triple superphosphate at 13 kg $ha^{-1}$. Potassium was applied as potassium salt at 50 kg $ha^{-1}$.

### 2.2. Examination of Willow Biomass Quality

Three-year-old willows were cut down manually with chainsaws in both experiments after the growing seasons ended. The harvest time was set when the soil was frozen, so willow was harvested in winter of the next year at both sites, i.e., in February 2016 and 2019. Representative biomass samples with a total mass of ca. 3 kg were collected during the harvest from whole plants of each cultivar and clone. The samples were packed into plastic bags and transported to the laboratory for analyses. First, the moisture content was determined at the temperature of 105 °C by the oven-dry method (EN ISO 18134−1:2015). The plant harvest, transport of tightly packed biomass samples and the laboratory work were planned so that the moisture content was determined on the next day after harvest, which eliminated potential additional moisture loss. After the biomass samples were dried and their moisture content calculated, the samples were ground in a laboratory mill with a 1 mm mesh sieve, which produced a homogeneous fraction for further analyses. The ground samples from each cultivar and clones from the two experiments were subsequently stored in closed laboratory containers and used for further analyses. Before the HHV was determined, the samples were placed in an oven at 105 °C, and analytical samples were collected from them and placed in a bomb calorimeter IKA C2000. HHV was determined by the dynamic method. Furthermore, a Eltra Tga-Thermostep thermogravimetric oven was used to determine the ash content at 550 °C and volatile matter and fixed carbon content at 650 °C (PN-EN ISO 18122:2016-01 and PN-EN ISO 18123:2016-01). Carbon (C), hydrogen (H) and sulphur (S) contents were then determined in an Eltra CHS 500 automatic analyser (PN-EN ISO 16948:2015-07 and PN-EN ISO 16994:2016-10). A total nitrogen assay in biomass was performed using Kjeldahl's method on a K-435 mineraliser and a B-324 Buchi distiller. The lower heating value (LHV) of each willow cultivar and clone biomass from the two sites in consecutive harvest rotations was calculated from the HHV, moisture content and hydrogen content, determined earlier in the laboratory (PN-EN ISO 18125:2017-07). All analyses were performed in three replicates, which means that altogether 12 biomass samples were analysed for each genotype (2 sites × 2 harvest rotations × 3 replicates) and the total number of analyses performed in the study was 180 (2 sites × 2 harvest rotations × 15 genotypes × 3 replicates).

### 2.3. Statistical Analysis

All ten characteristics of biomass quality: moisture content, ash content, fixed carbon content, volatile matter, HHV and LHV and the contents of carbon, hydrogen, sulphur and nitrogen were subjected to separate (unidimensional) statistical analyses. A repeated-measures ANOVA test was applied, with the effect of locations (Loc) and the effect of 15 willow genotypes (Gen) being the grouping factors and harvest rotations (Rot) being the repeated measure factor. This model took into account all possible interactions between the experimental factors mentioned above. The replications (experimental blocks) were nested in the location effect (Rep(Loc)). The significance of the factors' effect and their interactions were verified at the significant level of $\alpha = 0.05$. The percentage shares of all the effects under study in the total sum square (total SS) for a given analysis of variation were calculated. This yielded a measure of share in the variation under study, which was understood as the percent of explaining the variation by each individual analysis model effect. The significance of differences between the means was analysed with a Tukey test ($p < 0.05$), which was used to determine homogeneous sets.

A principal components analysis (PCA) was applied in the next stage, in which all ten biomass quality characteristics were analysed simultaneously. Since the characteristics under study were measured in different units and scales, the PCA was based on the results after the standardisation of characteristics, which was performed following the procedure for an unknown mean and the standard deviation for a population (1):

$$z_i = (x_i - mean)/std.dev \quad (1)$$

where $z_i$ is a variable following standardisation, $x_i$ is a variable before standardisation, *mean* is the mean of the sample and *std.dev* is the standard deviation of the sample.

The number of principal components for the PCA was determined by the Kaiser criterion, where the eigenvalues were greater than 1. The PCA results were presented as a table of factor loadings and a biplot. All statistical analyses were conducted with STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA, 2017).

## 3. Results and Discussion

### 3.1. Thermophysical Properties of Willow Biomass

The thermophysical characteristics (moisture content, ash content, fixed carbon, volatile matter, HHV and LHV) of willow biomass were differentiated by the site and genotype and the majority of them also by the harvest rotation and by the interactions of these factors (Table 1). The mean moisture content in willow biomass for all the genotypes sites and consecutive three-year harvest rotations was 48.9% (Figure 1). The contribution of the willow genotype to the biomass moisture content variation was the highest (81% of the total variation) (Table 1). In contrast, the interaction of location and genotype and consecutive harvest rotation did not have such a great impact on the variation of the willow biomass moisture content. The lowest mean moisture content was determined in the biomass of the Sprint cultivar (*S. viminalis*) and the highest was in the biomass of the UWM 155 clone (*S. dasyclados*) (45.2% and 52.5%, respectively) (Figure 1). Moreover, the willow biomass moisture content in this study was relatively low – it was below 50% in the majority of cases. In contrast, the biomass moisture content in willow harvested in 3- or 4-year rotations often exceeded 50% [36–38]. The biomass moisture content in a longer, 7-year rotation in *S. alba* exceeded 52%, and it was below 50% in *S. viminalis* [10]. Therefore, this confirmed that the willow species differentiates the moisture content significantly. The differences are even more apparent between species of different SRC types because the moisture content in black locust is generally lower (ca. 40%) and it is higher in poplar (ca. 60%) when compared to the willow biomass [35]. Kauter et al. [39] also report that a high moisture content at harvest (up to 55–60%) is one of the problematic features of woody biomass (poplar in this case). On the other hand, the weather conditions during the harvest as well as immediately before and after the harvest affect the biomass moisture content. Potential precipitation and high air humidity at harvest translate into an increase in the biomass moisture content. For this reason, the literature data for this biomass characteristic vary by up to several percentage points (pp) even within the same species and cultivation technology.

**Table 1.** Statistics *F* from the repeated measure variation analysis and the percentage share of effects in the total variation for the thermophysical characteristics of willow biomass.

| Source of Variation | *df* | Moisture | | Ash | | Fixed Carbon | | Volatile Matter | | HHV | | LHV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) |
| Location (Loc) | 1 | 31.3 ** | 0.4 | 11.8 ** | 0.6 | 104.9 ** | 10.3 | 127.4 ** | 9.9 | 763.0 ** | 48.9 | 480.0 ** | 7.9 |
| Rep(Loc) | 4 | 1.5 | 0.1 | 2.1 | 0.4 | 0.1 | 0.1 | 0.5 | 0.2 | 1.0 | 0.3 | 0.2 | 0.0 |
| Genotype (Gen) | 14 | 514.6 ** | 80.9 | 96.1 ** | 65.9 | 11.8 ** | 16.1 | 20.2 ** | 22.0 | 22.7 ** | 20.4 | 325.3 ** | 74.8 |
| Loc × Gen | 14 | 42.8 ** | 6.7 | 3.6 ** | 2.5 | 8.1 ** | 11.1 | 8.2 ** | 9.0 | 5.9 ** | 5.3 | 29.0 ** | 6.7 |
| Error 1 | 56 | - | 0.6 | - | 2.7 | - | 5.5 | - | 4.4 | - | 3.6 | - | 0.9 |
| Rotation (Rot) | 1 | 29.8 ** | 0.3 | 136.0 ** | 11.3 | 221.4 ** | 20.2 | 397.7 ** | 26.0 | 37.5 ** | 2.2 | 2.8 | 0.0 |
| Rot × Loc | 1 | 93.3 ** | 1.0 | 16.9 ** | 1.4 | 1.7 | 0.2 | 0.0 | 0.0 | 56.3 ** | 3.3 | 18.8 ** | 0.3 |
| Rot × Rep (Loc) | 4 | 1.5 | 0.1 | 0.9 | 0.3 | 0.4 | 0.1 | 0.9 | 0.2 | 0.3 | 0.1 | 1.7 | 0.1 |
| Rot × Gen | 14 | 27.0 ** | 4.0 | 5.5 ** | 6.4 | 9.7 ** | 12.4 | 11.6 ** | 10.6 | 5.3 ** | 4.4 | 13.2 ** | 3.2 |
| Rot × Loc × Gen | 14 | 36.6 ** | 5.4 | 3.3 ** | 3.9 | 14.9 ** | 19.1 | 15.4 ** | 14.1 | 9.7 ** | 8.1 | 20.8 ** | 5.1 |
| Error 2 | 56 | - | 0.6 | - | 4.7 | - | 5.1 | - | 3.7 | - | 3.3 | - | 1.0 |
| Total | | | 100.0 | | 100.0 | | 100.0 | | 100.0 | | 100.0 | | 100.0 |

Share (%); percentage share in the total sum of squares; ** $p < 0.01$.

Like moisture content, the ash content in biomass was determined to the greatest extent by the willow genotype (nearly 66%), followed by the harvest rotation (11%) and–to a lesser extent–by the other factors and their interactions (Table 1). The mean ash content in willow biomass harvested in three-year rotations was 1.26% d.m. for all the genotypes and sites. (Figure 2). The ash content in biomass obtained at Obory (mean 1.25% d.m.) was lower by only 0.2 pp compared to that obtained at Bałdy. The lowest ash content of all the genotypes under study was determined in the biomass of the UWM 198 clone of *S. triandra* (mean 0.99% d.m.). The Tur and Żubr cultivars (*S. viminalis*) and the UWM 093 clone (*S. acutifolia*) contained less ash compared to the other genotypes. The highest ash content was determined in biomass of the UWM 155 clone of *S. dasyclados* (1.43% d.m.). Therefore, the differences between the willow genotypes under study with respect to the ash content were large (up to 44%). Thus, the ash content in the willow biomass was determined by the genotype, i.e., genetic factors that were decisive for it. However, one cannot definitely determine what other (e.g., physiological) factors affected this phenomenon. Nevertheless, the very fact of identifying statistically significant differences between genotypes is of high scientific and practical value for both biomass producers and end-users. Moreover, it was found in an extensive study covering several locations and several dozen willow genotypes that the ash content in biomass was determined mainly by the genotype and ranged from less than 1% d.m. to more than 3% d.m. [28]. It was also shown that *S. purpurea*, which grows a large number of shoots of smaller diameter, contained less ash (ca. 1.6% d.m.), compared to *S. miyabeana*, which grew fewer shoots with a larger diameter (ca. 2.2% d.m.) [29,30,40,41]. The ash content as determined in another study in a three-year harvest rotation also varied between species (1.25–1.76%)–it was the lowest in *S. alba*, and the highest in *S. Smithiana* [42]. The mean ash content in willow biomass harvested in a 3- and 4-year rotation was 1.4% d.m. and 1.2% d.m., respectively [36]. Even higher ash content in willow biomass (1.9–3%) was found in another study [38,43]. Furthermore, the mean ash content in six willow genotypes harvested in a 7-year harvest rotation at three different sites was 1.3% d.m. [10]. Some authors have pointed out that the ash content decreases as the harvest cycle becomes longer [44,45]. Obviously, the ash content levels mentioned above should be regarded as generally low compared to the ash content in other biomass types, such as semi-woody biomass, straw and palm kernel shell [35,46,47].

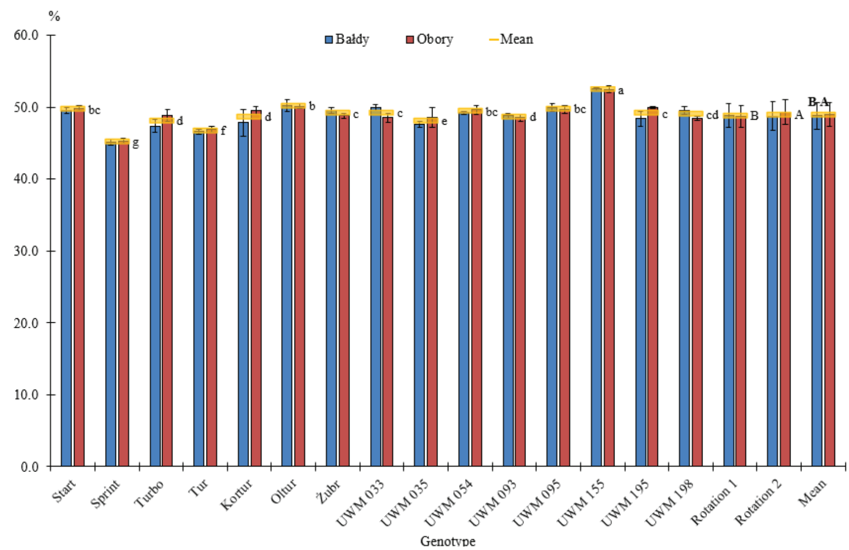


**Figure 1.** Moisture content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (error bars determine standard deviation; lower case letters a,b,c . . . denote homogeneous sets in Tukey's test for mean values calculated for genotypes regardless of the location; capital letters A,B denote homogeneous sets for mean values calculated for the harvest rotation; bold capital letters **A,B** denote homogeneous sets for mean values calculated for the habitats; ns denotes insignificant differences).

Fixed carbon and volatile matter content were determined to the greatest extent by the harvest rotation (20% and 26%, respectively) (Table 1). However, unlike for moisture content and ash content, an important role was played in the case of these two characteristics by other factors, such as the genotype (16% and 22%, respectively) and location (approx. 10%) and their interaction (9% and 19%, respectively). Therefore, it can be claimed that fixed carbon and volatile matter content were determined by all the main factors and their interactions and it is difficult to identify the factor with the greatest impact. The mean fixed carbon was 19.4% d.m. and it was slightly higher in the second harvest rotation and at Bałdy (Figure 3). Meanwhile, the mean value of this characteristic in the genotypes under study ranged from 18.8% d.m. to 19.7% d.m. The mean volatile matter content was 79.4% d.m. and it was slightly higher in the first harvest rotation and at Obory, and the maximum difference between the genotypes under study was 1.1 pp (Figure 4). The volatile matter content in willow biomass as determined in other studies ranged from 79% d.m. to over 83% d.m. [10,37]. It also lay within this range when determined for other willow species harvested in a three-year rotation [42].

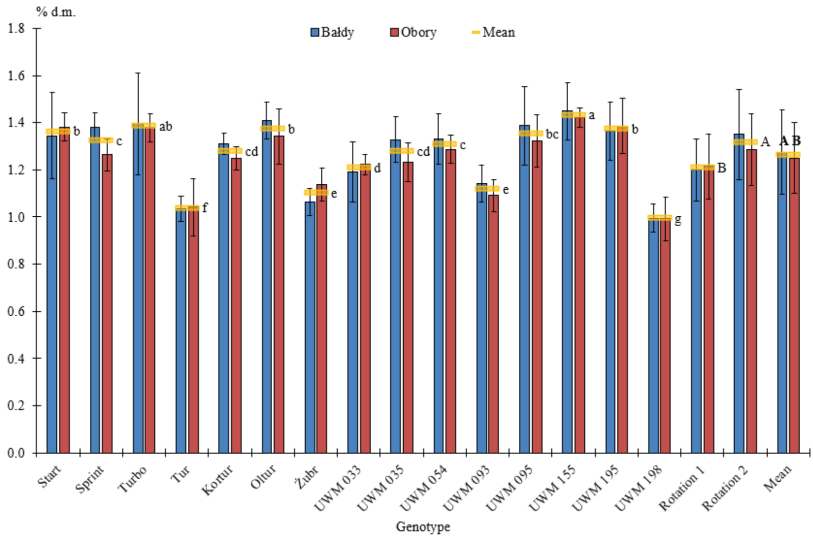


**Figure 2.** Ash content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

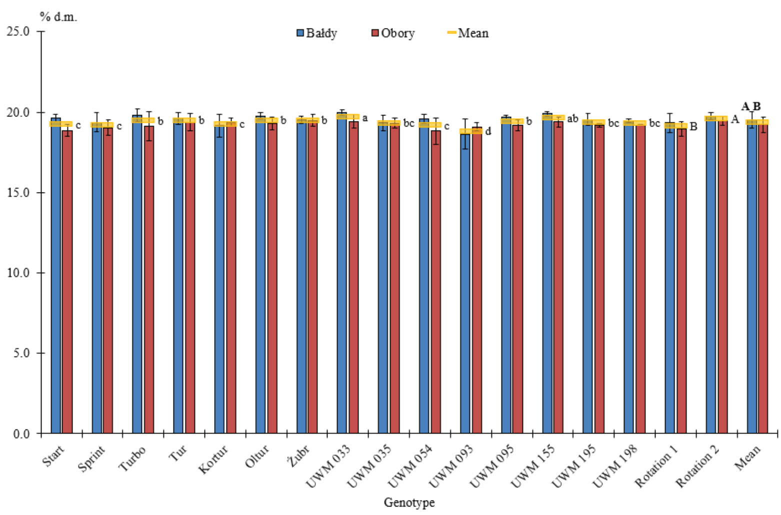


**Figure 3.** Fixed carbon content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

The analyses showed that HHV was determined to the greatest extent by location (49%), which was rather surprising. However, it appeared that the genotype (20%) also had a significant impact on this characteristic (Table 1). Different relationships were also observed in the case of the LHV, as this characteristic was found to be determined by the genotype to the greatest extent (75%), while the location determined it only by 8%. The mean HHV throughout the experiment was 19.53 MJ kg$^{-1}$ d.m., regardless of the location, genotype or harvest rotation. (Figure 5). The mean value of this characteristic for Bałdy was 19.68 MJ kg$^{-1}$ d.m. and it was higher than at Obory by 0.3 MJ kg$^{-1}$ d.m. Among the genotypes under study, the highest HHV was determined for the biomass of the UWM 093 clone of *S. acutifolia* (mean 19.79 MJ kg$^{-1}$ d.m.). It was lower by approx. 2% in the Żubr cultivar of *S. viminalis* and it was the lowest HHV among all the genotypes under study. Furthermore, the mean LHV, calculated from the HHV, moisture content and hydrogen content, was 8.20 MJ kg$^{-1}$ (Figure 6). However, it is noteworthy that the difference between the Sprint cultivar with the highest value of this characteristic (8.93 MJ kg$^{-1}$ *S. viminalis*) and the genotype with the lowest LHV (UWM 155 *S. dasyclados*) was nearly 17%. The mean LHV for biomass obtained at Bałdy was higher by approx. 3% compared to the mean value at Obory. The LHV determined in other studies for different willow genotypes harvested in 3-year rotations ranged from 7.7 MJ kg$^{-1}$ to 9.3 MJ kg$^{-1}$ [36,37]. Similar LHV was calculated for willow harvested in a 4-year and a longer, 7-year harvest rotation [10,36,38].

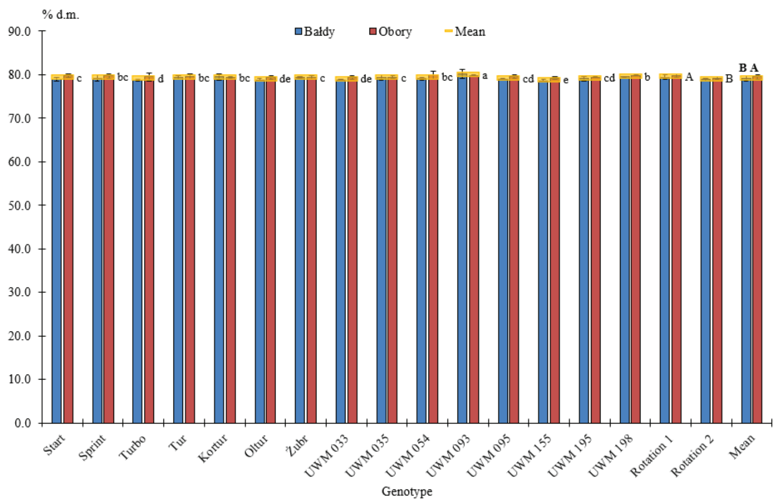


**Figure 4.** Volatile matter content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend see Figure 1).

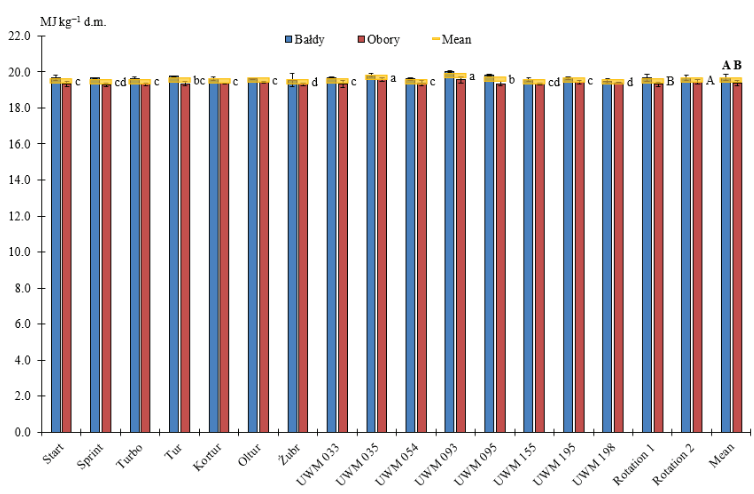


**Figure 5.** Higher heating value (HHV) of the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

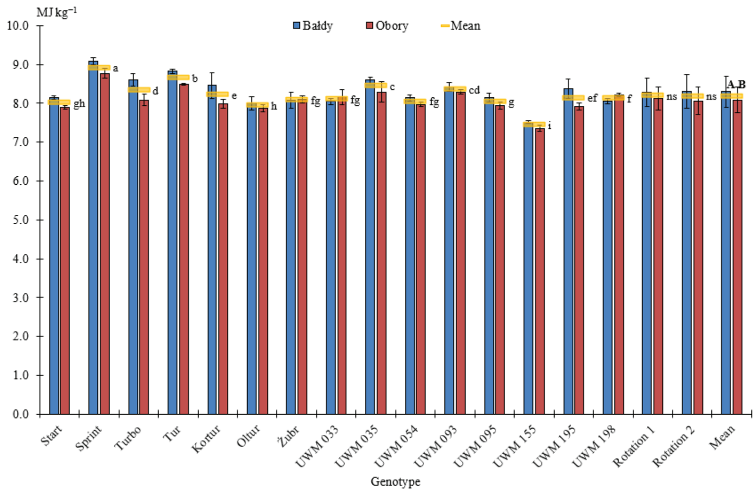


**Figure 6.** Lower heating value (LHV) of the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

### 3.2. Elemental Composition of Willow Biomass

The carbon (C), hydrogen (H) and nitrogen (N) contents in biomass were significantly differentiated by all three main factors (location, genotype, harvest rotation) and the interactions between them. The absence of any significant impact in the case of sulphur (S) was observed only for the harvest rotation (Table 2). In the case of C, the location had the greatest contribution to the variation of this characteristic (35%), followed by the genotype and interactions of these factors. The mean C content in biomass, regardless of the location, genotype and harvest rotation was 52.90% d.m. (Figure 7). It exceeded 53% d.m. in six genotypes, and it ranged from 52.3% to 52.9% d.m. in the other nine. Moreover, the mean C content in biomass obtained at Bałdy (53.3% d.m.) was higher by 0.9 pp compared to the biomass obtained at Obory. The mean content of C in willow biomass in a 3- and 4-year harvest rotation, as determined in other studies, was lower than in the current experiment and amounted to 51% and 49% d.m., respectively [36–38]. The carbon content determined in *S. alba* (50.2%) biomass in a 3-year rotation in another study was higher by 0.8 pp than in *S. viminalis* [42]. A similar mean C content (51% d.m.) was also found in willow biomass harvested in a 7-year rotation [10].

**Table 2.** Statistics *F* from the repeated measure variation analysis and the percentage share of effects in the total variation for the elemental composition of willow biomass.

| Source of Variation | *df* | C | | H | | S | | N | |
|---|---|---|---|---|---|---|---|---|---|
| | | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) | *F* | Share (%) |
| Location (Loc) | 1 | 480.8 ** | 35.4 | 140.8 ** | 11.1 | 257.9 ** | 17.7 | 903.3 ** | 17.9 |
| Rep(Loc) | 4 | 1.6 | 0.5 | 0.2 | 0.1 | 1.8 | 0.5 | 1.2 | 0.1 |
| Genotype (Gen) | 14 | 18.1 ** | 18.7 | 15.9 ** | 17.6 | 26.1 ** | 25.1 | 107.0 ** | 29.6 |
| Loc × Gen | 14 | 19.5 ** | 20.2 | 34.7 ** | 38.3 | 21.9 ** | 21.1 | 41.4 ** | 11.5 |
| Error 1 | 56 | - | 4.1 | - | 4.4 | - | 3.8 | - | 1.1 |
| Rotation (Rot) | 1 | 39.4 ** | 3.4 | 88.0 ** | 4.7 | 2.7 | 0.3 | 424.7 ** | 13.3 |
| Rot × Loc | 1 | 4.4 ** | 0.4 | 152.1 ** | 8.2 | 12.7 ** | 1.6 | 166.6 ** | 5.2 |
| Rot × Rep (Loc) | 4 | 0.2 | 0.1 | 1.2 | 0.3 | 1.1 | 0.6 | 2.5 | 0.3 |
| Rot × Gen | 14 | 5.1 ** | 6.0 | 10.8 ** | 8.1 | 8.1 ** | 14.2 | 28.4 ** | 12.4 |
| Rot × Loc × Gen | 14 | 5.4 ** | 6.5 | 5.6 ** | 4.2 | 4.6 ** | 8.0 | 15.5 ** | 6.8 |
| Error 2 | 56 | - | 4.8 | - | 3.0 | - | 7.0 | - | 1.8 |
| Total | | | 100.0 | | 100.0 | | 100.0 | | 100.0 |

Share (%); percentage share in the total sum of squares; ** $p < 0.01$.

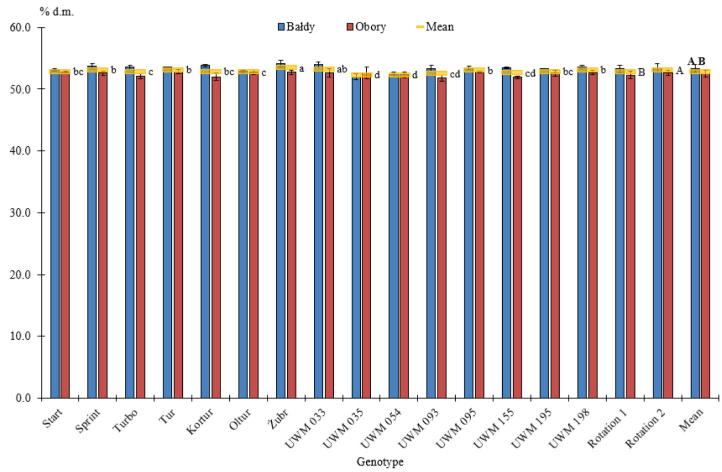


**Figure 7.** Carbon content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

The H content in biomass was determined to the greatest extent by the interaction of location and genotype (38%), followed by the genotype (18%) and location (11%) (Table 2). The mean H content in willow biomass was 6.23% d.m. (Figure 8). The biomass obtained at Obory contained more hydrogen by approx. 2% (6.31% d.m.) compared to the biomass obtained at Bałdy. Among the 15 genotypes under study, the mean value of this characteristic ranged from 6.03% d.m. to 6.43% d.m., for the genotypes of UWM 155 (*S. dasyclados*) and UWM 093 (*S. acutifolia*). It was also shown in other studies that the hydrogen content in willow biomass was close to, or exceeded, 6% d.m. [10,36–38].

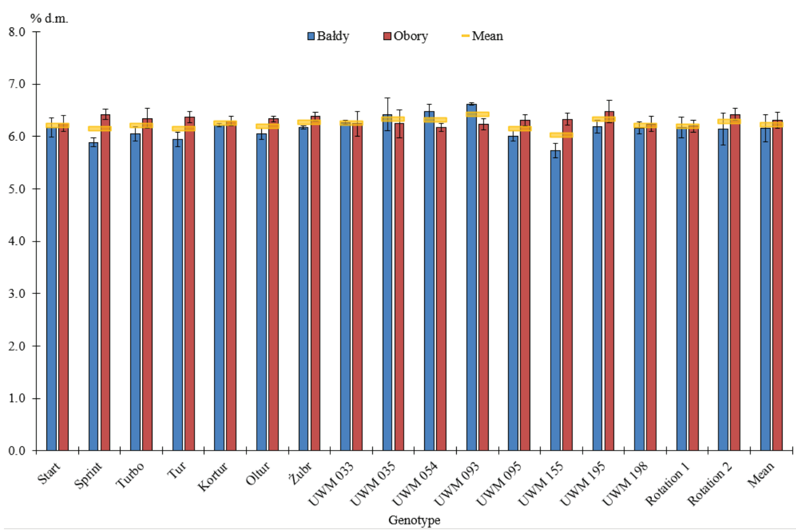


**Figure 8.** Hydrogen content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

The S content was determined to the greatest extent by the genotype (25%), followed by the interaction of location and genotype (21%) and by location (18%) (Table 2). The mean S content in the biomass was 0.032% d.m. (Figure 9). The sulphur content in the biomass at Bałdy (0.035% d.m.) was higher by approx. 19% than in the biomass at Obory. The values of this characteristic for the 15 genotypes under study ranged from 0.026 to 0.037% d.m., for the UWM 195 genotype (*S. fragilis*) and the Tur cultivar (*S. viminalis*) and the UWM 035 genotype (*S. pentandra*), respectively. This indicates that the differences in the sulphur content between the willow genotypes were rather large (up to 28%). The sulphur content in biomass determined in another study of the willow hybrid *S. trianda* × *S. viminalis* was ca. 0.03% d.m. [38]. More diverse values of this characteristic (0.014–0.048% d.m.) were found in studies of different willow genotypes harvested in a three-year rotation [37]. On the other hand, the mean S content in biomass obtained in a 7-year rotation was 0.039% d.m., ranging from 0.029% d.m to 0.052% d.m., for UWM 200 and the Turbo cultivar, respectively [10]. A still higher sulphur content (mean 0.070% d.m.) was determined in three-year biomass of the Inger cultivar willow grown at two sites in Denmark [33]. Moreover, this characteristic as measured in eight cultivars harvested at two different sites ranged from 0.055 to 0.082% d.m., for the Tordis and Terra Nowa cultivars, respectively.

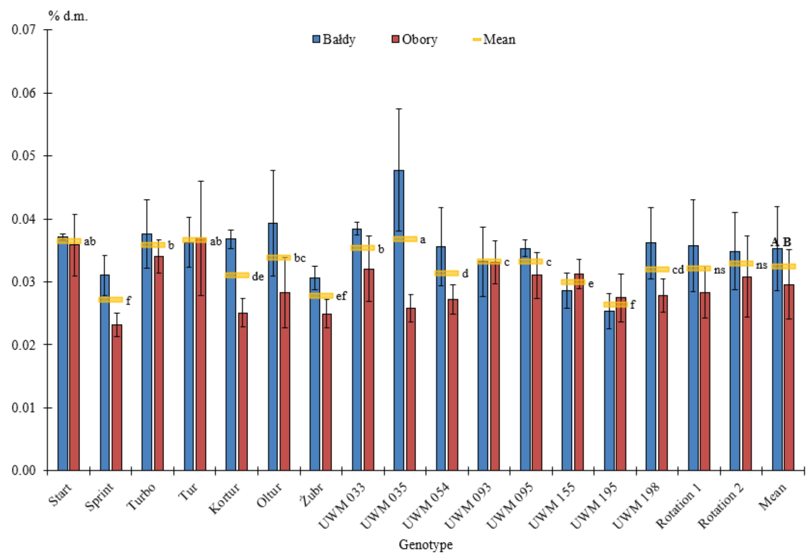


**Figure 9.** Sulphur content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

The N content in willow biomass was determined to the greatest extent by the genotype (30%), followed by location (18%) and harvest rotation (13%) (Table 2). The mean N content in biomass was 0.42% d.m. (Figure 10). The value of this characteristic was higher by approx. 16% in biomass obtained at Bałdy (0.45% d.m.) than at Obory. The values of this characteristic for the 15 genotypes under study ranged from 0.36% d.m to 0.51% d.m., for the Tur cultivar (*S. viminalis*) and the UWM 155 genotype (*S. dasyclados*), respectively. Therefore, the differences in the nitrogen content between the willow genotypes (29%) were high. Moreover, the willow biomass obtained in the second three-year harvest rotation (0.45% d.m.) contained more nitrogen by approx. 12% compared to the biomass harvested in the first rotation. The N content in willow biomass determined in other studies was also similar (0.46% d.m.) [38]. Furthermore, the N content in willow biomass harvested in a 3-year rotation in another study reached 0.61% d.m. [37]. Large significant differences in the nitrogen content (range 0.39–0.75% d.m.) in biomass of three-year old willow were also observed in Denmark between eight cultivars and two sites [33]. The mean N content in biomass harvested in a 7-year rotation was

0.32% d.m. [10]. Other studies also demonstrated considerable differences in the content of the assayed elements, both between sites and between cultivars and willow harvest rotations [48–52].

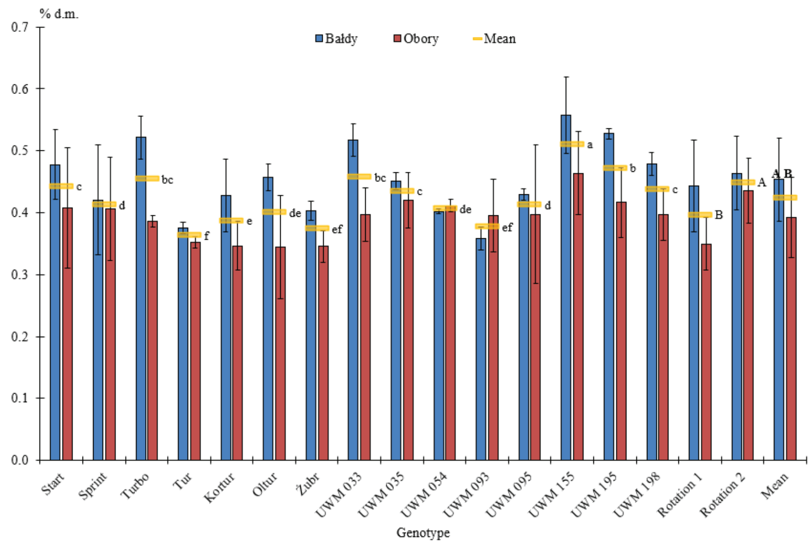


**Figure 10.** Nitrogen content in the biomass of 15 willow genotypes obtained at two locations in two consecutive three-year harvest rotations; (legend: see Figure 1).

### *3.3. Principal Component Analysis (PCA) and an Assessment of the Impact of the Factors under Analysis on Willow Biomass Properties*

The principal component analysis (PCA) used standardised values of all the biomass quality characteristics. The biplot showed that the willow genotypes grown at Bałdy are distinctly separated from those grown at Obory (Figure 11). This was caused by the first principal component PC1 which explained nearly 31% of the variation. The components included fixed carbon and the C and N contents, which had a positive sign of the factorial load (Table 3) and "pulled" nearly all the willow genotypes at Bałdy to the right of the graph. The opposite, left side of component PC1, with small exceptions, mainly included the genotypes growing at Obory, whose biomass contained high levels of hydrogen and volatile matter. It was found that these five biomass characteristics had a large strength of discrimination, i.e., separation of the two locations (sites). It is noteworthy that these characteristics had a great percentage share of the effects of the location × genotype interaction and in the principal effect of the location. The second principal component of the PCA is a purely genetic effect arising from the moisture and ash content in biomass and the LHV, which is negatively correlated with them. The effect of the PC2 component was based on the significant distinguishing of the genotypes at the locations under study. This principal component explained 24.3% of the total variation. The third principal component PC3 is an effect of the variation of HHV and sulphur content in biomass, which explained nearly 17% of the total variation. All three significant components PC1, PC2 and PC3 together explained 72% of the variation under analysis.

It is noteworthy that from among all the willow biomass characteristics, the sulphur content variation coefficient was the highest (20.8%) (Table 4). Among the principal factors under analysis, the sulphur content was differentiated to the greatest extent by location (16.9%), followed by rotation (13.3%) and genotype 10.8%. The variation coefficient for the nitrogen content in biomass was also high (17.2%). Moreover, the value order of the principal components under analysis was identical to the sulphur content. Ash content was the third biomass characteristic with a coefficient of variation above 10%. The coefficients of variation for the other characteristics under analysis were lower than 5% and the lowest values of this characteristic were calculated for volatile matter content.

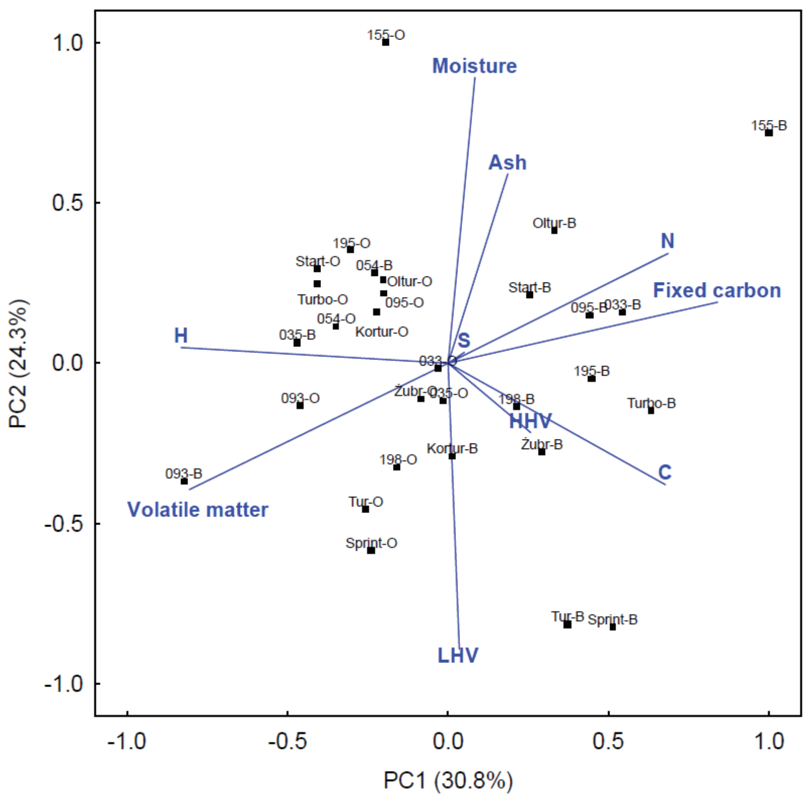


**Figure 11.** PCA biplot for tested willow biomass features. (To improve the readability of the chart, only the clone numbers are given without the note "UWM". The names of the varieties are given in full. "B" means Bałdy location, while "O" means Obory location).

**Table 3.** Factor loads of principal component analysis.

| Variable | PC1 | PC2 | PC3 |
|---|---|---|---|
| Moisture | 0.08 | **0.89** | −0.12 |
| Ash | **0.19** | **0.59** | 0.2 |
| Fixed carbon | **0.84** | 0.19 | 0.17 |
| Volatile matter | **−0.8** | −0.39 | −0.22 |
| HHV | 0.26 | −0.22 | **0.77** |
| LHV | 0.03 | **−0.89** | 0.31 |
| C | **0.68** | −0.38 | 0.15 |
| H | **−0.83** | 0.05 | 0.07 |
| S | 0.05 | 0.03 | **0.87** |
| N | **0.69** | 0.34 | 0.29 |
| Eigenvalue | 3.08 | 2.43 | 1.69 |
| Explained variance (%) | 30.8 | 24.3 | 16.9 |

Bold values indicate significance.

**Table 4.** Percentage coefficients of variation (CV) for location, genotype, harvest rotation and—in general—for the willow biomass characteristics under study.

| Variable | Location | Genotype | Rotation | Total |
|---|---|---|---|---|
| Moisture | 3.36 | 3.28 | 3.31 | 3.54 |
| Ash | 11.01 | 10.96 | 12.13 | 13.08 |
| Fixed carbon | 1.63 | 1.09 | 1.86 | 2.63 |
| Volatile matter | 0.46 | 0.34 | 0.55 | 0.70 |
| HHV | 0.97 | 0.51 | 0.58 | 1.10 |
| LHV | 4.42 | 4.12 | 4.13 | 4.62 |
| C | 1.21 | 0.62 | 0.74 | 1.38 |
| H | 2.99 | 1.56 | 2.02 | 3.60 |
| S | 16.89 | 10.77 | 13.31 | 20.84 |
| N | 13.36 | 9.64 | 12.94 | 17.15 |

## 4. Conclusions

The current study emphasised the significance of the impact of genotype (genetic factors), location (environmental factors) and harvest rotation and interactions of these factors on the variation of thermophysical properties and elemental composition of willow grown in the SRC system. Multidimensional analyses were conducted on a large number of biomass samples obtained from 15 genotypes grown at two different sites and harvested in two consecutive three-year harvest rotations. The genotype was found to largely determine the moisture content, ash content and the LHV. Therefore, it is noteworthy that to obtain willow biomass containing relatively low levels of ash and moisture and a high LHV, the right species, cultivars or clones need to be grown. In the current study, the lowest moisture content (and the highest LHV) was found in the biomass of *S. viminalis*. On the other hand, these characteristics were the least beneficial in the biomass of an *S. dasyclados* genotype. Moreover, in the case of LHV, the difference between these two genotypes was nearly 17% in favour of *S. viminalis*. The lowest ash contents were found in biomass of *S. triandra*, the Tur and Żubr cultivars of *S. viminalis* and a genotype of *S. acutifolia*, which contained a lower level of ash compared to the other genotypes. However, the highest value of this characteristic was again found in the biomass of a *S. dasyclados* clone. The location of the plantation and the local environmental conditions, as well as the genotype and the interactions of these factors may have a significant effect on the elemental biomass composition (C, H, N, S content). Therefore, one can expect a variation in the individual element contents in biomass obtained at different locations despite the fact that the same willow species, cultivars or clones are grown there. Therefore, it can be claimed the genetic diversity of willow, as well as the possibility of modifying the biomass composition by plant management show that these factors can be employed to optimise the quality of biomass obtained from an SRC plantation. However, to achieve it, more research is necessary, which will involve cooperation and information exchange between breeders of new cultivars, biomass producers and biomaterial end users, both in Poland and other countries and regions of the world, where willow biomass is cultivated and utilised.

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# Willow Biomass Crops Are a Carbon Negative or Low-Carbon Feedstock Depending on Prior Land Use and Transportation Distances to End Users

**Sheng Yang [1], Timothy A. Volk [2,*] and Marie-Odile P. Fortier [3]**

1 Department of Environmental Resources Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, USA; sunrise322@gmail.com
2 Department of Sustainable Resources Management, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, USA
3 Department of Civil and Environmental Engineering, University of California, Merced, CA 95343, USA; mfortier2@ucmerced.edu
* Correspondence: tavolk@esf.edu; Tel.: +1-315-470-6774

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**Abstract:** Few life cycle assessments (LCAs) on willow biomass production have investigated the effects of key geographically specific parameters. This study uses a spatial LCA model for willow biomass production to determine spatially explicit greenhouse gas (GHG) emissions and energy return on investment (EROI), including land use conversion from pasture and cropland or grassland. There were negative GHG emissions on 92% of the land identified as suitable for willow biomass production, indicating this system's potential for climate change mitigation. For willow planted on cropland or pasture, life cycle GHG emissions ranged from −53.2 to −176.9 kg $CO_{2eq}$ $Mg^{-1}$. When willow was grown on grassland the projected decrease in soil organic carbon resulted in a slightly positive GHG balance. Changes in soil organic carbon (SOC) associated with land use change, transportation distance, and willow yield had the greatest impacts on GHG emissions. Results from the uncertainty analysis exhibited large variations in GHG emissions between counties arising from differences in these parameters. The average EROI across the entire region was 19.2. Willow biomass can be a carbon negative or low-carbon energy source with a high EROI in regions with similar infrastructure, transportation distances, and growing conditions such as soil characteristics, land cover types, and climate.

**Keywords:** willow biomass; soil organic carbon; life cycle assessment; spatial analysis; greenhouse gas emissions; energy return on investment

## 1. Introduction

Over several decades in North America and Europe, short rotation woody crops (SRWC), such as willow and poplar, have been increasingly recognized as important renewable energy sources because of their multiple environmental and rural development benefits. As a low-carbon energy source, willow biomass is helpful in decreasing greenhouse gas (GHG) emissions when it is used to replace fossil fuels, benefitting local rural communities by providing employment and improving energy independence, and providing multiple ecosystem services by decreasing soil erosion, improving water quality, and increasing biodiversity [1–3]. For example, willow can support biodiversity by functioning as natural habitats or as ecological corridors connecting patches in increasingly fragmented landscapes in the US [4]. In some situations, there are concerns that large scale deployment of willow could impact landscape aesthetics and diversity if a large proportion of one particular land type, such as natural grassland, in a given areas is converted to willow. The most recent US Billion-Ton report projected that 411 million to 736 million dry tons of energy crops, including willow, could be produced annually in 2040 with a price of $60 per dry Mg or less under baseline and high-yield case assumptions, respectively [5]. New York State recently adopted aggressive goals to reduce greenhouse gas emissions by 85% by 2050 [6,7].

Environmental indicators of renewable energy systems include GHG emissions, productivity of bioenergy crops [8], and energy return on fossil fuel inputs. Life cycle assessment (LCA) is a widely accepted method used to quantify the environmental impacts for processes or products across their life cycle. LCA is a tool used to assess the GHG emissions and other environmental impacts of bioenergy crop production including cultivation, harvesting, and transporting biomass to end users [9–11]. In addition, in the US Energy Investment and Security Act (P.L. 110–140, subtitle A), LCA has been identified as the standard methodology to determine if biofuels meet requirements for GHG reductions required for the National Renewable Fuel Standard.

In North America and Europe, a large number of studies have used LCA to evaluate environmental impacts and energy return on energy investment (EROI) of willow biomass crop production. Djomo et al. (2011) reviewed 26 papers and reported that the range of EROI for willow was between 3:1 and 16:1 and GHG emissions ranged from 0.7 to 10.6 g $CO_2$ $MJ^{-1}$ at the farm gate [9]. Since 2011, additional LCAs on willow crop production systems have been conducted for the US [1], Asia [12], and Europe [13–15]. The EROI in these studies ranges from 11.0:1 to 43.4:1 for willow biomass delivered to facility that converts the biomass to bioenergy, biofuels, or bioproducts.

The life cycle GHG emissions range from 33.7 to 100 kg $CO_{2eq}$ per oven dry Mg of willow chip production including delivery to power plants without including belowground carbon sequestration, or changes in soil organic carbon (SOC) associated with land use change (LUC) [10,16,17]. However, it has been demonstrated that belowground carbon, (i.e., carbon sequestered in the coarse roots and stool) is substantial [18] and can reduce GHG emissions by as much as 138.4 kg $CO_{2eq}$ per Mg biomass [1]. Results of SOC changes under willow cultivation are inconclusive to date in New York State because changes have only been measured at a limited number of sites [19]. Recently, detailed studies have been conducted by Argonne National Laboratory to predict SOC change associated with LUC using the CENTURY model, thus providing estimates of this critical component of GHG emissions of bioenergy crop feedstock production [20,21]. However, LCAs that incorporate SOC changes in willow feedstock production have been lacking in the US.

In previous LCAs that did not include changes in SOC, the three largest contributors to the life cycle GHG emissions are fertilization, transport, and harvesting [11,14,16,17,22–24]. In two LCAs that include SOC change in Sweden, yield was found to be the most important factor for climate change mitigation [13,14]. These four factors are subject to a large magnitude of uncertainty in LCA of willow production in different geographical locations [1,14,20,21]; therefore, incorporating spatial variability in LCA modeling is one approach to address this uncertainty. An LCA that considered spatial variability and changes in SOC content had an average EROI of 30:1 and determined that 84.3 Mg carbon $ha^{-1}$ would be sequestered in the soil during a 100-year time frame in Sweden [14]. However, studies with SOC change from land use changes with finer spatial scales that can incorporate more variability on landscape levels are lacking in the US and other parts of the world.

The objectives of this study were to conduct spatial LCA of willow biomass production and delivery of chips to an end user including SOC change and location-specific modeling of GHG emissions and fossil fuel consumption to investigate variations across five counties in central and northern New York State. In this study, biomass growth data from 480 ha willow biomass crops and other recently collected primary and GIS data from the region were used as data sources to create an LCA model of willow biomass production that yields cradle-to-gate GHG emissions and EROI.

## 2. Materials and Methods

### 2.1. Scope of LCA and Life Cycle Inventory

A baseline LCA model for willow supply chain system was generated in SimaPro 8.2 using inventories from the Ecoinvent 3.3 and USLCI databases. The goal of the LCA was to estimate GHG emissions and the energy balance of willow production in New York State including direct land use change, with willow cultivation starting on land currently classified as either pasture or cropland as separate scenarios. The scope of the LCA includes the nursery and the main production system as two stages of the supply chain and ends with the delivery of willow chips to the plant gate of an end user (Figure 1). Within the boundaries for this study only direct land use change (i.e., when land used for a specific purpose like crop production is converted to another use, willow production in this paper) is considered. This study assesses the global warming impact and energy balance, because these two attributes are critical to evaluate willow biomass as a source of renewable energy. The geographic boundaries of this analysis include suitable lands for growing willow in five counties in central and northern New York State (NY), namely Oneida, Jefferson, Oswego, Lewis, and St. Lawrence (Figure 2), where two facilities have used willow for a portion of their fuel supply for power and heat production. The temporal boundaries cover seven 3-year rotations of growing and harvesting willow crop within 22 years, including one site preparation year. Data supports consistent willow production over seven rotations [18] and this timespan has been used for previous LCAs [1] in the region. The LCA includes all equipment usage and materials consumption, e.g., tractor use and diesel.

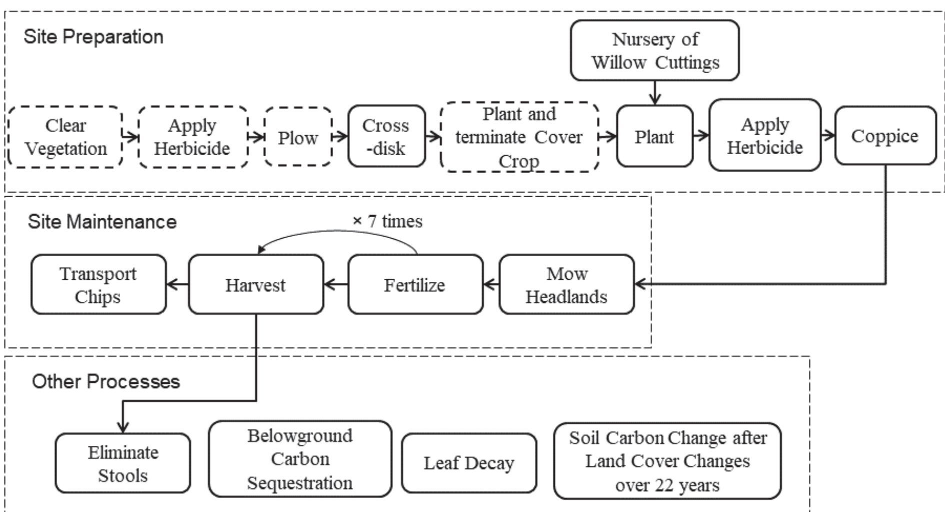


**Figure 1.** System diagram of willow production supply chain with boundaries and major processes affecting greenhouse gas (GHG) emissions and energy consumption. Site preparation and planting processes occur once in the lifetime of the willow crop.

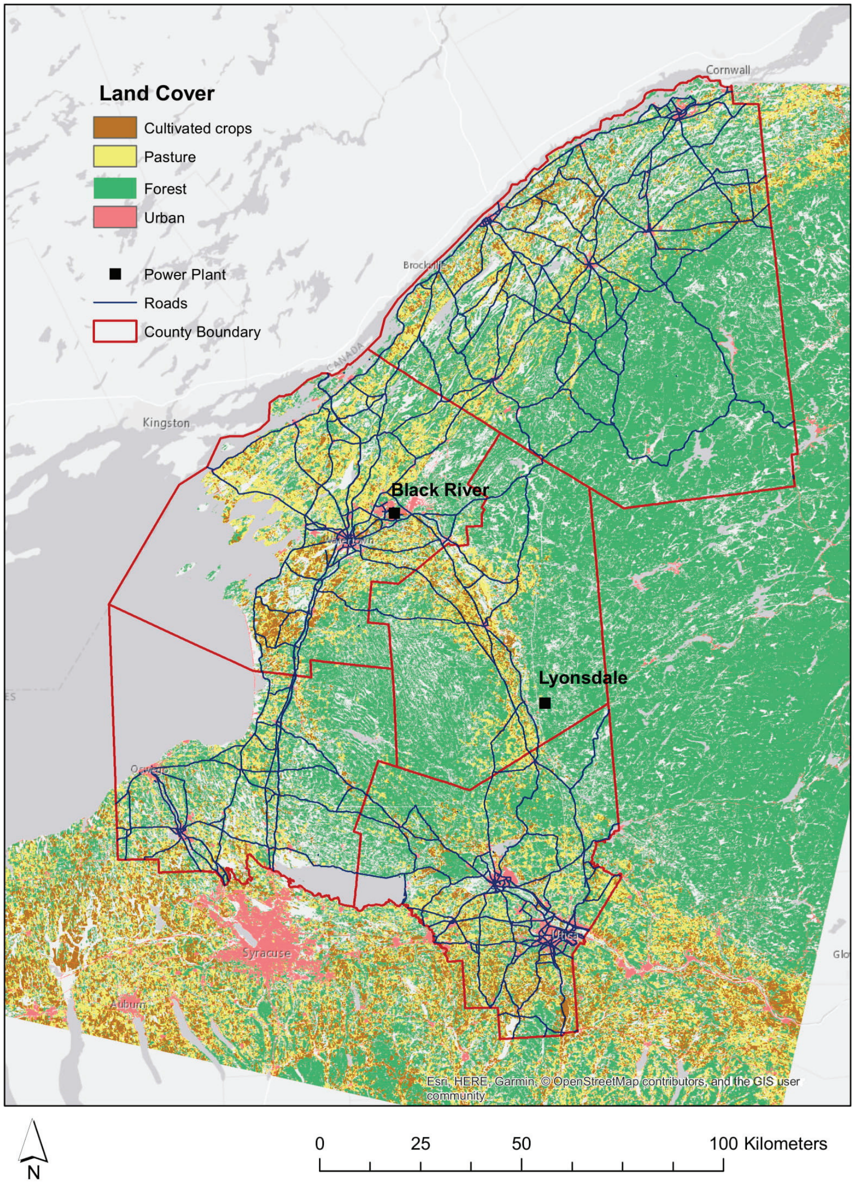


**Figure 2.** Five counties in central and northern New York State (Jefferson, Lewis, Oneida, Oswego, and St. Lawrence) where the spatial life cycle assessment (LCA) was conducted. The two power plants that have used willow as a portion of their fuel source shown as squares, Black River and Lyonsdale are owned by ReEnergy. Only primary roads are shown in the figure.

The functional unit of this LCA is one oven-dry Mg of willow biomass chips delivered to an end user. This function unit was chosen because mass is commonly used in the field and is used in willow LCA [1,4,9] which is an important factor in this study. This functional unit choice matches the cradle-to-gate scope of this LCA and allows for the results to be subsequently used in future LCAs that extend the scope to bioenergy production.

All life cycle inventories used in the LCA model are from the Ecoinvent database and USLCI database (Table S1), including mowing, fertilizing, planting, harvesting, and transporting chips, with necessary adjustments according to field operations. For example, the harvesting process in willow production is modeled by computing hourly diesel consumption (95.4 L $h^{-1}$ [25]) and including forestry harvester production adjusted for a total of 5000 working hours of the forage harvester from interviewing an equipment expert. The planting process in Ecoinvent 3 has the planting rate of 5 tractor hours $ha^{-1}$ compared to 1 h $ha^{-1}$ that has been measured for planting willow in this region [26]. Therefore, a ratio of 0.2 was applied to the planting process in Ecoinvent 3 to represent the process of planting willow cuttings. The baseline estimates of environmental impacts in kg $CO_{2eq}$ of these processes were calculated by the EPA TRACI 2.1 life cycle impact assessment method using SimaPro 8.2 based on the mean values of modeled input parameters. The baseline energy balance in MJ (nonrenewable fossil fuels) for each process was computed by the cumulative energy demand life cycle impact assessment method. The energy content of willow biomass, GHG emissions per unit energy consumption, e.g., $CO_2$ per MJ, and EROI were based on the higher heating value (HHV) of 19.6 GJ $Mg^{-1}$ of willow biomass [27].

The key parameters determining the energy and material consumption of the system are listed in Table 1. The baseline values are used for calculations for each field. The sensitivity analysis of the model was conducted using Python code for key parameters that have at least 10% contribution to the total impact or have impacts on multiple processes listed in Table 1 (e.g., yield, which affects both transport and belowground biomass). The process of sensitivity analysis starts with varying one parameter at a time while keeping all the other parameters constant, and the resulting ranges of environmental impact values represent the level of sensitivity of the LCA results to the specific parameter. Sensitivity analyses were conducted separately for pasture and cropland scenarios in the five counties. The minimum and maximum parameter values are 80% and 120% of baseline values to place a benchmark for comparisons among parameters, except for the wagon number, with a minimum of one and a maximum of three, and transportation distances.

**Table 1.** Modeled input parameters for baseline LCA and sensitivity analysis.

| Parameter | Minimum | Baseline | Maximum |
|---|---|---|---|
| Yield (Mg $ha^{-1}$) [1] | 225.1 | 260.3 | 295.65 |
| Headland (as % of total land) | 8% | 10% | 12% |
| Urea fertilizer (kg $ha^{-1}$) | 89.68 | 112.1 | 134.5 |
| Wagons with tractor ($field^{-1}$) | 1 | 2 | 3 |
| Moisture content (%) [27] | 35.2 | 44.0 | 52.8 |
| Leaf nitrogen (%) [28] | 1.85 | 2.32 | 2.78 |
| Threshold harvesting rate (ha $h^{-1}$) [2] | 1.40 | 1.75 | 2.10 |
| Transport distance Jefferson (km) [3] | 4 | 31 | 65 |
| Transport distance Lewis (km) | 1 | 26 | 52 |
| Transport distance Oneida (km) | 13 | 62 | 95 |
| Transport distance Oswego (km) | 53 | 90 | 124 |
| Transport distance Oswego (km) | 34 | 84 | 145 |

[1] For seven 3-year rotations [1]. [2] Values represent the threshold speed of harvester where maximum throughput is reached [29]. [3] GIS analysis of road network in Jefferson County was used for the base case analysis. Distances for other counties were used for sensitivity and Monte Carlo analysis. Transportation distances are one way trips and are doubled when included in analysis.

Uncertainty analysis aims to include all factors' probability distribution functions (PDFs) at once to determine the PDF of LCA results. Uncertainty analysis was also conducted in Python code to evaluate the probability of environmental impacts when the uncertainties of all key parameters are included in the model. The code randomly drew parameter values from uniform distributions and ran the model 10,000 times to obtain resulting PDFs for each scenario. Each parameter was assumed to be uniformly distributed and the ranges of variation for each parameter were determined based on expert knowledge, GIS analysis, and the existing scientific literature (Table 1).

*2.2. Willow Supply Chain System*

To accurately depict the system for this LCA, a comprehensive list of field operation steps and processes in the willow production supply chain system as well as details of each process, e.g., application rates, machineries, material, and fuel consumption, were obtained from previous literature or through interviewing experts of willow biomass production who are working on the 480 ha willow biomass crops in central and northern NY (Figure 1, Table S1). The willow production system starts with a nursery system of willow cuttings as described in a previous study [1]. For existing grassland, the main production system starts with site preparation in the first and second year of establishment, including clearing existing vegetation, herbicide, plowing, disking, rock-picking, sowing and terminating cover crop, and planting willow cuttings. For a conservative estimate, all grassland parcels were assumed to have lower soil pH values and rocks so lime additions and picking rock were applied in these parcels. For cropland, most site preparation steps are not necessary except cross-disking. The willow shoots are coppiced after the first growing season. At the end of every 3-year rotation, willow stems are harvested with a single pass cut and chip system, blown into wagons, loaded to trucks, and transported to end users. There are seven consecutive 3-year rotations modeled, and following the final harvest, the re-sprouting crop is sprayed with herbicide and the stools are ground down. Fertilizer is applied at 100 kg N $ha^{-1}$ in urea once every 3 years at the beginning of each rotation. Headlands around the field are mowed annually but there are no other regular field activities (Figure 1).

The nitrous oxide emissions from leaf decay are calculated based on the method by the Intergovernmental Panel on Climate Change (IPCC) 2006 which takes into account the total amount of leaf litter and the nitrogen content in leaf biomass assuming that 1% of leaf biomass leads to nitrous oxide emissions over 22 years [30]. In addition, nitrous oxide emissions were computed as 1% of applied fertilizer, i.e., 1 kg nitrous oxide per 100 kg N applied in the field and of N contributed in leaf fall. The amount of N contributed from foliage was calculated from leaf biomass based on the leaf/shoot biomass ratio, aboveground biomass yield, and N concentration reported by Sleight et al. (2015) [31]. In addition, the amount of belowground carbon sequestration is obtained by applying the root/shoot ratio by Sleight et al. (2015) and using the aboveground biomass yield [31]. For example, out of an entire willow plant, shoots comprise 50.8% of biomass, whereas aboveground stool, belowground stool, and coarse root are 30.7% biomass. This results in a root/shoot ratio of 0.6 and belowground biomass of 18 Mg/ha including coarse roots and stools given an aboveground yield of 30 Mg $ha^{-1}$ in a rotation. Carbon sequestration in fine roots cycles several times per year so it is not included in the belowground carbon pool [18]. The root/shoot ratio in Sleight et al. (2015) is based on the data from the third year of the third rotation [31]. The amount of root biomass usually levels off or may slightly increase after the third rotation or 12–14 years [32], so belowground biomass is no longer accumulated after the third rotation, which leads to a conservative estimate of belowground carbon in this study. Finally, after seven 3-year rotations, the willow crop is ended by harvesting, applying herbicide, and grinding the stools into the soil; therefore, roots and belowground stools are counted as additions to belowground carbon sequestration within the time scope of this study.

In addition, the analysis includes the processes of SOC changes associated with direct land use change (LUC). Indirect LUC is not considered in this study because relevant factors, such as policy, markets, food production technology improvement, and other factors that impact indirect LUC, are outside the scope of this study. The amount of SOC change was determined for four scenarios separately including two starting land cover categories, namely grassland and cropland, and two soil depths, 30 and 100 cm, corresponding to the SOC data available from Qin et al. (2016a) and Qin et al. (2016b) [20,21]. This SOC data from Argonne National Lab is based on 30-year annualized change from 2011 to 2040 in Mg C $ha^{-1}$ $yr^{-1}$, and we applied this SOC rate over 22 years, which is the temporal scope of this study. In addition, there are multiple scenarios in the SOC data. For example, Qin et al. assume that the land was either in grassland or pasture for 130 years prior to being converted to willow, and in yield-increase or yield-constant scenarios [20,21]. In this study, we averaged data over all scenarios in the two LUC scenarios of cropland and grassland to willow. Although there are spatial resolution differences between SOC data and land use data, the current resolution of SOC data, which is at the county scale, is sufficient for between county variation analysis. We included an indication of the spatial resolution of the different datasets (Table 2). In all cases, we selected the finest scale resolution available to capture the variation of the changes in GHG and EROI across the landscape. The soil change data from Qin et al. (2016 a & b) and Dunn et al. (2014) is available at the county level for two different land use change scenarios—from annual crops to willow or from grassland/pasture to willow—and for two different soil depths—to 30 cm and to 100 cm depths [20,21,33]. We applied these results using the land uses that were identified using the 2011 National Land Cover Database (NLCD) data, which is available at a resolution of 30 m, to allow us to look at potential land use change impacts at a resolution finer than the county.

**Table 2.** Raster data source, spatial resolution, and source used in land use change analysis.

| Data | Data Source | Spatial Resolution | Source |
|---|---|---|---|
| Land use cover | National Land Cover Database (NLCD) | 30 m | [34] |
| SOC change associated with land use change | Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) | County | [20,21,33] |
| Soils data used for parcel selection and NCCPI index for yield estimates [1] | Soil Survey Geographical Database (SSURGO) | 10 m | https://datagateway.nrcs.usda.gov/ |

[1] NCCPI is the National Commodity Crop Productivity Index.

### *2.3. Identification of Suitable Lands for Willow Crops in GIS*

The GIS analysis for the identification of suitable lands for potential willow crops is based on multiple datasets to select and process parcels through a range of criteria. First, land cover information was obtained from the 2011 NLCD [34], which has an overall accuracy of 88% on level I Anderson classification [35]. Second, the slopes of parcels were derived from elevation data with 1 arc-second or approximately 30 m resolution developed by the U.S. Geological Survey (USGS) National Geospatial Program (https://www2.usgs.gov/ngpo/). Third, hydrology data were derived from Cyber Security and Critical Infrastructure Coordination (CSCIC) Accident Location Information System (ALIS) database (https://gis.ny.gov/gisdata/) including both linear and areal maps representing rivers and lakes, respectively. Fourth, the soil data were derived from the SSURGO soil database including soil attributes such as soil types and productivity in a 10 m resolution raster map covering New York State. Fifth, tax parcel data were obtained from property tax offices in each county in vector format with land use code and polygon representing land use types and boundaries for each tax parcel. Finally, the road network data in New York State were derived from the Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset containing primary and secondary roads available from the US Census Bureau. Spatial resolutions of raster data are summarized in Table 2. SSURGO soil data of 10 m resolution was generalized to 30 m to conform to the spatial resolution of land cover, elevation, and slope data. All resulting data layers were averaged and applied within parcel boundaries. In addition, soil carbon data were applied to parcels based on which county a parcel is located. These data were processed using the Spatial Analyst toolbox in ArcGIS 10.1 developed by Environmental Systems Research Institute, Inc. (Redlands, CA, USA). The suitable lands for willow crop in this study are generated based on multiple criteria regarding land cover, land use classes, slope, water areas, and spatial connectivity (Figure S1). This method improved the GIS model for generating suitable lands in Castellano et al. (2009) by excluding scattered lands less than 8 ha after examining spatial continuity [36]. The suitable lands also excluded slopes greater than 8% due to limitations for forage harvesters that are used to harvest willow and water/wetland areas. The resulting suitable lands include four land cover classes of shrub/scrub, grassland, pasture, and cropland in tax parcels of agricultural land use corresponding to land cover class codes of 52, 71, 81, and 82, respectively, in Anderson land cover classification system in the NLCD dataset. The land cover class for a given parcel is determined by majority rule; the parcel is assigned to the land cover class with highest proportional coverage in the parcel. The transportation distance from suitable lands to one of two end users in the region was calculated based on road network data of primary and secondary roads where trucks are allowed using Network Analyst in ArcGIS. The biomass yields of willow in suitable lands in each parcel were estimated by the equation in the Renewable Fuels Roadmap Appendix E and scaled to dry Mg $ha^{-1}$ based on the National Commodity Crop Productivity Index (NCCPI) contained in SSURGO soil layers [37]. The equation is based on yield data from the field and can be validated. NCCPI applies natural relationships of soil, landscape, and climate factors to model the productivity of commodity crops. The equation (1) for estimating willow yield is

$$\text{Yield (ODT ac}^{-1}\text{ yr}^{-1}) = (50.5 + 119 \times \text{NCCPI} + 1.275 \times 5) \times 0.028 \times 2 \times 0.845 \times 0.9273, \quad (1)$$

where mean NCCPI values of each parcel were input from soil data layer and utilized in the equation to provide the amount of oven dry ton (ODT) willow biomass per year per acre. NCCPI was used to estimate willow yields because the SSURGO data is available at a finer resolution than other yield recent yield estimates at a coarser scale [38].

The maps of land cover changes were generated by comparing original land cover maps with the suitable lands to examine types of land covers in each suitable parcel to be converted to willow. The land cover information is necessary to determine SOC change after willow establishment due to different rate of SOC change in conversion of grassland and cropland [20,21] and used to allocate site preparation activities. The resulting maps of land cover change, biomass yield, and transportation distance for suitable parcels set the stages for the LCA scenarios.

### *2.4. LCA Modeling on Landscape Scales*

The LCA model in this study incorporates spatial variations of input parameters based on the GIS analysis results. The LCA model includes parameters with high spatial variability including (1) willow yield, (2) transportation distance from farm gate to power plants, (3) the land use conversion process when establishing willow crops related to different site preparation processes, and (4) SOC change in grassland and cropland. For SOC change modeling, the grassland case includes land designated as shrub and grassland in NLCD data, and the cropland case includes pasture and cropland in NLCD data. The annual SOC change rate is shown in Table 3, in which SOC changes were modeled separately for the five counties over 22 years. We applied Argonne's work as our input data shown in Table 3 and averaged it by the willow production over 21 years in the two LUC scenarios (grassland to willow and cropland to willow) in two soil depths of 30 and 100 cm. For example, in the original Argonne data sets, Jefferson county in New York State has −0.19 and −0.31 Mg C $ha^{-1}$ $yr^{-1}$ for yield increase and yield constant scenarios, respectively, for pasture to willow LUC. The average of the two is a loss of soil carbon at the rate of −0.25 Mg C $ha^{-1}$ $yr^{-1}$, which is the rate used in our model. The one-way transportation distance from each parcel to the closest end user was doubled in the LCA model to account for a roundtrip to and from the end user. These parameters vary across tax parcels and by land cover types; therefore, separate baseline LCA scenarios were analyzed for each parcel across the five counties to determine variations of environmental impacts within the counties. In addition, spatial variations were also incorporated in the sensitivity analysis of the LCA model. Sensitivity analysis and uncertainty analysis were conducted separately for each of the five counties.

**Table 3.** Soil organic carbon (SOC) annual change rate (Mg C $ha^{-1}$ $yr^{-1}$) in four scenarios of various soil depths and land cover classes from [20,21]. The rates were applied across 22 years. Cropland includes pasture and cropland land cover in National Land Cover Data base (NLCD).

| County | SOC Annual Change Rate (Mg C $ha^{-1}$ $yr^{-1}$) | | | |
|---|---|---|---|---|
| | 30 cm Soil Cropland | 30 cm Soil Grassland | 100 cm Soil Cropland | 100 cm Soil Grassland |
| Jefferson | 0.24 | −0.25 | 0.37 | −0.35 |
| Lewis | 0.34 | −0.43 | 0.46 | −0.58 |
| Oneida | 0.32 | −0.29 | 0.47 | −0.41 |
| Oswego | 0.31 | −0.29 | 0.45 | −0.41 |
| St. Lawrence | 0.19 | −0.19 | 0.30 | −0.27 |

## 3. Results

### 3.1. Baseline LCA Results

The baseline LCA results show differences in the life cycle GHG emissions in multiple scenarios of land cover and soil depths. Using the baseline parameters in Table 1, the life cycle GHG emissions of producing and delivering 1 Mg biomass are 27.7 kg $CO_{2eq}$ on grassland converted to willow including SOC change within 30cm soil depth over 22 years (Figure 3). The number decreases to −126.8 kg $CO_{2eq}$ $Mg^{-1}$ biomass (a net sequestration of carbon for the cradle-to-gate system) when willow is grown on cropland or pasture due to the different SOC change rate in 30-cm soil. The difference between cropland and pasture, due to less site preparation in cropland, is 2.43 kg $CO_{2eq}$ $Mg^{-1}$, which is minor compared with the SOC change difference. For a 100-cm soil depth, the total life cycle GHG emissions are 58.7 kg $CO_{2eq}$ $Mg^{-1}$ for grassland and −167.1 kg $CO_{2eq}$ $Mg^{-1}$ for cropland. The increased magnitudes are the results of higher rates of SOC change in deeper soil. Based on the energy content of 19.6 GJ $Mg^{-1}$ for willow biomass [27], the emission factor, or amount of GHG emissions per GJ, is 1.4 kg $CO_2$ $GJ^{-1}$ for the 100-cm grassland scenario and it is −6.5 kg $CO_2$ $GJ^{-1}$ for the 100 cropland scenario. The energy consumption for the production process in grassland is 969.6 MJ for 1 Mg biomass (Figure S2) and the net EROI is 19.2. For cropland, this number decreased to 937.9 MJ for 1 Mg biomass and the EROI increased to 19.8 due to fewer steps in the site preparation process.

Transportation is the largest energy investment in the system, accounting for 540.3 MJ for 1 Mg biomass which is 55.7% of total energy consumption of the grassland scenario (Figure S2), for the 62-km roundtrip to and from the end user which is the average distance in Jefferson County (Table 1). Harvesting and fertilizing are the next two largest energy inputs, accounting for 139.8 and 164.6 MJ $Mg^{-1}$, or 14% and 17% of the total energy consumption of grassland scenario, respectively.

### 3.2. Spatial LCA Results across the Landscape

There are 9718 tax parcels (210,799 ha) suitable for growing willow in the five counties in central and northern NY (Table S2). Among these suitable parcels, pasture and cultivated cropland are the most common types and comprise the largest areas in all five counties, totaling 9018 parcels and occupying 88.7% or 186,870 ha of total suitable area. Among the five counties, Jefferson County and Oneida County showed the highest potential yield in pasture/cropland with a mean estimated yield of approximately 12.1 and 12.0 Mg $ha^{-1}$ $yr^{-1}$, respectively (Table S3). Lewis County and Oswego County have lower estimated yields on pasture/cropland with mean values of 10.8 and 11.3 Mg $ha^{-1}$ $yr^{-1}$, respectively. Within each county there are considerable variations of NCCPI values ranging from 0.03 to 0.96 in both grassland and cropland, reflecting various soil conditions, climate, water availability, and landscape values (Table S4). The estimated yield from NCCPI showed that cropland, i.e., pasture and cultivated crop in NLCD, on average has a 1 Mg $ha^{-1}$ $yr^{-1}$ higher yield of willow biomass than grassland, i.e., shrub and grassland in NLCD (Table S3) which still showed high potential with yields around 10 Mg ha$^{-1}$ yr$^{-1}$. These estimated numbers are consistent with measured yield numbers in recent trials in the area and with other modeled yield numbers for willow in the US [28,38,39].

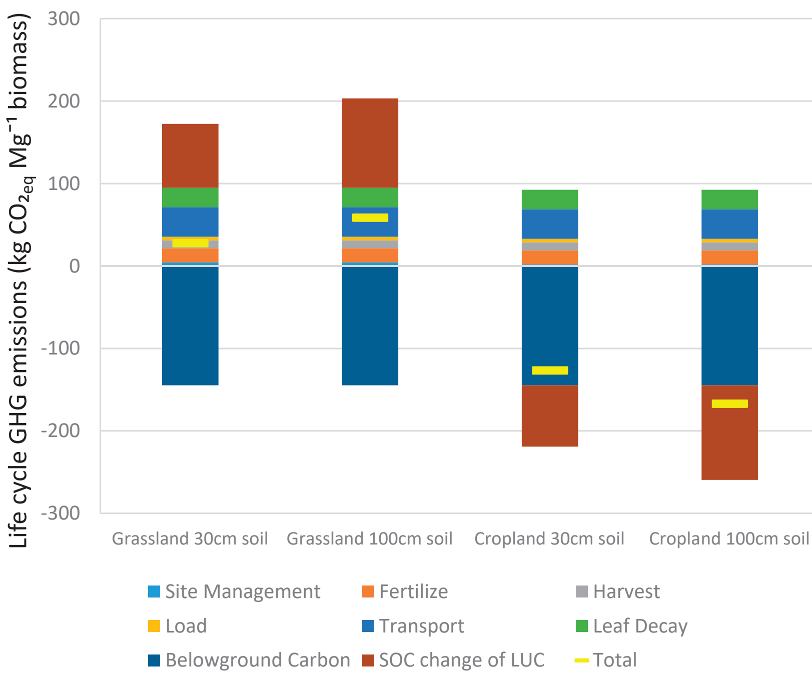


**Figure 3.** Life cycle GHG emissions from producing and delivering 1 Mg biomass represented by the yellow bar in four scenarios including 30 and 100 cm soil depths with grassland and cropland land cover converted to willow. The legend is read from left to right starting with site management as the first positive category, followed by fertilizer through to leaf decay.

The calculated production over seven rotations show a large variation among parcels (Figure 4) across the five counties (Figure 5), reflecting various environmental factors. A large number of parcels with high potential for biomass production are located in southwest and northeast Jefferson County with yield estimates greater than 14 Mg ha$^{-1}$ yr$^{-1}$ and relatively short distances to the Black River power plant. In addition, parcels in the southern parts of Oswego County and Oneida County, and the eastern parts of St. Lawrence County show relatively high yield estimates larger than 12 Mg ha$^{-1}$ yr$^{-1}$. However, the longer transportation distances in these areas can be limiting factors for biomass production, both in terms of GHG emissions and economics. In Lewis County, although yield estimates are around 10 Mg ha$^{-1}$ yr$^{-1}$ for many parcels, the shorter distances to end users are advantageous for efficient biomass production. In sum, it is advisable to consider yield potential for producing willow biomass because of variable conditions across geographical locations in the area.

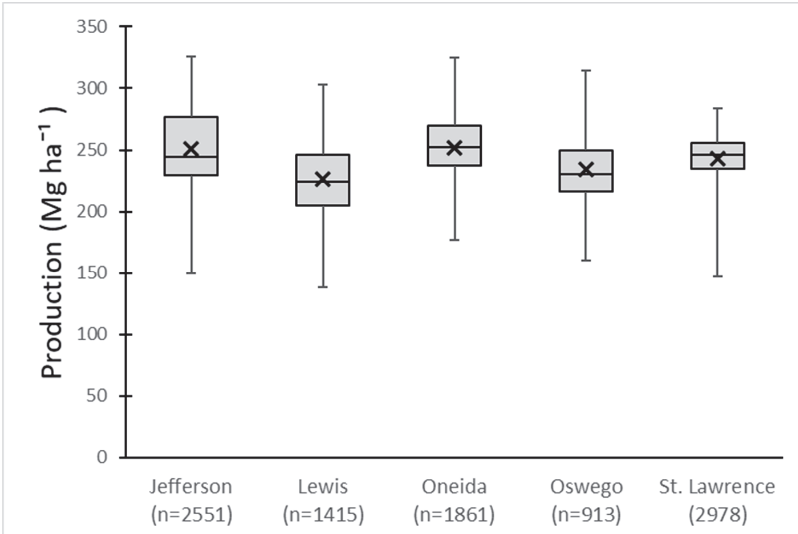


**Figure 4.** Distribution of yield estimates over seven rotations based on National Commodity Crop Productivity Index (NCCPI) indices from the Soil Survey Geographical Database (SSURGO) soil data layer for parcels in five counties. The lines in boxes are 25th percentile, median, and 75th percentile. The cross markers represent mean values. The whiskers are minimum and maximum values.

The spatial nature of this LCA modeling process resulted in a broader range of items being included in the uncertainty analysis than has previously been done for willow biomass crops. The LCA model generated life cycle GHG emissions and energy consumption for each parcel using site-specific yield, land cover, SOC change rate, and transportation distance data across the five counties. There is considerable variation in the life cycle GHG emissions among land cover classes within each county. Parcels classified as cropland resulted in net-negative life cycle $CO_2$ emissions, whereas most grassland parcels have net-positive $CO_2$ emissions (Figures 6 and 7), reflecting the different SOC changes of the two land cover categories. In the 30-cm grassland scenario in Jefferson county, one standard deviation is 28.2 kg $CO_{2eq}$ $Mg^{-1}$, accounting for 57% of the mean value of 49.4 kg $CO_{2eq}$ $Mg^{-1}$ in the county. The range is from −13.47 to 108.25 kg $CO_{2eq}$ $Mg^{-1}$ in the county. In the 30-cm cropland scenario in St. Lawrence, one standard deviation is 37.57 kg $CO_{2eq}$ $Mg^{-1}$, accounting for 71% of the mean −53.17 kg $CO_{2eq}$ $Mg^{-1}$, and the life cycle GHG emissions range from 21.45 to −122.46 kg $CO_{2eq}$ $Mg^{-1}$. Many parcels in Jefferson county that are close to an end user have large life cycle GHG emissions because they are classified as grassland and/or they have lower yield estimates (Figure S3).

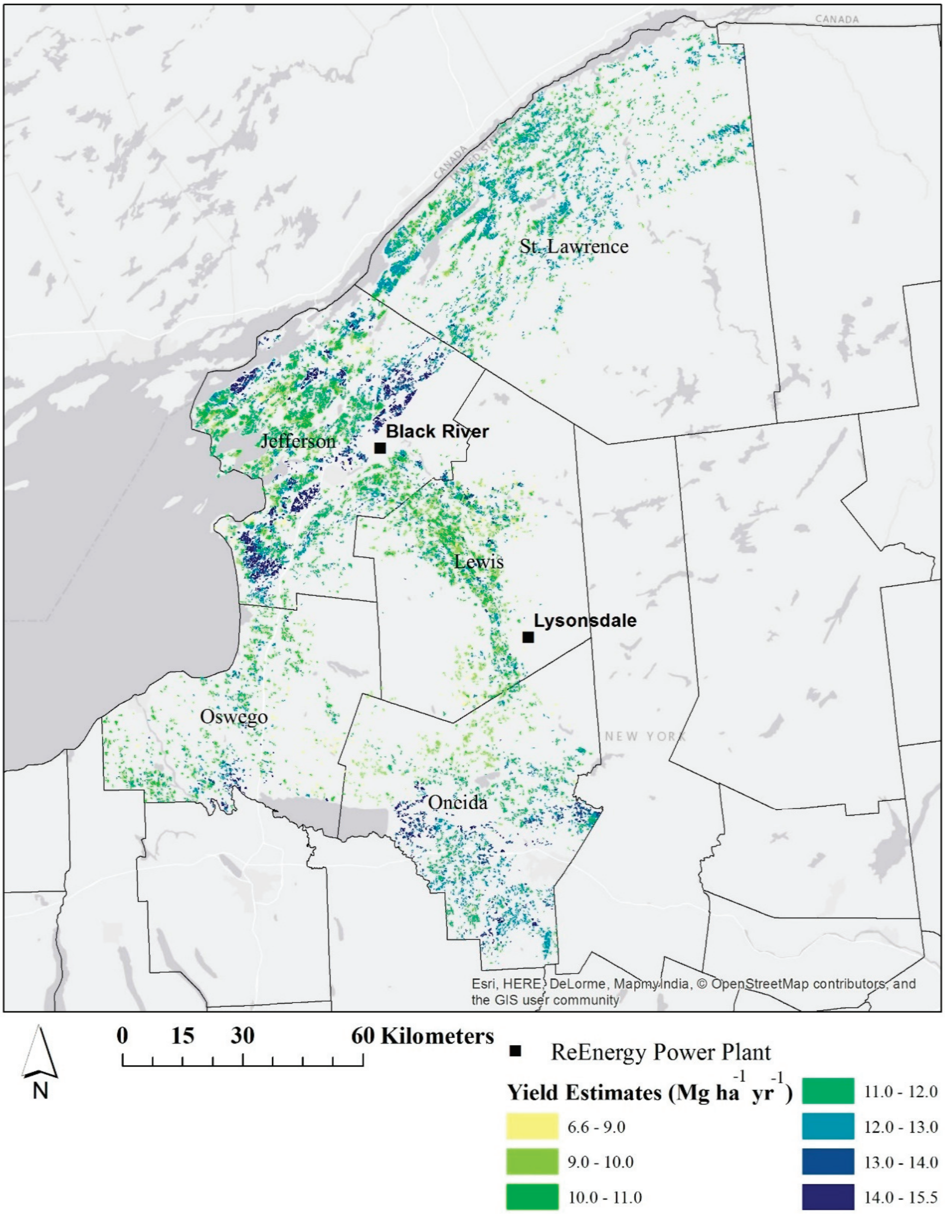


**Figure 5.** Yield estimates in parcels suitable for willow biomass crops in five counties in central and northern New York. Yields are estimated based on average NCCPI values of each parcel from SSURGO soil data layer.

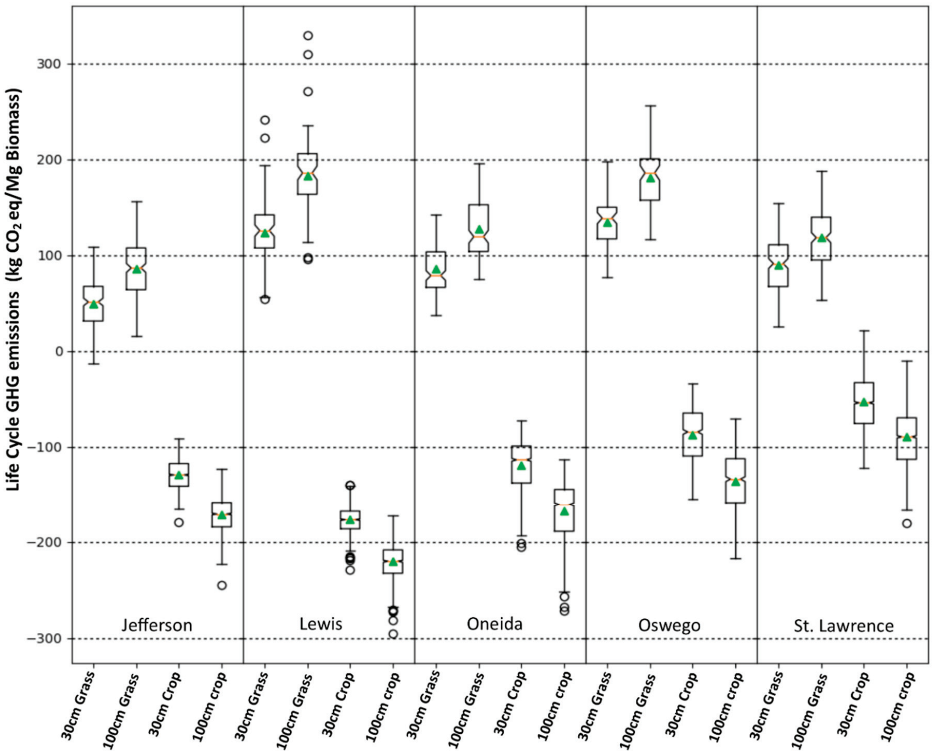


**Figure 6.** Boxplots showing distributions of willow biomass crop life cycle GHG emissions from parcel level LCA results in five counties in upstate NY. The upper bound, the notch, and lower bound represent 75th percentile, median, and 25th percentile, respectively. The green triangle indicates the mean.

The amount of uncertainty in energy consumption varied between counties and prior land uses (Figures 8 and 9). Cropland parcels usually have lower energy consumption compared to other parcels due a higher yield and a lower energy investment in site preparation and management operations (Figure 8). The largest mean energy consumption, 2078 MJ $Mg^{-1}$ biomass, is in the St. Lawrence grassland scenario and is more than double the energy input of the mean result in Lewis County (1002 MJ $Mg^{-1}$ biomass). These correspond to an EROI of 8.95 in the St. Lawrence grassland scenario and 18.6 in Lewis County. This difference is mostly caused by transport distances to the end users in the two counties. Furthermore, the variations within individual counties are considerable. In the grassland scenario in Lewis County, the standard deviation is 198.7 MJ $Mg^{-1}$, accounting for 19.8% of the 1002 MJ $Mg^{-1}$ mean energy consumption in the county, and the number ranges from 515.5 to 1518 MJ $Mg^{-1}$ (i.e., EROI from 36.08 to 12.26), almost a threefold increase. Similarly, for the cropland scenario in Lewis County, the standard deviation is 155.5 MJ compared to the mean of 910.4 MJ $Mg^{-1}$ and the range of energy consumption values is from 538.9 to 1422 MJ $Mg^{-1}$ (i.e., EROI from 34.51 to 13.08). This suggests that selection of where to grow willow crops within inside a county has an impact on both energy consumption and the EROI of the system.

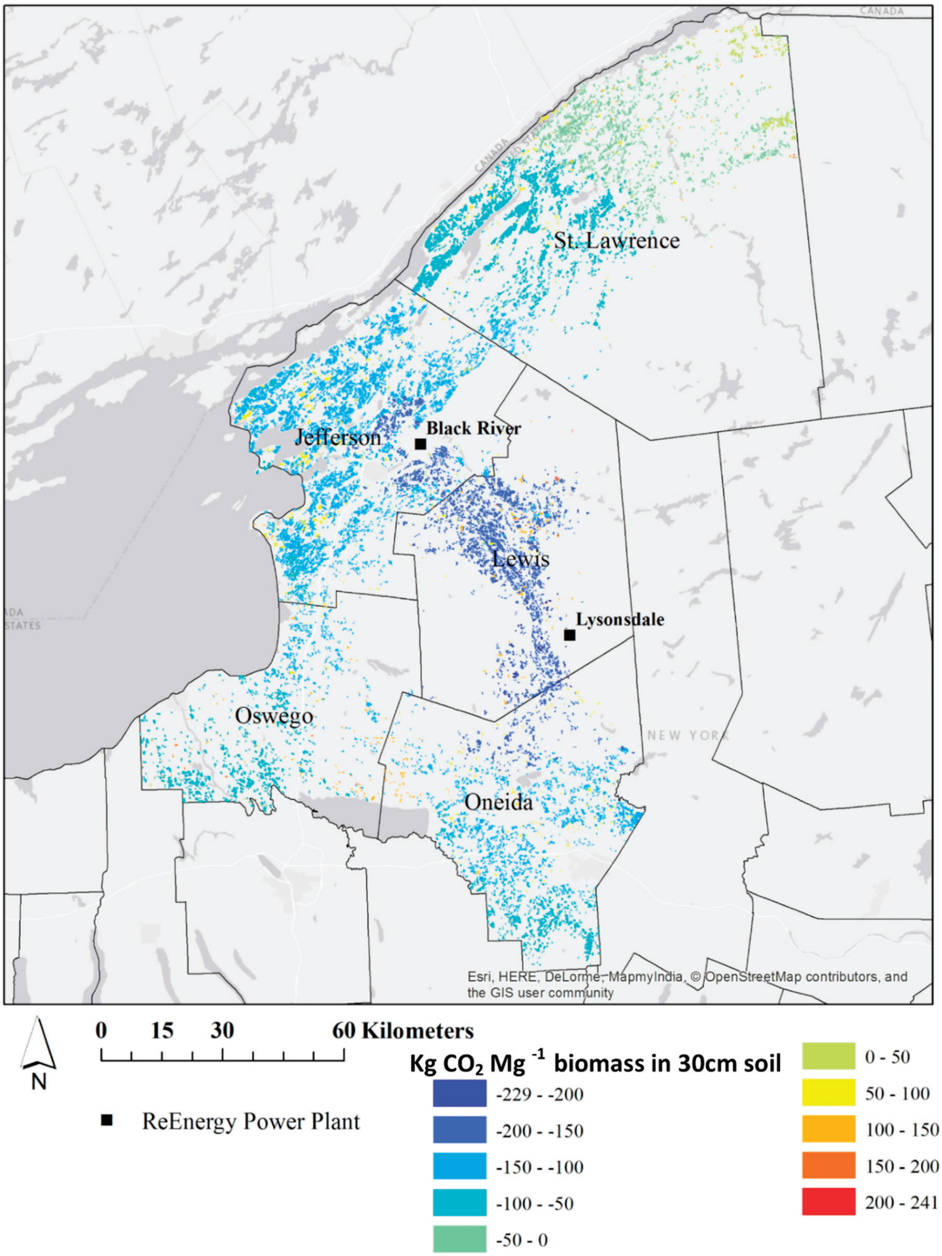


**Figure 7.** Life cycle willow GHG emissions measured in kg $CO_{2eq}$ of producing 1 Mg dry biomass with SOC changes modeled for a 30 cm depth in suitable parcels in five counties. The high levels of $CO_2$ sequestration (in blue) occur mostly near the end use facilities (Black River and Lyonsdale).

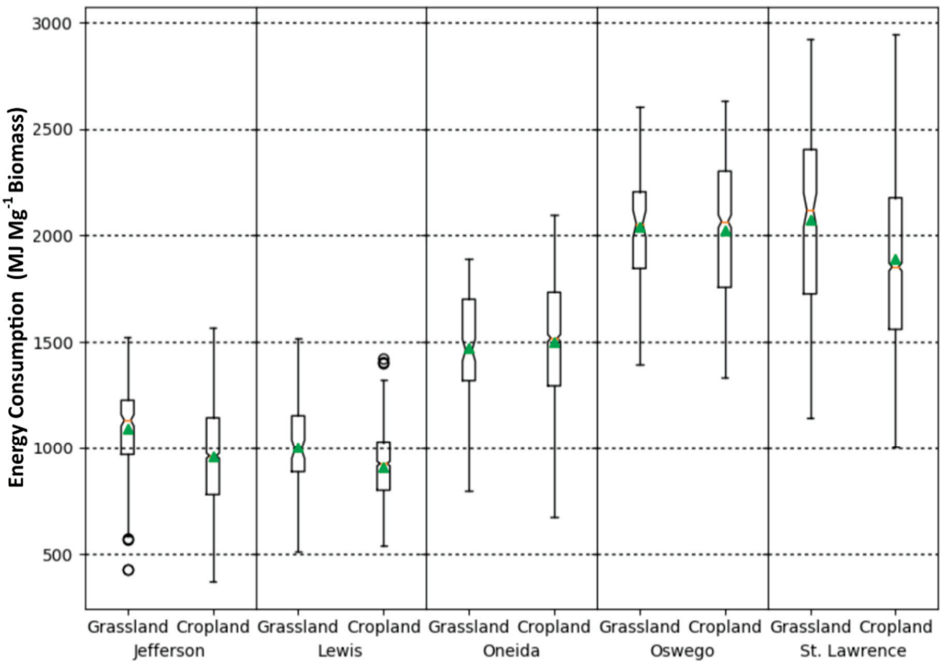


**Figure 8.** Boxplots of energy consumption to produce 1 Mg of willow biomass from parcel level LCA in five counties in central and northern NY. The upper and lower bounds of boxplots represent 75% and 25% quantiles, respectively. The notches represent median values and the triangles represent mean. For each county, the energy consumption is shown separately for grassland and cropland due to differences in yield and site preparation steps for the two land cover classes.

### *3.3. Sensitivity Analysis of Life Cycle GHG Emissions*

The sensitivity analysis, conducted based on Table 1 parameters, shows that yield, transport distance, and moisture content of willow biomass are the most influential factors for the life cycle GHG emissions (Figure 10) in all counties in cropland with 30-cm soil depth. The response of life cycle GHG emissions to yield is counterintuitive, as increased yield caused higher net GHG emissions in the sensitivity analysis. This occurs because the change associated with the fixed increase in SOC being spread over more Mg is larger than the increase in belowground carbon that occurs when yield increases. The transportation distance and moisture content cause substantial variability in Oneida, Oswego, and St. Lawrence counties where baseline transportation distances are large. This result suggests that GHG emissions can be reduced by selecting fields close to end users, e.g., power plants.

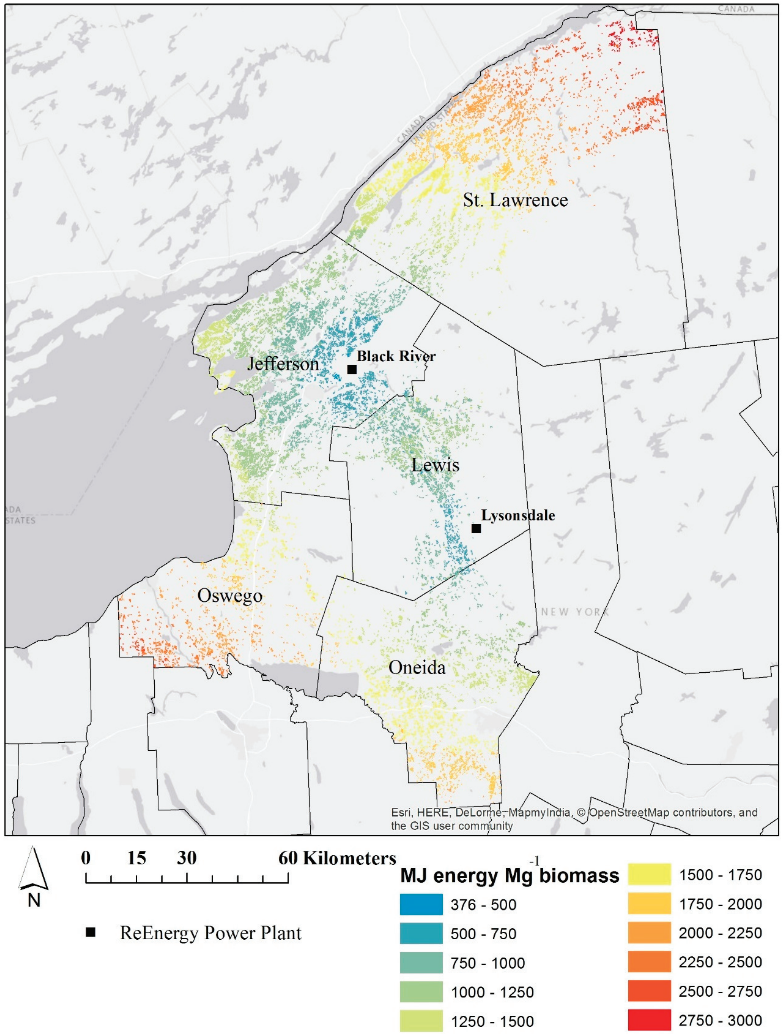


**Figure 9.** Energy consumption to produce 1 Mg willow biomass in the five counties in Central and Northern New York based on parcel-level LCA modeling.

The life cycle GHG emissions of parcels in all counties are related to the transportation distance, but they showed variability as well. Most pasture/cropland parcels cluster below zero net GHG emissions and have a clear increasing pattern with rising transportation distance (Figure 11). Similarly, shrub/grassland parcels cluster above zero net GHG emissions and are more scattered near smaller transportation distances due to relatively larger influences from other factors.

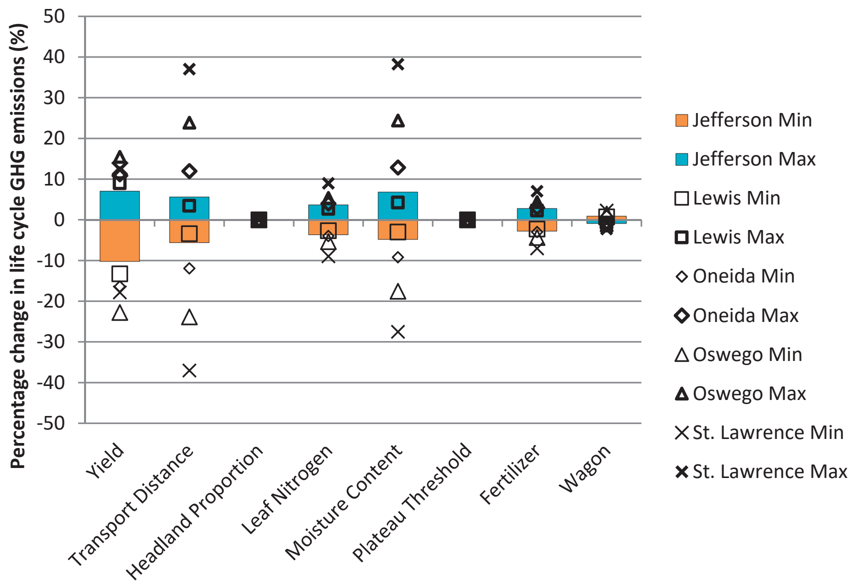


**Figure 10.** Range of life cycle GHG emissions expressed as the percentage of the baseline life cycle GHG emissions by varying each parameter individually in sensitivity analysis to its minimum ("Min") or maximum ("Max") value. Baseline parameter values and their variations are shown in Table 1. Plateau threshold represents threshold harvesting speed value that provides maximum throughput for the harvester.

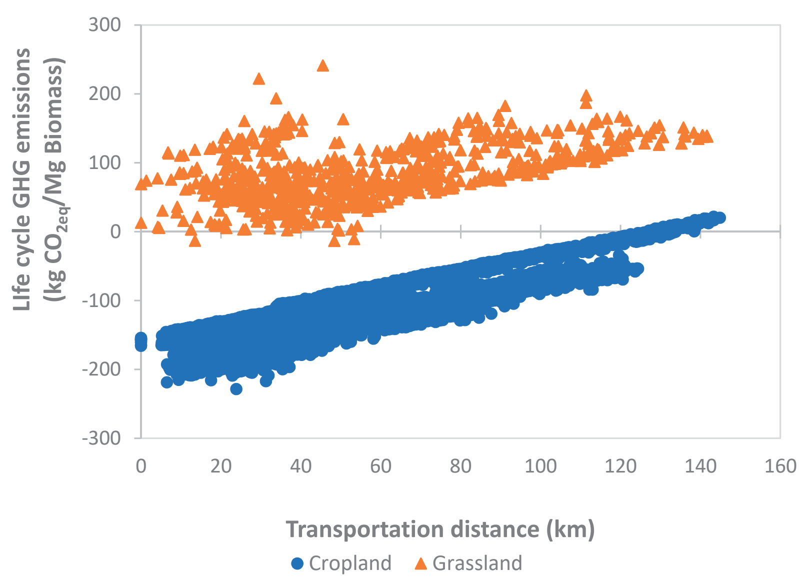


**Figure 11.** Parcel-level life cycle GHG emissions of five counties in shrub/grassland and pasture/cropland plotted against one way transportation distances.

### *3.4. Uncertainty Analysis of Life Cycle GHG Emissions*

To address the variability of GHG emissions in parcels despite the observed relation with transportation distance, Monte Carlo analyses of pasture and cropland in 30-cm soil were conducted. The distributions of life cycle GHG emissions in the five counties followed normal distributions (Figure 12) with different mean and standard deviations due to the uncertainty of varying SOC change rate, transport distance, yield, and other input parameters. The mean values of these distributions represent the life cycle GHG emissions values with the highest probability given the distributions of parameters in Table 1. Most counties have distinctive life cycle GHG emissions values, i.e., the chance of having the same values are very small or close to zero between Lewis County and Oswego County. However, a few counties, e.g., Jefferson and Oneida, have a higher probability of having similar life cycle GHG emissions values due to large overlaps of their probability distribution, although some of their parameters are very different, e.g., the baseline transport distance of Oneida County is twice that of Jefferson County.

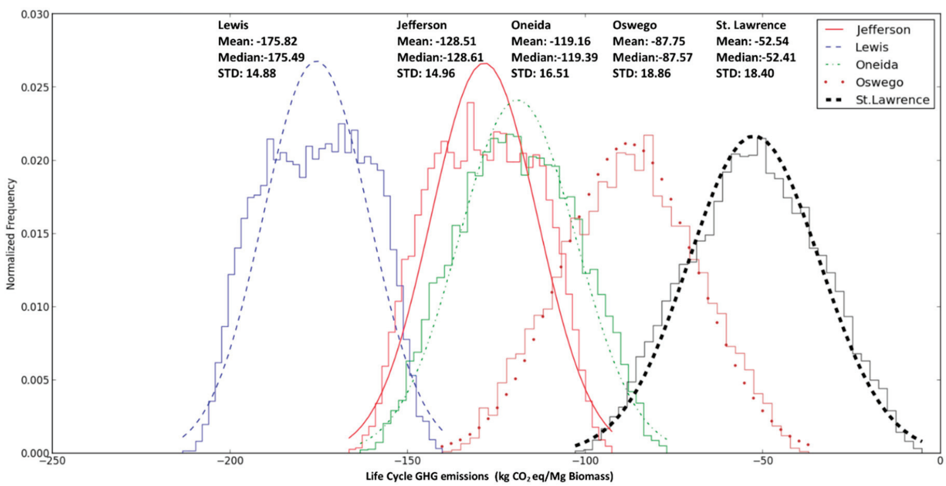


**Figure 12.** Monte Carlo uncertainty analysis for 30 cm soil depth for cropland/pasture in five counties. Contour step lines are the actual distributions of life cycle GHG emissions from 10,000 simulations. Bell shape lines represent normal distribution with same mean and standard deviation as the distributions. Mean and standard deviation of Monte Carlo analysis are listed above bell shape line of each county.

## 4. Discussion

This study illustrates that willow crops are a biomass feedstock that is carbon-negative across the landscape when it is grown on land that was formerly in cropland/pasture, which makes up 88.6% of the suitable parcels identified (Table S3), and is a low-carbon feedstock when grown on grassland. When cropland/pasture is converted to willow, the baseline GHG emissions are −126.8 kg $CO_{2eq}$ $Mg^{-1}$ biomass while the spatial analysis shows that some parcels have GHG emissions below −200 kg $CO_{2eq}$ $Mg^{-1}$ biomass. The negative life cycle emissions for willow grown on cropland occur across almost all of the parcels in the five county regions, except for a couple of percent that are above 0 kg $CO_{2eq}$ $Mg^{-1}$ when one way transportation distances exceed 126 km. When willow is grown on former grassland, which makes up 11.4% of the identified suitable parcels, the baseline life cycle GHG emissions are 27.7 kg $CO_{2eq}$ $Mg^{-1}$ biomass and over 99% of all parcels are positive. The feedstock from these parcels can be considered a low carbon source of biomass. A previous LCA of willow grown in the region reported negative GHG emissions for all the scenarios, which included different transportation distances, high and low yields, and the application of N fertilizer or no fertilizer [1].

A review of LCAs in Europe and North America reported slightly positive GHG emissions (14–207 kg $CO_{2eq}$ $Mg^{-1}$), but most of these studies excluded an assessment of belowground carbon and SOC changes associated with direct land use change [9]. Both these factors were included in this study using the best available, but limited, data and their influence on the results highlights a need for additional studies to refine this information. For willow grown on former cropland/pasture in this study there is the potential to sequester carbon while producing feedstock that can be used to provide a range of bioenergy and bioproducts and simultaneously create jobs and provide a range of other ecosystem services like improved water and soil quality and enhanced biodiversity [40].

The variations in life cycle GHG emissions between and within counties are substantial and driven by multiple parameters that have different resolutions ranging from the sub parcel (e.g., SSURGO at 10 m resolution) to county level (e.g., SOC change). For the cropland 30-cm soil scenarios, the GHG emissions differed by county ranging from −176.9 kg $CO_{2eq}$ $Mg^{-1}$ in Lewis to −53.2 kg $CO_{2eq}$ $Mg^{-1}$ in St. Lawrence. For the grassland 30-cm soil scenarios, Jefferson has the lowest mean GHG emissions: 49.4 kg $CO_{2eq}$ $Mg^{-1}$ compared to 134.2 kg $CO_{2eq}$ $Mg^{-1}$ in Oswego (Figure 7). Although Jefferson and Lewis counties are both close to the two end users, the life cycle GHG emissions for grassland in Lewis County had larger values due to higher rates of SOC change (Table 3) and lower yield (Table S3) than Jefferson County (49.4 kg $CO_{2eq}$ $Mg^{-1}$). The transportation distance for Lewis County is generally much smaller than Oneida County, however, the life cycle GHG emissions of Oneida County in grassland are lower than Lewis County due to higher yields and a similar SOC change rate. The impact of transportation distances, yield estimates, which also impacted values for belowground biomass and harvesting operations, and changes in SOC on GHG emissions varied parcel to parcel in this study, creating complex patterns across the landscape (Figure 7). Using LCA and other tools that use a systems approach to analysis and create a framework for examining the interactions among different components is important to understand the overall GHG emissions from these systems and the factors that need to be addressed to further improve and reduce uncertainty for willow systems.

The net-positive life cycle GHG emissions from grassland compared to the negative net emissions for cropland are largely due to the different modeled changes in SOC associated with land use change. The baseline results use an average SOC change rate across the five counties of 0.28 Mg carbon $ha^{-1}$ $yr^{-1}$ (ranging from 0.19 to 0.34 Mg carbon $ha^{-1}$ $yr^{-1}$) sequestration rate for 30-cm soil in cropland/pasture and −0.29 Mg carbon $ha^{-1}$ $yr^{-1}$ change rate (ranging from −0.19 to −0.43 Mg carbon $ha^{-1}$ $yr^{-1}$) (Table 3) in hay/grasslands after conversion to willow crops [19]. The SOC change rate in 100-cm soil is higher than that in 30-cm soil, because the SOC modeling of 100-cm simulates both topsoil (0–30cm) and subsoil (30–100cm) including additional soil organic matter pool for the subsoil [19]. However, the majority of willow in northern NY is growing on marginal land and the soil depth is often limited due to perched water tables, hardpans, or bedrock. Previous assessments of rooting depth in willow in the region limited sampling to 45 cm because soil conditions limited root development in almost all cases [17]. Thus, while SOC changes are reported here to 100 cm depth, the number of sites where willow will be grown in this region and changes will occur to this depth are probably limited. Incorporating the best available data on soil carbon change due to land use change for a willow energy crop into a spatial LCA is an important step forward in the understanding of these systems, but the data is only available on the county level and does not capture the range of variation across the landscape. The results of this study emphasize the importance of this change in the overall GHG balance of these systems and that better data on these changes are needed. For example, SSURGO soil data is at spatial scale of 10 m, and potential future improvement of current county-level SOC data from CENTURY would support more detailed parcel-level soil SOC modeling from LUC including soil variations at the parcel level.

We incorporated SOC change associated with direct land use change in this study because of the impact it has on the results for willow biomass as well as biofuels that are produced from this material [41]. The baseline GHG emissions in this study (30 cm depth) without SOC change was −52.3 kg $CO_{2eq}$ $Mg^{-1}$ for cropland and −49.9 kg $CO_{2eq}$ $Mg^{-1}$ for grassland, which were similar to the −52.7 kg $CO_{2eq}$ $Mg^{-1}$ value for the high yield-fertilized-long transportation distance scenario reported in an earlier study [1]. When SOC change is included, the baseline values in this study become −126.8 kg $CO_{2eq}$ $Mg^{-1}$ for cropland and 27.7 $CO_{2eq}$ $Mg^{-1}$ for grassland. For both grassland and cropland, SOC change is the second largest factor, after belowground carbon, contributing to the overall life cycle GHG emissions. Caputo et al. (2013) included belowground biomass but not SOC changes and had negative GHG emissions in all their scenarios [1]. Few of the studies reviewed by Djomo et al. (2011) included changes in soil carbon or belowground carbon stored in coarse roots and stools, and the GHG impact of these studies were all positive, ranging from 0.7 to 10.6 g $CO_{2eq}$ $MJ^{-1}$ (13.7–208.8 kg $CO_{2eq}$ $Mg^{-1}$) [9]. The inclusion of the SOC and belowground carbon included in this study results in negative GHG emissions for cropland and slightly positive values for grassland that are at the low end of the range reported by Djomo et al. (2011) [9]. In a more recent LCA that included soil carbon sequestration [42], the life cycle GHG emissions of willow biomass production were estimated as 0.8 g $CO_{2eq}$ $MJ^{-1}$ for arable land, −10.4 g $CO_{2eq}$ $MJ^{-1}$ for marginal pastureland, and −31.8 g $CO_{2eq}$ $MJ^{-1}$ for marginal abandoned land in 100-cm soil depth. For the three scenarios there were changes in SOC (28.5 kg C $ha^{-1}$ $yr^{-1}$ for arable land, SOC gain of 153.4 kg C $ha^{-1}$ $yr^{-1}$ for marginal pastureland, and SOC loss of 31.5 kg C $ha^{-1}$ $yr^{-1}$ for marginal abandoned land) in contrast to the SOC increases in cropland but decreases in grassland used in this study. However, the differences of life cycle GHG emissions by SOC change were relatively minor compared to other processes such as transportation [42]. The inclusion of changes in SOC carbon associated with land use change is important to understand the impacts and benefits of these systems, but better data is needed to understand these patterns.

There is a limited amount of data available on changes in SOC under willow, especially in North America, and the results are inconclusive. A meta-analysis showed that a transition from cropland to short rotation coppice willow or poplar increased SOC by 5.0% ± 7.8% and by 3.7% ± 14.6% when these crops were planted on grassland [43]. These analyses only had 18 data points for cropland and seven for grassland, so there is large amount of uncertainty. An earlier analysis suggested an increase in SOC over time when poplar or willow are planted on cropland and no change or a slight decrease when planted on grassland, but model results vary based on the time period of the assessment [20,21]. For example, losses of 7–8% of soil C were suggested for data collected in the first 5 years after willow is planted on grassland, but for studies that had time frames longer than 5 years there is no significant change from the baseline [20,21]. A side by side study of willow and grassland over a 2-year period showed that willow was a net carbon sink even when biomass was harvested while the grassland was a net source of carbon [44]. This study is limited to one site and, as is the case with all studies, is influenced by site and management practices both before and during the study. A soil C chronosequence study, ranging from 5 to 19 years old, for willow in the region of the US where this study occurs suggests little change over that time period [19]. The data on SOC changes associated with willow biomass crops is limited and uncertain. We used the best available data based on SOC change associated with direct land use change based on modeling done by the Argonne National Lab using the CENTURY model, but this data was only available at the county level. More information on the dynamics of direct land use change for woody crops as well as a better understanding of long-term change in soil C are needed to reduce uncertainty and the overall GHG balance of willow systems across the landscape.

The inclusion of belowground biomass in this and other studies is important because of the magnitude of its impact. In this study, it is the largest single carbon sink, but as is the case with SOC data, information on this important component of the system is limited. In the 30-cm soil grassland scenario, belowground carbon accounts for −144.71 kg $CO_{2eq}$ $Mg^{-1}$ (45.6% of the total impacts in absolute numbers) and the SOC change accounts for 77.55 kg $CO_{2eq}$ $Mg^{-1}$ (24.5% of the total impacts). One study in the US of the carbon stored in belowground biomass suggests it changes over several rotations and is substantial, 45.3 ± 4.4 Mg $CO_{2eq}$ $ha^{-1}$ (25.4 Mg C $ha^{-1}$) [32]. This is 1.6 to almost 3 times greater than the increase in soil carbon in willow relative to cropland and exceeded the losses in SOC replacing grassland. In another recent study, root:shoot ratios varied among cultivars (0.46–0.72) at one site but not at a second site (0.63–0.65) [31] but some of these differences were reduced when yields were used as a covariate in the analysis. The belowground biomass values used in this study are proportional to the aboveground biomass [31]; therefore, increasing the yield of stem biomass in turn increases belowground carbon sequestration. This allowed us to apply these belowground values on a parcel by parcel basis across the landscape, but there is a need for more detailed information on how the belowground portion of these system changes across sites and with different cultivars and management systems.

Aboveground biomass yield is the most widely studied aspect of SRWC because it is the main product generated from these systems. In this study, changes in yield across the landscape had a direct impact on belowground biomass values, throughput of the harvester, and influenced the impact of changes in SOC, which was a fixed value per ha for grassland or cropland across an entire county. By using the relationship between NCCPI and yield from a previous study, we were able to assign yield at the sub parcel level because NCCPI data is available at a 10 m resolution and the land cover data we used was available at 30 m. This data effectively represented yields that have been measured in research and commercial scale trials across the region. Recently developed models used to predict yield across the continental US used 800 m grid (64 ha) for climate data and a 1024 ha parcel size for soils data [38]. Using this model to predict yields in this study would have further limited our ability to assess changes across the landscape.

While transportation distance from the field to the gate of the end use facility has been noted as an important factor in the GHG emissions of willow and other energy crops in the past, this current spatial LCA analysis illustrates the importance of understanding how transportation distance interacts with other factors. In Caputo et al. (2014), there are two haul distance scenarios to biorefineries, namely long haul distance and short haul distance [1]. The baseline case in this study is similar to the short haul distance scenario in Caputo et al. (2014) with an average 35.5 km to biorefineries. The life cycle GHG emissions result of −126.8 kg $CO_{2eq}$ $Mg^{-1}$ biomass in this study is at the lower end of the GHG emissions range from −83.1 to −138.3 $CO_{2eq}$ $Mg^{-1}$ of short haul distances scenarios in Caputo et al. (2014) [1]. Sensitivity analyses in recent LCA studies of willow biomass crops in Sweden [14] and in Spain [45] showed that transportation distance had the largest influence on life cycle GHG emissions. In this study, transportation was consistently one of the top three factors influencing GHG emissions, but its impact was modified by other factors. For example, sensitivity analysis showed that transportation distances changed GHG emissions less than 5% in Jefferson county but by more than 10% for Oneida county. However, the resulting distribution of GHG emissions for Jefferson and Oneida county in the uncertainty analysis are similar because of other factors such as modeled SOC increases on cropland, which were 30% higher in Oneida than in Jefferson. Integrating multiple factors in a spatial LCA provides valuable information to support decision making on where to establish willow biomass crops if one of the goals is to minimize GHG emissions.

Harvesting accounts for 9.48 kg $CO_{2eq}$ $Mg^{-1}$ in all scenarios and is the second largest impact among crop management activities after fertilizer, so improvements in harvester efficiency can contribute to GHG emission reductions. This number is about 27% lower than the 13 kg $CO_{2eq}$ $Mg^{-1}$ value in a previous study [1] due to improvements in harvester efficiency of single pass cut and chip operations modeled in this study and improved data for harvester operation and fuel consumption that have been made over the past few years [29,46]. Site management is an integrated category including all site preparation, planting, and site maintenance processes, specifically including processes #1 to # 15 and process #20 in Table S1. Site management activities are a small component of the total life cycle GHG emissions because they only occur once in the 25-year time span of this system, accounting for 4.40 kg $CO_{2eq}$ $Mg^{-1}$ in 30 cm grassland scenarios and are slightly lower for cropland (1.97 kg $CO_{2eq}$ $Mg^{-1}$) scenarios because fewer site preparation operations are required.

Willow biomass has a high energy ratio in central and northern New York State; the energy consumption was estimated as 969.6 MJ for 1 Mg biomass, and the net EROI is 19.2. For cropland, this number dropped to 937.9 MJ for 1 Mg biomass and increased to 19.8 as EROI. The overall GHG impact and energy balance of an energy system will depend on the conversion technology and final end products generated from the willow biomass.

The energy consumption values are mainly affected by transportation distance to the end users (Black River and Lyonsdale). The parcels near the power plants show less than 500 MJ $Mg^{-1}$ energy consumption compared with over 2750 MJ $Mg^{-1}$ in energy consumption in parcels further away (Figure 9). The geographical distributions of energy consumption demonstrate that parcels further away from end users tend to have higher energy input largely due to increasing the transportation distance. However, the pattern of increasing energy consumption is not strictly circular centering around the end users because it is also impacted by the spatial distribution of yield and land cover types and the tortuosity of the roads in portions of the study region.

Harvesting and fertilization are the two largest energy inputs to willow biomass production, which agrees with other studies [1,9,14]. These management activities contribute 14% (harvesting) and 17% (fertilization) of the total energy consumption of 969.6 MJ $Mg^{-1}$ for the baseline grassland scenario. The energy demand of willow biomass production in Caputo et al. (2014) ranges from 445.0 to 1052.4 MJ $Mg^{-1}$ biomass for eight scenarios with variations in transportation distance, yield, and fertilizer application [1]. Energy inputs in this study are larger than six of the eight scenarios in Caputo et al. (2014), with the four lowest energy inputs being scenarios that exclude fertilizer inputs and the associated input of 164.6 MJ $Mg^{-1}$. Another difference is the inclusion in this study of a process to load chips from piles on the ground into trucks for delivery to an end user, which is the most common practice in the region. In this study, the energy input associated with loading chips was about 35% higher than site management energy inputs for grassland and 2.8 times greater for the cropland scenario because it is an activity that occurs multiple times over the life of the crop. As a result, the range of EROI values in this study (8.95 in the St. Lawrence grassland scenario to 18.6 in the Lewis county cropland scenario) is on the lower end compared to the range of EROIs of 18.3 to 43.4 in Caputo et al. (2014) [1]. However, this study's EROI values are at the high end of the 3–16 values for cradle-to-plant LCA studies reviewed in Djomo et al. (2011) [9]. Harvesting throughput values in our study are based on more recent data that showed a substantial improvement in harvester throughput [29,46] that results in lower energy consumption per Mg of biomass and a higher EROI. Further improvements in harvesting and chip loading operations may be possible to further lower energy inputs into the system.

One approach to increase EROI in this system, and reduce GHG emissions, is to replace synthetic fertilizer with organic amendments or eliminate fertilizer applications, as long as the yield can be maintained. However, the yield response of willow to different rates of fertilizer is not well defined with most previous studies in the region (except for Adegbidi et al. (2001) [47]) showing no statistical improvement in yield with fertilizer additions [48,49]. However, a recent meta data analysis of willow fertilization trials across North America and Europe indicated that there was a lot of variation in yield response, but an overall positive trend was present [50]. Another option to shift fossil fuels based fertilizer energy inputs is to use organic waste materials like manure or biosolids, which Heller et al. (2003) suggested could increase EROI by 33–45% [51]. Regional studies showed that these materials produce yields comparable to commercial fertilizer [49,52]. While we included a range of fertilizer additions in the sensitivity analysis of this study, we did not include an associated change in yield because of the uncertainty of this relationship. Being able to further define the yield response to fertilizer additions across a range of soil types and site conditions would allow a better assessment of the impact of fertilizer on EROI and GHG emissions in willow systems.

## 5. Conclusions

Knowledge of how GHG emissions and energy ratios of willow biomass crops change across the landscape is useful information when evaluating the benefits and impacts of this system and an associated conversion facility. This study provides insights about how land cover, transportation distance, and yield vary among parcels where willow can be grown and how they interact to result in various life cycle GHG emissions and energy ratios. Across the vast majority of the region cropland/pasture converted to willow sequestered carbon until the haul distance was greater than 125 km regardless of other parameters such as yield. Key variables contributing to this result are the projected increase in SOC when willow is planted on cropland and the accumulation of carbon in the below ground portions of the willow plants. Grassland that was converted to willow almost always had slightly positive life cycle GHG emissions based on the projected increase in SOC. The importance of SOC change and belowground carbon indicates that more precise and accurate data on these parameters is needed to refine these results in order to more completely understand patterns across the landscape.

Energy inputs needed to produce one Mg of willow biomass crops were largely dependent on the transportation distance to the end users. The haul distance from the willow crop to the end user has continually been shown to be a key factor related to energy use, but it is one that is not easily changed until renewable biodiesel or electric power become common for tractor trailers. Other changes that can be made to the system to reduce energy inputs include replacing synthetic fertilizer with organic amendments or not applying fertilizer altogether as long as yields are maintained, and improving the efficiency of the harvesting system.

Sensitivity analysis of the life cycle GHG emissions for the five counties showed that yield, transportation distance, moisture content of biomass, and fertilizer use are among the most critical parameters that contribute to the overall GHG emissions of willow biomass across five counties. The moisture content of the biomass impacts the GHG emissions associated with transportation but is a factor that has some potential to be managed. The Monte Carlo uncertainty analysis showed that with the shorter haul distances in Lewis County, the most likely GHG emissions are around −175 kg $CO_{2eq}$ per Mg, whereas in areas with long distances, like St. Lawrence county, emissions are less negative (−50 kg $CO_{2eq}$ per Mg). The probabilities and ranges of GHG emission values in the five counties can be estimated based on the resulting normal distribution curves, providing informative guidelines for land managers, policy makers, and scientists.

**Supplementary Materials:** The Supporting Information document containing **Tables S1–S4** (which provide detailed information on the inputs used to determine the greenhouse gas emissions and energy return on investment (EROI) of willow biomass crops growing across a five county region in upstate NY. Table S1 provides input data for specific operations involved in all stages of willow growth from site preparation to harvesting through to removing the willow plants after seven rotations. Data sources for each of these steps is included in this table. Table S2 provides data at the county level on the number and area of parcels in different land use categories (grassland, pasture, cropland) that were identified as being suitable for the production of willow biomass crops. Information on cropland and pasture are provided separately in this table but are grouped together into a single category when they are used as input into the LCA model. Another key input into the model is willow biomass crop yield. Yield in each county for both grassland and cropland are summarized by county. The model used to predict yield was based on the NCCPI (National Commodity Crop Productivity Index) that is available in the Soil Survey Geographic database (SSURGO). Table S4 summarizes the NCCPI values by county and land cover type.) and **Figures S1–S4** (which provide additional information on the methods and results of the spatial LCA of willow biomass crops across the five county region in upstate NY. Figure S1 is a flow chart that explains the steps that were used to identify suitable land for willow biomass production in the five county region. County level output of this analysis is provided in Table S2. Figure S2 provides a breakdown of the energy consumption to grow willow on either grassland or cropland broken down by stages in the production, harvesting and transportation of the biomass to an end user. Figure S3 provides a county level snapshot of how the greenhouse gas emissions for the suitable parcels of land vary across one county in the study. Other figures in the paper include all five counties at a much smaller scale, which eliminates some of the detail that is available. Figure S4 provides base case (EROI) results for willow biomass crops grown in upstate NY and compares these results to other literature values.) is available online at http://www.mdpi.com/1996-1073/13/16/4251/s1.

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# Saccharification Yield through Enzymatic Hydrolysis of the Steam-Exploded Pinewood

**Merve Nazli Borand [1,*], Asli Isler Kaya [2] and Filiz Karaosmanoglu [2]**

[1] Energy Systems Engineering Department, Faculty of Engineering, Merkez Campus, Yalova University, 77100 Yalova, Turkey

[2] Chemical Engineering Department, Faculty of Chemical and Metallurgical Engineering, Ayazaga Campus Istanbul Technical University, 34467 Istanbul, Turkey; isleras@itu.edu.tr (A.I.K.); filiz@itu.edu.tr (F.K.)

* Correspondence: nazli.erdonmez@yalova.edu.tr; Tel.: +90-226-815-53-80

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**Abstract:** Pressure, temperature, and retention time are the most studied parameters in steam explosion pretreatment. However, this work aimed to fix these parameters and to evaluate the influences of several less investigated steam explosion parameters on the saccharification yield in hydrolysis. In this study, firstly, pinewood samples smaller than 200 μm were treated with steam explosion at 190 °C for 10 min. The variable parameters were biomass loading, $N_2$ pressure, and release time. Steam-exploded samples were hydrolyzed with the *Trichoderma reesei* enzyme for saccharification for 72 h. The sugar content of the resultant products was analyzed to estimate the yield of sugars (such as glucose, xylose, galactose, mannose, and arabinose). The best glucose yield in the pulp was achieved with 4 g of sample, $N_2$ pressure of 0.44 MPa, and short release time (22 s). These conditions gave a glucose yield of 97.72% in the pulp, and the xylose, mannose, galactose, and arabinose yields in the liquid fraction were found to be 85.59%, 87.76%, 86.43%, and 90.3%, respectively.

**Keywords:** lignocellulosic biomass; hydrothermal pretreatment; enzymatic hydrolysis; sugar yield; high-performance liquid chromatography (HPLC) analysis

## 1. Introduction

Recently, attention on biorefineries has increased dramatically because of the environmental and economic impacts of fossil sources. Biorefineries use biomass as a feedstock to produce biofuels, biopower, biomaterials, and biochemicals instead of fossil sources [1,2]. Biorefineries can use a wide variety of biomasses, from microalgae to wood. Biorefineries provide flexibility in terms of both feedstock and resultant products, i.e., the different feedstocks that can be used and the different products that can be produced in one biorefinery [3,4]. Biorefineries that use wood as feedstock are called lignocellulosic feedstock biorefineries (LCFs). LCFs are one of the primary alternative candidates to fossil-based biorefineries due to their wide availability, easy accessibility, low cost, and the diverse nature of their feedstock [5]. Lignocellulosic biomass contains mainly cellulose (25–50%), hemicellulose (15–30%), and lignin (10–35%) [6–8]. Cellulose is the leading sugar source for lignocellulosic bioethanol production. Whereas cellulose has polymeric glucan chains that contain glucose monomers, hemicellulose has polymeric structures that are formed from hexoses and pentose, and it may involve sugar acids [6,9]. Lignin, a chemical compound that provides rigidity to plants, is formed from phenolic monomers [6]. Its higher lignin ratio makes the lignocellulose structure more rigid, and the recalcitrant structure of lignocellulosic biomass makes bioconversion more complicated compared to that of first-generation bioethanol feedstocks [10]. Despite its potential, its recalcitrant structure is a significant barrier to the commercialization of lignocellulosic bioethanol. Therefore, pretreatment methods should be applied to eliminate these barriers.

The main objectives of pretreatment methods can be summarized as breaking the structure of lignocellulose, reducing the crystalline structure of cellulose, increasing the porosity of the surface of the lignocellulosic feedstock, increasing the surface area, and providing enzyme accessibility in the cellulose [11,12]. The cost of lignocellulosic biomass pretreatment accounts for nearly 33% of the total bioethanol production cost [13]. Therefore, the application of efficient and less chemical and energy-dependent pretreatment methods will decrease the total cost of bioethanol production.

Steam explosion, a commonly used physicochemical pretreatment technique, is a hydrothermal method in which lignocellulosic biomass is treated with high-pressure saturated steam, and later, the pressure is suddenly dropped [13]. Therefore, it causes explosive decompression of the structure of lignocellulosic biomass. In the steam explosion method, both physical forces and chemical processes are applied to lignocellulosic biomass [14]. The presence of water creates an acidity effect in the medium, and a sudden pressure drop causes the separation of fibers. It quickly provides enzyme accessibility to the cellulose structure. A liquid fraction and pulp are formed during steam explosion pretreatment. Whereas the liquid fraction contains mainly sugars from the hemicellulose structure, the pulp contains both cellulose and lignin. The pretreatment temperature and pressure are usually set between 160 and 260 °C, and 0.69 and 4.83 MPa, respectively [15]. Higher temperatures could cause hemicellulose degradation and lignin transformation. The retention time differs from seconds to minutes, and later, the pressure is suddenly decreased to atmospheric pressure. The main benefits of steam explosion pretreatment can be summarized as significantly lower environmental effects, a lower capital investment cost, lower usage of hazardous chemicals, and the opportunity to operate under moderate conditions to produce a higher saccharification yield [16]. In addition, the steam explosion process causes a reduction in energy consumption compared with conventional physical pretreatment methods to obtain a similar particle size reduction [17,18]. However, the main disadvantage of the steam explosion process is the production of some inhibitory compounds, such as furfural and 5-Hydroxymethylfurfural (HMF), which result from the degradation of sugars during pretreatment. These compounds decrease the efficiency of enzymatic hydrolysis and fermentation [16,19].

Hydrolysis breaks the polymeric cellulose structure and produces glucose monomers. After the hydrolysis of lignocellulosic feedstock, the hexose sugar yield can range from 0.5 to 0.75 *g*/*g* cellulose [20]. The saccharification yield indicates the hydrolysis yield for bioethanol production. Enzymatic hydrolysis is performed with the cellulase enzyme, which is commonly produced by soft-rot fungi such as *Trichoderma* sp., *Penicillium* sp., and *Aspergillus* sp. [20,21].

In steam explosion studies, mostly, reaction temperature and retention time have been investigated. Alvira et al. (2016) examined different reaction temperatures and retention times on the sugar yield for wheat straw. The highest glucose and xylose yield were found to be 97.9% and 91.1% at 190 °C reaction temperature for a ten-minute retention time, respectively. It was indicated that at this pretreatment temperature and retention time, sugar degradation and toxic formation were decreased [17]. Simangunsong et al. (2020) pretreated beech wood with steam explosion at 150, 170, 190, and 210 °C for 2.5, 5, 10, and 15 min. They stated that the highest sugar recovery was achieved when the severity factor was 3.65 (190 °C and 10 min) [22]. Bondesson and Galbe (2016) found the highest total glucose and xylose yield to be 0.32 *g*/*g* biomass at 190 °C and 10 min [23]. Therefore, the reaction temperature and the retention time were selected to be 190 °C and 10 min in this study [17,22,23].

In the literature, no detailed study was found regarding other pretreatment parameters such as biomass loading, $N_2$ pressure, and release time. Thus, the aim of this work was to fix reaction temperature and retention time and to evaluate the influences of biomass loading, $N_2$ pressure, and release time on the saccharification yield in hydrolysis.

## 2. Materials and Methods

### 2.1. Feedstock Characterization

In the experimental part of this study, Northern US Pinewood from Moscow/Idaho was used. To analyze saccharification, pinewood was shaved with chopper twice and then sieved. Samples smaller than 200 µm were used in the experiment. All experiments were conducted with the same pine wood timber. The moisture, ash, lignin, and extractive content analysis were conducted according to American Society for Testing and Materials (ASTM) E1756-01, ASTM E1755-01, ASTM E1758-01, and ASTM E 1690, respectively [24–27]. For moisture content analysis, 2 g of sample was weighed accurately and placed in an oven at 104 °C. The oven-dried sample was reweighed every 4 h until a ± 0.1% change in the weight percent solids from the previous measurement was recorded. The difference between the final and initial weight represented the moisture content of the sample [24]. For ash content analysis, a 1 mg sample was measured and placed in a tarred crucible, and crucibles were placed in a muffle furnace at 600 °C for 24 h. The difference between final and initial weight represented the ash content of the sample [25]. For lignin content analysis, a 200 mg sample was weighed and placed in a test tube. Then 2 mL 72% sulfuric acid was added and incubated for 60 min at 30 °C with regular stirring. Primary hydrolysate was then transferred into a 200 mL Erlenmeyer flask with 56 mL of distilled water (final sulfuric acid concentration of *v/v* 4%). The flask was placed in a pressure tube in a water bath for incubating at 30 °C for 60 min. The secondary hydrolysate was filtered through the crucibles and washed with 40 mL of distilled water. The solid fraction (lignin) was oven-dried for one night and weighed. The secondary hydrolysate was used for sugar analysis [26]. The content of individual sugars was analyzed using high-performance liquid chromatography (HPLC) according to the "Analysis of Biomass Sugars Using a Novel HPLC Method", which is detailed in Section 2.4 [28]. The Soxhlet extraction was used to determine extractive content analysis. Approximately 3 g of the sample was mixed with 150 mL of solvent. Dichloromethane (DCM), ethanol, and water were used as the solvent. The extraction time was 12 h for DCM and 24 h for ethanol and water. Then, extracted solids were washed with fresh ethanol and oven-dried for one night at 40 °C [27]. The chemical composition of untreated pinewood is presented in Table 1.

**Table 1.** The chemical composition of untreated pinewood.

| Component | Content (%) |
|---|---|
| Glucan | 26.43 |
| Xylan | 18.86 |
| Mannan | 6.45 |
| Galactan | 3.92 |
| Arabinan | 1.54 |
| Lignin | 34.25 |
| Extractives | 6.77 |
| Ash | 1.78 |

### 2.2. Steam Explosion Pretreatment

A Parr reactor (High-Pressure/High-Temperature reactor, 600 mL, Parr Instrument Company, Moline, IL, USA) was used for steam explosion pretreatment. Figure 1 shows the experiment diagram of the steam explosion pretreatment. First, for solid loading, the sample (4 or 8 g) was measured accurately. Then, it was mixed with 200 mL of deionized water and heated to steam explosion temperature with constant stirring. The hot mixture that included both solid/liquid mixture was then placed in a hydrothermal steel reactor. The reactor was closed tightly, the temperature was set at 190 °C, the mixer speed in the reactor was set to 1000 rpm, and the retention time was 10 min. The pressure of the reactor at 190 °C was measured as being between 1.6 and 1.8 MPa. The pressure in the reactor consisted of the pressure of the water in the sample and the pressure of nitrogen. The valve that releases the gas inside the hydrothermal reactor was opened suddenly, and the pressure was equalized to atmospheric pressure in 22 or 46 s. The shortest release time of 22 s was selected because sudden pressure drops can damage the moving equipment, such as the mixer in the reactor. The released pressurized gas was collected and condensed in a vessel, and the liquid fraction was obtained. While the gas was releasing, some solid particles passed through the valve due to the high-pressure drop. Thus, filtration was applied to collect the solid particles from the liquid phase. Therefore, solid particles were separated from the liquid phase. For purification of the solid phase, deionized water wash and vacuum filters were applied.

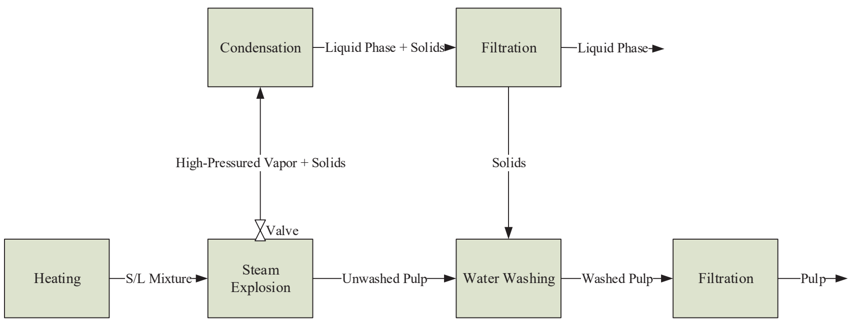


**Figure 1.** The experiment diagram of the steam explosion pretreatment.

In the steam explosion pretreatment method, the variable parameters were the solid loading (g), the presence of $N_2$ pressure, and the release time, as shown in Table 2. The optimal hemicellulose solubilization and hydrolysis was found at the temperature of 190 °C and the retention time of 10 min [12]. At these conditions, the severity factor ($R_0$) was calculated as 3.65.

**Table 2.** Steam explosion experiment design.

| Experimental Group | Temperature (°C) | Biomass Loading (g) | Nitrogen Pressure (MPa) | Release Time (s) |
|---|---|---|---|---|
| S1 | 190 | 4 | 0 | 22 |
| S2 | 190 | 4 | 0.44 | 22 |
| S3 | 190 | 4 | 0.44 | 46 |
| S4 | 190 | 4 | 0 | 46 |
| S5 | 190 | 8 | 0.44 | 46 |
| S6 | 190 | 8 | 0 | 22 |
| S7 | 190 | 8 | 0.44 | 22 |
| S8 | 190 | 8 | 0 | 46 |

A $2^3$ experimental design was applied, and eight experiments were conducted. All experiments were conducted in triplicate. Experimental groups were coded based on experimental conditions.

### 2.3. Hydrolysis of Pretreated Samples

In the enzymatic reaction of steam-exploded samples, commercial cellulase (*Trichoderma reesei* ATCC 26921, lyophilized powder, ≥1 unit/mg solid) was used as an enzyme and purchased from Sigma-Aldrich, Merck Group, Darmstadt, Germany. The enzymatic hydrolysis method is described in detail by the analytical procedure for the enzymatic saccharification of lignocellulosic biomass [29]. The enzyme concentration was prepared to be 4 FPU/mL. The enzyme was diluted with 50 mM of citrate buffer solution [30]. Steam-exploded samples of 400 milligrams were placed in individual plastic shaker bath tubes. Then, 40 mL of enzyme solution was added to the samples. The biomass-to-enzyme solution ratio was set at 10:1 (*w*/*v*). Plastic shaker bath tubes were placed in an orbital shaker bath for 72 h, and the temperature and speed were set at 50 °C and 300 rpm, respectively

### 2.4. Sugar Analysis

For sugar analysis, the sample was cooled to room temperature. Then, 5 mL of filtrate was placed in a test tube, inositol was added, and the solution was stirred. Then, 0.161 g of $PbCO_3$ was added and mixed. After centrifuging all samples, the liquid part was transferred to a small ion-exchange cartridge (0.5 mL of both IR 120 $H^+$ resin and IR 402 OH resin). The supernatant was filtered, and the filtrate was collected in an HPLC vial. To prepare the standard solution, 10 mg of glucose and 5 mg of each sugar were mixed and diluted to 100 mL with DI water. The solution was filtered into samples [28]. HPLC was used to measure the concentrations of sugar monomers such as glucose, xylose, galactose, mannose, and arabinose. For HPLC, the Waters Breeze system and two Rezex RPM columns in series (7.8 mm × 30 cm, Phenomenex, Torrance, CA, USA) and Waters HPLC (Waters, Milford, MA, USA) columns for carbohydrate were used, on elution with water (mobile phase) with a flow rate of 0.5 mL/min and operated at 90 °C. Thirty-milliliter samples were injected. A refractive index detector (ERC RefractoMax 520, Thermo Scientific, Waltham, MA, USA) was used for the non-chromophoric sugars. Data analysis was conducted using the Breeze software package.

## 3. Results and Discussion

### 3.1. Sugar Analysis

The optimal solid loading (4 or 8 g), presence of $N_2$ (0 or 0.44 MPa), and release time (22 and 46 s) for the pretreatment were tested. The lignin content of steam-exploded samples is presented before the HPLC results because the HPLC analysis was conducted using the second filtrate of lignin determination. All samples were analyzed and are shown in Table 3.

**Table 3.** The chemical composition of steam-exploded pulp.

| | Lignin (*w*/*w*, %) | Ash (*w*/*w*, %) | Glucose (*w*/*w*, %) | Xylose (*w*/*w*, %) | Mannose (*w*/*w*, %) | Galactose (*w*/*w*, %) | Arabinose (*w*/*w*, %) |
|---|---|---|---|---|---|---|---|
| S1 | 33.2 ± 0.18 | 3.38 ± 0.21 | 21.19 ± 0.10 | 1.41 ± 0.12 | 0.62 ± 0.06 | 0.57 ± 0.05 | 0.02 ± 0.00 |
| S2 | 33.85 ± 0.26 | 3.45 ± 0.26 | 24.85 ± 0.18 | 1.74 ± 0.16 | 0.54 ± 0.04 | 0.31 ± 0.06 | 0.03 ± 0.01 |
| S3 | 34.45 ± 0.22 | 3.64 ± 0.28 | 24.55 ± 0.21 | 1.83 ± 0.12 | 0.58 ± 0.09 | 0.43 ± 0.07 | 0.02 ± 0.01 |
| S4 | 35.3 ± 0.19 | 4.09 ± 0.32 | 21.56 ± 0.06 | 1.50 ± 0.16 | 0.61 ± 0.07 | 0.27 ± 0.08 | 0.03 ± 0.01 |
| S5 | 36.2 ± 0.22 | 4.24 ± 0.24 | 20.81 ± 0.20 | 1.50 ± 0.06 | 0.65 ± 0.06 | 0.51 ± 0.04 | 0.03 ± 0.01 |
| S6 | 35.65 ± 0.20 | 4.18 ± 0.20 | 19.99 ± 0.10 | 1.40 ± 0.10 | 0.76 ± 0.04 | 0.49 ± 0.08 | 0.01 ± 0.01 |
| S7 | 33.6 ± 0.21 | 4.04 ± 0.18 | 21.84 ± 0.16 | 1.70 ± 0.18 | 0.73 ± 0.05 | 0.52 ± 0.08 | 0.03 ± 0.00 |
| S8 | 33.2 ± 0.26 | 3.87 ± 0.23 | 19.06 ± 0.12 | 1.32 ± 0.06 | 1.22 ± 0.16 | 0.45 ± 0.04 | 0.03 ± 0.01 |

Data are presented as mean ± SD ($n$ = 3).

The lignin contents of S1, S2, S3, and S4 were lower than in S5, S6, S7, and S8. This result indicates that the biomass loading affects the lignin content. Higher lignin content can be explained by hemicellulose solubilization in the pulp, lignin condensation in the surface of the biomass fiber, and the formation of pseudo-lignin because of sugar degradation processes [31]. More biomass loading causes cellulose and hemicellulose degradation and produces more inhibitors such as HMF, furfural, and acetic acid. These inhibitors decrease the yield of bioethanol fermentation [32]. It is expected that mostly insoluble cellulose and lignin particles are to be found in the pulp [31]. When the cellulose ratio decreased due to the degradation of cellulose, the lignin ratio in the pulp increased. Therefore, to reduce the cellulose ratio, degradation should be prevented. A smaller biomass loading produced a higher saccharification yield in the enzymatic hydrolysis step. To compare the effects of the biomass loading on steam explosion pretreatment in the pulp, S1, S2, S3, and S4 included 4 g of biomass loading that was pretreated with steam explosion. In contrast, S5, S6, S7, and S8 included 8 g of biomass loading. The S1–S6, S2–S7, S3–S5, and S4–S8 comparisons, in which every parameter except biomass loading was constant, showed that the saccharification yield was higher when 4 g of the steam-exploded sample was used than when 8 g of the steam-exploded sample was used, because the degradation of components was higher in the latter case. Reducing the solid loading from 70% to 10% decreased the hardness of biomass from 592 to 266 g [33]. According to Lam et al. (2013), reducing biomass hardness results from breaking the crystalline structure of biomass [34]. Balan et al. (2020) tried different biomass loadings (1% and 5%) and evaluated the impact on enzymatic hydrolysis. At the same pretreatment conditions, when higher solid biomass (5%) was applied, glucose and xylose yields were reduced from 88% to 67% and 75% to 59%, respectively [35]. Therefore, lower solid biomass loading caused more breakage of the crystalline structure and higher sugar yield.

S1–S2, S3–S4, S5–S8, and S6–S7 comparisons, in which every parameter except $N_2$ was constant, were conducted. The addition of $N_2$ in S2, S3, S5, and S7 was associated with more glucose and xylose recovery than in non-$N_2$ added samples. $N_2$ molecules are smaller than water and other gases ($CO_2$ and $SO_2$) that are also used for explosion. Therefore, $N_2$ penetrates the cells of the biomass, and expands and breaks the cellulosic structure when the pressure drops [36]. When $N_2$ increases the pressure, the conversion of polymeric to monomeric sugars becomes easier. Stenberg et al. (1998) tested spruce and pine woodchips with steam explosion. $SO_2$ was added as a catalyst during steam explosion. They applied steam at a temperature of 210 °C and with a residence time of 5.5 min. The total sugar recovery was found to be 42.1%, and only glucose and mannose were detected [37].

For the S1–S4, S2–S3, S5–S7, and S6–S8 comparisons, in which every parameter except the release time was constant, a shorter release time (22 s) (S1, S2, S6, and S7) was associated with a higher saccharification yield than a longer release time (46 s). A sudden pressure drop caused the biomass structure to break easier than a slower pressure drop. Although it has been indicated that the release time varies from seconds to minutes, no studies exist regarding the release time in the literature. The saccharification yields are presented in Figures 2 and 3.

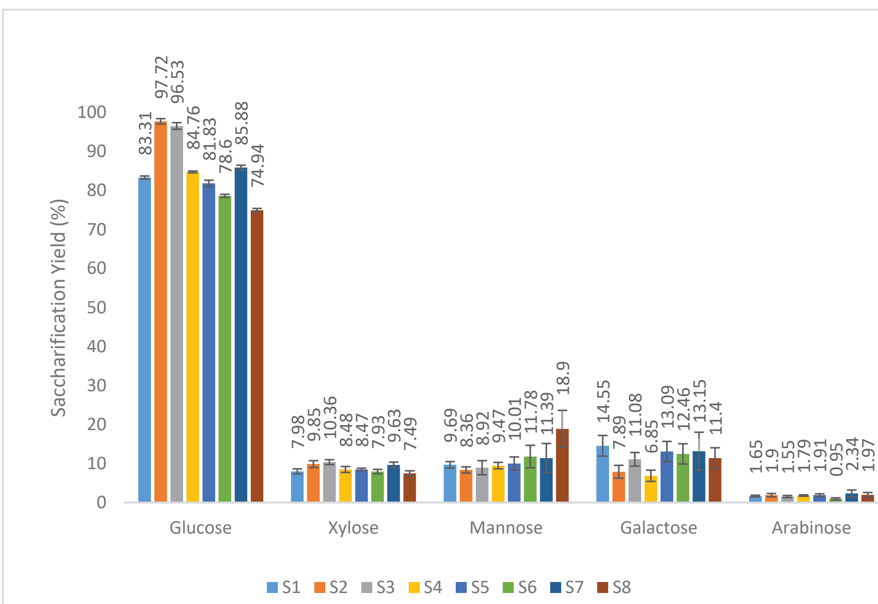


**Figure 2.** Saccharification yield in pulp.

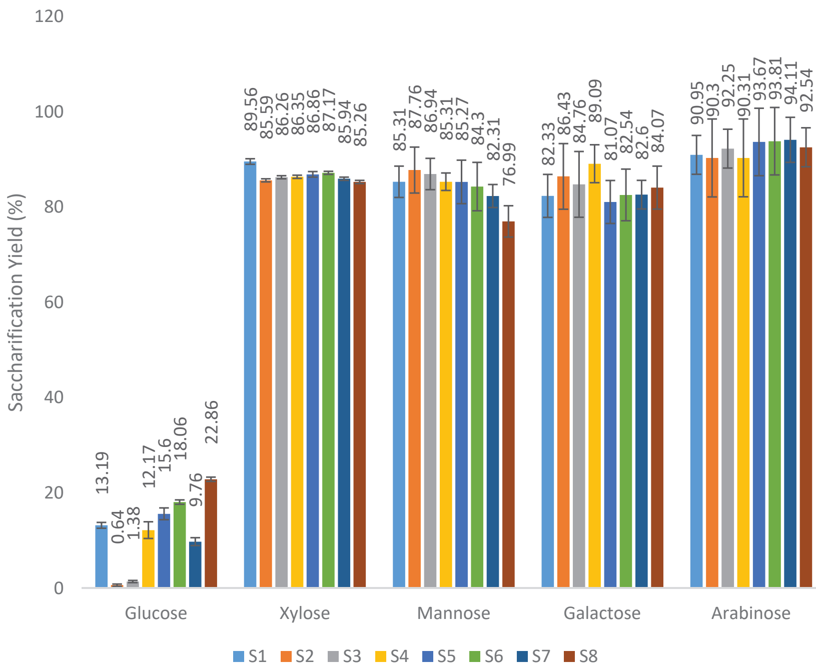


**Figure 3.** Saccharification yield in liquid fraction.

Figures 2 and 3 show that, under all conditions, the majority of the glucose was found in the pulp, while hemicellulosic sugars were found in the liquid fraction. Thus, these results are applicable to steam explosion. S2 had the maximum glucose yield (97.72%), while S1 had the maximum xylose yield (89.56%). According to the conditions applied in this study, the highest glucose recovery occurred when the temperature was 190 °C, the biomass loading was 4 g, the $N_2$ pressure was 0.44 MPa, the retention time was 10 min, and the release time was 22 s. In addition, the lowest glucose occurred in the liquid phase at the S2 condition. The maximum xylose recovery was found when the biomass loading was 4 g, the $N_2$ pressure was 0 MPa, the retention time was 10 min, and the release time was 22 s. Alfani et al. (2000) compared the glucose yield under different steam explosion pretreatment conditions, such as temperature and retention time. They used wheat straw as feedstock, and the best glucose yield was found to be 89% after 48 h of hydrolysis when the steam explosion parameters were a temperature of 217 °C and a retention time of 10 min [38]. Spruce wood was subjected to steam explosion and enzymatic hydrolysis by Pielhop et al. (2016). The maximum glucose yield was found to be 81% at a temperature of 235 °C with a retention time of 10 min [39]. Enzymatic hydrolysis of steam-exploded cotton stalk was tested by Keshav et al. (2016). The steam explosion parameters were set as 200 °C, 5 min, and 4.13 MPa. Then, alkali extraction with 3% NaOH was applied at room temperature for six hours on the steam-exploded cotton stalk. This study only gave the overall saccharification yield (82.13%), instead of the yields of individual sugars such as glucose and xylose [40]. Tabata et al. (2017) used rice husks for steam explosion. Different parameters were tested, and they found that the steam explosion treatment conditions of 3.0 MPa, 235–236 °C, and 3–5 min were optimal for enzymatic saccharification of rice husk. Under these conditions, a maximum glucose yield of 87.7% was achieved [41]. Alvira et al. (2016) examined influences of reaction temperature (170, 180, 190, 200, and 210 °C) and retention time (5, 10, 20, 25, and 30 min) on sugar yield for wheat straw. The maximum glucose and xylose yield were found to be 97.9% and 91.1% at 190 °C reaction temperature for ten-minute retention time, respectively [17]. Another temperature comparison was made by Raud et al.

(2019). They tried 150, 170, 190, and 200 °C. The glucose yield was found to be 3.5, 8, 21, and 24.3 g glucose/100 g biomass, respectively [36]. Guerrero et al. (2017) pretreated agricultural waste of banana trees with steam explosion. They tried different pretreatment temperatures. The results of this study show that glucose and xylose yields were 95.7% and 74.9% at 177 °C, and 90.8% and 75.1% at 198 °C, respectively [42]. Russ et al. (2016) evaluated the steam explosion temperature effects on wheat straw. They tested 175, 195, 215, and 230 °C for 10 min. They found that the highest glucose conversion (97%) at 215 °C. In addition, they indicated that the glucose conversion decreased when the temperature was above 215 °C [43]. Yang et al. (2011) tested the conversion of unwashed steam-exploded corn stover to bioethanol. The natural corn stalk was chipped to a size of 1–2 cm and steam exploded at 1.5 MPa and 210 °C for 10 min. Steam-exploded corn stover was used directly for enzymatic hydrolysis. Therefore, inhibitors did not separate from corn stover. The glucose and xylose yields were found to be 71.48% and 86.66%, respectively. The reason for the low result is the inhibitors found in the raw material during the enzymatic hydrolysis [44]. Dekker and Wallis (1983) indicated that steam explosion for 4 min at 200 °C removed 90% of the xylan present in sugarcane bagasse [45]. In this study, xylan removal from the pulp was calculated to be at least 89.64% (S3) and was a maximum of 92.51% (S8).

Because the main component for bioethanol production is glucose, S2 is the best choice for steam explosion. As shown by the results for S2, when 100 g of pinewood was steam exploded, hydrolyzed with the enzyme, and then fermented, 12.698 g of bioethanol (499 mg bioethanol/g cellulose) was theoretically produced. For this calculation, the theoretical conversion of glucose to bioethanol was accepted as 0.511 g bioethanol/g glucose [46,47]. Raud et al. (2018) investigated nitrogen and flue gas during explosion pretreatment. Their best results were found to be 9.0–9.4 g of ethanol/100 g of biomass [48]. Kumagai et al. (2014) pretreated softwood and hardwood samples with steam explosion and collected 359.3 mg bioethanol/g cellulose (87% of the glucose yield) and 75.4 mg bioethanol/g cellulose (92% of the glucose yield) for Hinoki cypress (softwood) and eucalyptus (hardwood), respectively [49]. Safari et al. (2017) used the pine tree for dilute alkali pretreatment. According to their results, the best result (211.452 mg bioethanol/g biomass) was found with 2% (*w*/*v*) NaOH at 180 °C [50].

### 3.2. Experimental Design and Statistical Analysis

Central Composite Design (CCD) was used for the optimization of glucose yield in the solid fraction and xylose yield in the liquid fraction. The release time (X1), $N_2$ pressure (X2), and biomass loading (actual factor) were selected for the independent variables, as shown in Table 4. Glucose yield (R1) and xylose yield were used as the dependent output variables. A statistical package (Design-Expert 12, Stat-Ease, Minneapolis, MN, USA) was used to evaluate CCD.

**Table 4.** The chemical composition of steam-exploded pulp.

| Independent Variables | Unit | Symbol | Low Level (−1) | High Level (+1) |
|---|---|---|---|---|
| Retention time | s | X1 | 22 | 46 |
| $N_2$ pressure | MPa | X2 | 0 | 0.44 |
| Biomass loading | g | AF | 4 | 8 |

Figures 4 and 5 present the response surface of glucose yield in the solid fraction and xylose yield in the liquid fraction. In both figures, it is clearly seen that lower biomass loading and shorter release time cause higher yield. However, nitrogen pressure increases the glucose in the solid fraction yield while decreases the xylose yield in the liquid fraction. According to response surface results, glucose yield (Equation (1)) and xylose yield (Equation (2)) equations were calculated as below where *A*: release time (s), *B*: nitrogen pressure (MPa), and *C*: biomass loading (g).

$$\begin{aligned} Glucose\ Yield\ (\%) &= 84.398 + 0.203A + 53.103B - 0.405C - 0.158A \times B \\ &+ 0.042A \times C - 3.753B \times C \end{aligned} \quad (1)$$

$$Xylose\ Yield\ (\%) = 95.032 - 0.157A - 22.526B - 0.720C + 0.353A \times B + 0.008A \times C + 1.366B \times C \quad (2)$$

*t*-Tests were applied between experimental groups for each sugar to determine whether factors such as biomass loading, nitrogen pressure, and release time are important. To understand the importance of biomass loading, S1–S6, S2–S7, S3–S5, and S4–S8 comparisons were conducted. S1–S2, S3–S4, S5–S8, and S6–S7 comparisons were conducted to determine the importance of nitrogen pressure, and S1–S4, S2–S3, S5–S7, and S6–S8 comparisons were performed to determine the significance of the release time. The results indicate significance differences among all experiment groups for glucose ($p < 0.05$). Changes in the biomass loading, nitrogen pressure, and release time affected the glucose yield. While comparing the results, it was found that a lower biomass loading (4 g of the sample instead of 8 g of sample), nitrogen gas addition in the reactor, and a short release time (22 s) increased the glucose yield. However, the results did not indicate any significance differences among experimental groups for hemicellulose (xylose, mannose, galactose, and arabinose) ($p > 0.05$).

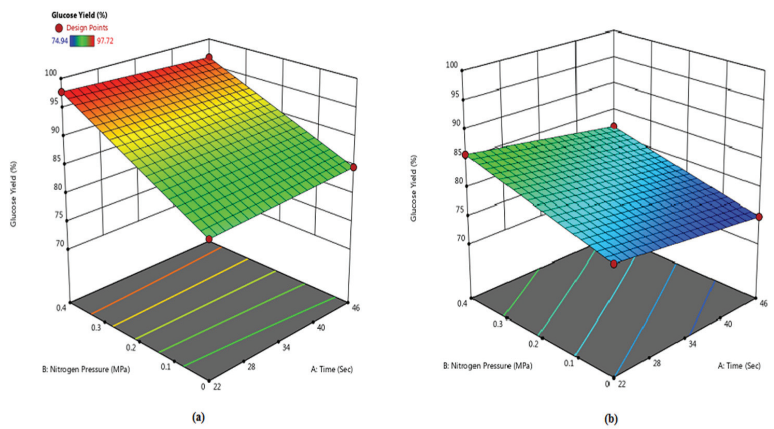


**Figure 4.** Response surface of glucose yield in solid fraction (**a**) 4 g biomass loading (**b**) 8 g biomass loading.

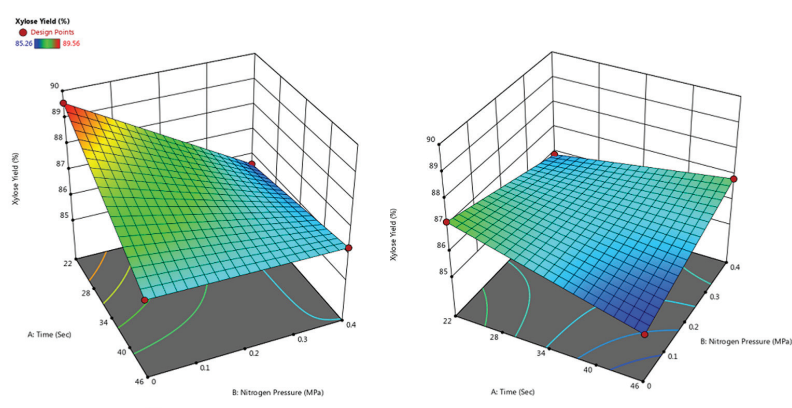


**Figure 5.** Response surface of xylose yield in solid fraction (**a**) 4 g biomass loading (**b**) 8 g biomass loading.

## 4. Conclusions

In this work the influences of $N_2$ pressure, biomass loading, and release time during steam explosion pretreatment on the saccharification yield in hydrolysis was evaluated. For the steam explosion pretreatment, particles with a maximum size of 200 μm were used. The solid and liquid phases occurred after the steam explosion. The chemical characterization results show that the solid phase included mainly glucose and the liquid fraction contained mainly hemicellulose. According to the results, the highest glucose yield was found to be 97.72% in the pulp with an $N_2$ pressure of 0.44 MPa, biomass loading of 4 g, and a release time of 22 s, while the highest xylose yield was found to be 89.56% in the liquid fraction with an $N_2$ pressure of 0 MPa, biomass loading of 4 g, and a release time of 22 s. These results indicate that lower biomass loading (4 g) and shorter release time have higher glucose and xylose yield than higher biomass loading (8 g) and longer release time (46 s). Although nitrogen pressure increases the yield of glucose in the solid phase, it decreases the yield of xylose in the liquid phase.

**Author Contributions:** Conceptualization, methodology, validation, writing—review and editing, M.N.B., A.I.K., F.K.; formal analysis, investigation, resources, data curation, M.N.B.; writing—original draft preparation, M.N.B., A.I.K.; supervision, project administration, funding acquisition, F.K. All authors have read and agreed to the published version of the manuscript.

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# Willow Cultivation as Feedstock for Bioenergy-External Production Cost

**Ewelina Olba-Zięty [1,*], Mariusz Jerzy Stolarski [1], Michał Krzyżaniak [1] and Kazimierz Warmiński [2]**

1 Centre for Bioeconomy and Renewable Energies, Department of Plant Breeding and Seed Production, Faculty of Environmental Management and Agriculture, University of Warmia and Mazury in Olsztyn, 10-724 Olsztyn, Poland; mariusz.stolarski@uwm.edu.pl (M.J.S.); michal.krzyzaniak@uwm.edu.pl (M.K.)

2 Centre for Bioeconomy and Renewable Energies, Department of Chemistry, Faculty of Environmental Management and Agriculture, University of Warmia and Mazury in Olsztyn, 10-720 Olsztyn, Poland; kazimierz.warminski@uwm.edu.pl

* Correspondence: e.olba-ziety@uwm.edu.pl; Tel.: +48-89-5234397

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**Abstract:** Biomass remains one of the most important materials for the production of renewable energy in the European Union. Willow can be one of the sources of biomass, and its production can also be profitable on soils with low quality. A proper selection of raw material for energy production should be based not only on the cost effectiveness or crop yield, but also on the environmental impact and the cost it incurs. The aim of this work was to evaluate the external environmental costs of the production of willow chips of seven willow genotypes, produced for energy generation on marginal cropping lands. The environmental external costs of chips production were estimated against the amount of emissions calculated according to the LCA method (ReCiPe Midpoint) and its monetary value. The external environmental cost of willow chips production amounted to €212 ha$^{-1}$ year$^{-1}$, which constituted 23% of the total production cost of willow chips. The external cost of production of 1 Mg d.m. of willow chips for the best yielding variety averaged €21.5, which corresponded to 27% of the total production cost. The research demonstrated that a proper selection of an optimal variety may lead to the reduction of the external cost.

**Keywords:** externalities; economic analysis; willow biomass production; new varieties; sustainable production

## 1. Introduction

The development of renewable energy has stimulated the growing interest in biomass [1], which is its main source in both Poland and the whole EU [2]. Biomass for energy purposes is mostly obtained from forests, but also includes short-rotation coppice (SRC) [3], herbaceous crops and other streams of residues [1,4].

The need for the diversification of the material sources has led to the establishment of dedicated plantations of woody biomass, which ensure the availability of consistent quality biomass for most of the year [5]. Of all the natural perennial crops grown in Poland, willow attracts special attention [2]. The literature includes many works describing the suitability of willow as a resource for energy production [6]: electricity, heat [7–9] and biofuel [10,11]. It has been demonstrated that production of willow wood pellet, in comparison with the generation of electric power and production of biofuels, has the smallest impact in all environmental impact categories. In turn, electric power generation is the second best option in terms of environmental emissions (except for blue water consumption and particulate matter $PM_{2.5}$) to use willow for energy purposes. Production of biofuels has the strongest impact in most of the environmental impact categories [12]. Finally, analysis of the production of bioethanol and biomethane from lignocellulosic biomass (straw) has proved that bioethanol production has a weaker impact on the environment than production of biomethane as co-fermentation of lignocellulosic biomass substrates leads to the production of high density biofuels, although reaching a higher $CO_2$ equivalent emission per energy unit globally [13].

The willow yield, depending on many factors such as species, variety, climatic conditions, plantation technology soil conditions and many others, may reach 34 Mg $ha^{-1}$ $year^{-1}$ d.m. under optimal conditions, although typical yields are around 8–12 Mg $ha^{-1}$ $year^{-1}$ d.m. [14]. Under certain environmental and economic conditions, willow can be grown profitably [15–18]. Considering the issue of soil competitiveness for food production and non-food production, including energy purposes, it is worth noting that willow can be grown on marginal cropping lands [2,10,19–21]. What also transpires from many relevant studies is that willow seems an appealing choice because of the limited greenhouse gas emissions caused by its production [7,11,19,22,23].

The evaluation of willow production for energy purposes is often carried out through Life Cycle Assessment (LCA) [24–27]. This method allows an evaluation of the product impact on the environment in all its phases, namely from the harvesting of raw material to the generation of a product, and even further into its disposal and recycling [28]. LCA is a holistic approach with respect to the environment, but it is not until LCA is integrated with an economic assessment that decision makers can gain full insight to evaluate the environmental and economic impact of a product. A feasibility study is part of every product's analysis, but it overlooks a whole group of costs generated in its life cycle. These costs are the external costs related to the environmental impact of different elements/stages of production [29]. Internal costs are defined by the price paid by the consumer. External costs are mainly the costs borne by the society in the form of taxes, as well as costs of the losses to the quality of the environment and natural capital as well as costs of restoring the quality of natural resources, i.e., air, water and soil. In his review, Stern [30] indicated that climate change proves market failure, called externality in economics. The external ecological effects follow not only from the climate change, but also the changes in the air, water and soil quality; they in turn have impact on human health and environment.

The literature provides examples of methods for making an economic assessment of the environmental impact [31]. The most popular are (ExternE) [32] "External Costs of Energy," a method of calculating external environmental cost, mainly based on the market prices, and "Willingness to pay," which was implemented in the EcoSense model. Stepwise2006 [33,34] is a method of budget constraint. Monetary values of indicators for three damage categories are provided: Quality-Adjusted Life Years (QALYs) for impacts on human wellbeing, Biodiversity Adjusted Hectare Years (BAHYs) for impacts on ecosystems, and monetary units (EUR2003) for impacts on resource productivity [31]. Ecovalue08 [35,36] is a method which takes advantage of both contingent valuation and the market price; it is used for the monetization of the impact indicators in midpoint category. EPS [37–39] is an approach which makes use of the WTP (willingness to pay) for human health evaluated using contingent valuation (value taken from ExternE), and averting behaviour method, developed for LCIA on the endpoint level. Ecotax02 [40,41] is a method where the weight ratios come from the taxes and environmental fees in effect in Sweden. LIME 1-2 [42,43]—life cycle impact assessment method based on endpoint modelling is an approach based on the preferences determined through an experimental method in the category of human health Disability-Adjusted Life Year (DALY), social resources (jen), and bio-diversity through Expected Increase in Number of Extinct Species (EINES) and Net Primary Production (NPP). EVR [44–46] is a method of cost reduction based on the cost necessary to reduce the current pollution and resource depletion to a sustainable level.

Monetization, or an economic assessment of the environmental impact, is defined by many authors and in many approaches [46,47], although further studies in this scope are still necessary. It is important that external costs should be included in the economic assessment, i.e., internalizatised, as it allows one to fully evaluate the cost of production [34,48–51]. Therefore, an assessment of the external cost incurred during the production of materials is one of the aspects which should constitute a complex evaluation of the material in the production of renewable energy [52]. Dias et al. [7] demonstrated in their research that the use of biomass for bioenergy generation could be a valuable approach to mollify climate change and it might generate economic benefits as well, although it is important to ensure that this source of energy does not entail other environmental costs. Hence, the identification and evaluation of external environmental costs belong to applied science.

An assessment of external environmental costs will not only allow one to estimate the full cost of willow chip production for energy purposes but will also make it possible to identify sources of these costs and assess costs of emission to the environment due to the implemented production stages, applied production means and other decisions affecting the entire production process. In the light of the above, the aim of this research was to make an evaluation of external environmental cost of the seven genotypes of willow chips production including cultivation, harvesting, chipping and transporting. In addition, an attempt was made to identify production stages responsible for specific external costs, and to determine which environmental impact categories generate the highest costs.

## 2. Materials and Methods

### *2.1. Field Experiment*

The research was based on experimental data obtained from a willow plantation where seven genotypes were grown, including five varieties (Star, Tur, Turbo, Żubr—previously clone UWM 006, Ekotur—previously clone UWM 043 and two clones (UWM 155 and UWM 035), bred in the Department of Plant Breeding and Seed Production of the UWM in Olsztyn. All of these varieties and clones will be referred to here as varieties. A plantation of 10.5 ha was located in north-eastern Poland, in the village of Samławki (53°59′ N, 21°05′ E), on a field of the Research Station in Łężany, owned by the University of Warmia and Mazury in Olsztyn (UWM). The plantation was established in 2010 and run for three-year harvesting cycles. It was assumed that the plantation would be used for 21 years and later terminated. The field research included the preparation of the farmland (glyphosate spray of 1.44 kg ha$^{-1}$ of active substance), fertilization of 300 kg of PRP Sol (a calcium and a magnesium fertilizer mixed with minerals specific to PRP technology and agglomerated by a soluble plant-based binder—lignosulphonate), harrowing and mechanical planting of cuttings with a step planter. The preparation also included spraying with a soil herbicide (1.58 kg$^{-1}$ of active substance), mechanical weeding and spraying with a herbicide against monocotyledon weeds (0.13 kg ha$^{-1}$ of active substance). In each cycle, fertilization was done: N—90 kg ha$^{-1}$ (as ammonium nitrate), $P_2O_5$ —30 kg ha$^{-1}$ (as triple superphosphate) and $K_2O$—60 kg ha$^{-1}$ (as potassium chloride). The crops were harvested every three years. Willow crops were harvested with a single stage forage harvester Claas Jaguar 830 modified for short rotation coppices. Chips were collected from the harvester with three tractors with trailers and transported to the farmstead, where they were loaded with a telescopic loader onto trucks and transported to a conversion plant. The road transport was conducted with 80 m$^3$ containers, which totalled approximately 25 Mg of fresh chips, and transported to a conversion plant over a distance of 50 km; the same distance after biomass unloading was added. The details of the plantation management were described in the previous articles on the crop yield and its suitability as a substrate for the biorefinery [53], energy value [6], production cost and economic feasibility [18], and environmental impact of production [24].

The analyses feature the following functional units: 1 ha of the plantation, 1 Mg of dry mass and 1 GJ of energy. The system boundaries assumed for a from cradle to gate (including the transport distance of 50 km) included the plantation and harvest of the analysed varieties of willow, chipping and transport to the conversion plant.

### *2.2. Internal Cost*

The evaluation of the internal cost [18] included the direct cost of performing all of the phases and operations, together with the use of fuel, materials and instruments for the plantation of the analysed varieties of willow, as well as harvesting, chipping and transporting. The evaluation of the internal cost was based on the prices in effect in 2012. The analysis of the environmental external cost included the impact evaluation for year 2015, so the internal cost was adjusted to the 2015 prices, against the rate of inflation in Poland, in line with ISO recommendations [54]. The rate of inflation in Poland by the Polish Central Bank in the consecutive years (2013–2015) was 0.8%, 0.1% and −0.7% respectively.

### 2.3. External Cost

The external environmental cost of willow chips production of the analysed varieties was determined on the basis of the amount of emissions, according to the Life Cycle Assessment method, and with the use of the Sima Pro software, as well as the monetary value of the emissions at midpoint category, proposed in the Environmental Prices handbook of the EU 28 version [46] (Table 1).

**Table 1.** Monetary value (€) of impact categories.

| Impact Category | Unit | Environmental Price as External Cost |
|---|---|---|
| Climate change | €kg $CO_2$ eq$^{-1}$ | 0.057 |
| Ozone depletion | €kg CFC-11 eq$^{-1}$ | 30.4 |
| Human toxicity | €kg 1,4-DB eq$^{-1}$ | 0.214 |
| Photochemical oxidant formation | €kg NMVOC$^{-1}$ | 2.1 |
| Particulate matter formation | €kg $PM_{10}$ eq$^{-1}$ | 69 |
| Ionising radiation | €kg $U_{235}$ eq$^{-1}$ | 0.0473 |
| Terrestrial acidification | €kg $SO_2$ eq$^{-1}$ | 5.4 |
| Freshwater eutrophication | €kg P eq$^{-1}$ | 1.9 |
| Marine eutrophication | €kg N eq$^{-1}$ | 3.11 |
| Terrestrial ecotoxicity | €kg 1,4-DB eq$^{-1}$ | 8.89 |
| Freshwater ecotoxicity | €kg 1,4-DB eq$^{-1}$ | 0.0369 |
| Marine ecotoxicity | €kg 1,4-DB eq$^{-1}$ | 0.00756 |
| Agricultural land occupation * | €$m^2a^{-1}$ | 0.0261 |
| Urban land occupation * | €$m^2a^{-1}$ | 0.0261 |

* Value of external cost of land use was taken for the evaluation of the environmental external cost in the impact category of agricultural land occupation and urban land occupation. Source: [46].

The monetary value of the emissions reflects the social cost and the cost of polluting the natural environment. They are expressed in euro per kilogram of the pollutant. The environmental prices indicate a loss of welfare following from one additional kilogram of pollution or a decibel of noise emitted into the environment. The use of environmental prices in the life cycle assessment allows one to evaluate the environmental footprint generated by a particular product or service.

Life Cycle Assessment is a standardized method (ISO 14040-44) of a quantitative analysis of the total environmental impact of products or services in their life cycles delineated by the system boundaries, namely the life phases included in the analysis. It is based on the identified and determined amount of the used materials and energy as well as residues and other emissions entered into the environment. Subsequently, the impact of these processes on the environment is evaluated both for the utilization of resources and the emission of pollutants. The LCA analysis for the varieties of willow presented in work [24] were determined by the CML 2 baseline 2000 method; however, for the sake of this analysis, the results originating from the life cycle impact assessment of willow cultivation were determined according to ReCiPe Midpoint (H). 14 impact categories were investigated: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation and urban land occupation (Table 2).

**Table 2.** Data from LCIA of 1 Mg d.m. willow chips taken for the analysis.

| Impact Category | Unit | Start | Tur | Turbo | Żubr | UWM 035 | Ekotur | UWM 155 | Average |
|---|---|---|---|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | 45.26 | 74.22 | 46.55 | 27.63 | 59.92 | 31.91 | 108.44 | 44.89 |
| Ozone depletion | kg CFC-11 eq | 0.000012 | 0.000017 | 0.000012 | 0.000009 | 0.000014 | 0.000010 | 0.000021 | 0.000012 |
| Human toxicity | kg 1,4-DB eq | 12.54 | 19.74 | 12.65 | 7.90 | 15.47 | 8.91 | 25.33 | 11.95 |
| Photochemical oxidant formation | kg NMVOC | 0.70 | 0.87 | 0.71 | 0.57 | 0.77 | 0.60 | 1.06 | 0.68 |
| Particulate matter formation | kg $PM_{10}$ eq | 0.26 | 0.35 | 0.26 | 0.19 | 0.30 | 0.21 | 0.44 | 0.25 |
| Ionising radiation | kg $U_{235}$ eq | 5.41 | 7.62 | 5.49 | 3.92 | 6.31 | 4.25 | 9.57 | 5.22 |
| Terrestrial acidification | kg $SO_2$ eq | 0.76 | 1.15 | 0.76 | 0.50 | 0.92 | 0.56 | 1.47 | 0.72 |
| Freshwater eutrophication | kg P eq | 0.034 | 0.060 | 0.034 | 0.017 | 0.044 | 0.021 | 0.078 | 0.032 |
| Marine eutrophication | kg N eq | 0.39 | 0.58 | 0.40 | 0.27 | 0.47 | 0.29 | 0.74 | 0.37 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0.011 | 0.015 | 0.011 | 0.008 | 0.012 | 0.008 | 0.019 | 0.010 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 0.25 | 0.39 | 0.25 | 0.16 | 0.30 | 0.18 | 0.50 | 0.24 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.28 | 0.43 | 0.28 | 0.18 | 0.34 | 0.20 | 0.55 | 0.26 |
| Agricultural land occupation | $m^2a$ | 1.09 | 1.49 | 1.10 | 0.81 | 1.25 | 0.87 | 1.86 | 1.05 |
| Urban land occupation | $m^2a$ | 0.59 | 0.76 | 0.60 | 0.47 | 0.66 | 0.50 | 0.94 | 0.58 |

## 3. Results and Discussion

Table 3 shows the total production cost of the willow varieties. The differences in the costs, both internal and external ones, followed from the varied crop yields obtained from the plantation. The lowest production cost and yield was found for UWM 155 (sum of cost €530 $ha^{-1}$ $year^{-1}$; average of yield 3.6 Mg $ha^{-1}$ $year^{-1}$ d.m.) and Tur (sum of cost €599 $ha^{-1}$ $year^{-1}$; average 4.8 Mg $ha^{-1}$ $year^{-1}$ d.m.) [53]; the highest percentage of external cost to total cost was observed for these varieties, namely 29% and 27%, respectively. The highest yielding varieties were Żubr (average 18.5 Mg $ha^{-1}$ $year^{-1}$ d.m.) and Ekotur (15.0 Mg $ha^{-1}$ $year^{-1}$ d.m.). The different costs of harvesting and transporting resulted in significant differences in the total cost [6]. Obviously, any additional application of production means will increase the external costs in any production, which is corroborated by Notarnicola [47]. The average yield from the remaining varieties amounted to 9.4 Mg $ha^{-1}$ $year^{-1}$ d.m. As far as the production cost of the willow chips analysed per 1 ha of land, the highest internal and external cost were incurred by production of Żubr and Ekotur (€1527 $ha^{-1}$ $year^{-1}$; €1289 $ha^{-1}$ $year^{-1}$). These two varieties also rendered in the highest value of revenue. This was important as the profitability of willow cultivation is most sensitive to the price and productivity of biomass [55]. For the highest yielding Żubr and Ekotur, the share of external cost was 20% and 21%, respectively (23% on average for all varieties). Comparable results were observed for poplar chips on mineral fertilization (24%) [56].

**Table 3.** Equivalent annual cost of production depending willow variety (€$ha^{-1}$ $year^{-1}$).

| Willow Variety | Sum of Cost (€$ha^{-1}$ $Year^{-1}$) | | |
|---|---|---|---|
| | Internal | External | Total |
| Start | 669 | 205 | 873 |
| Tur | 439 | 160 | 599 |
| Turbo | 669 | 208 | 877 |
| Żubr | 1221 | 306 | 1527 |
| UWM 035 | 540 | 181 | 721 |
| Ekotur | 1019 | 270 | 1289 |
| UWM 155 | 375 | 155 | 530 |
| Average | 706 | 212 | 918 |

The average total cost of production per 1 Mg d.m. of willow chips was €94.0, of which €29.2 was the external cost. The average share of external cost in the total production cost of 1 Mg d.m. of willow chips was 31% (from 27% for Żubr and 28% for Ekotur to 38% for UWM 155) (Table 4). The internal cost of 1 Mg UWM 155 willow chips was 1.5 times higher than for Żubr, while the external cost was 2.5 times higher. In other research, the share of external cost in the production of 1 Mg d.m. of poplar on mineral fertilization was lower and equalled 23% [56].

**Table 4.** Equivalent cost of production 1 Mg d.m. depending on willow variety (€ $Mg^{-1}$ d.m.).

| Willow Variety | Cost (€ $Mg^{-1}$ d.m.) | | |
|---|---|---|---|
| | Internal | External | Total |
| Start | 65.8 | 30.3 | 96.1 |
| Tur | 79.9 | 43.4 | 123.3 |
| Turbo | 65.8 | 30.7 | 96.5 |
| Żubr | 57.2 | 21.5 | 78.7 |
| UWM 035 | 71.5 | 35.8 | 107.3 |
| Ekotur | 59.0 | 23.5 | 82.5 |
| UWM 155 | 89.3 | 55.5 | 144.8 |
| Average | 64.7 | 29.2 | 94.0 |

The analysis of the production of willow varieties for energy purposes indicates that both the internal and external cost were the lowest for the Żubr and Ekotur varieties, and so was the share of the external cost to the total cost. The average cost of producing 1 GJ was €5.53, of which the internal cost was €3.81, and the external €1.72 (Table 5). The differences in the calorific value [54] decreased the share of the internal cost for the variety of a calorific value and increased the share of the external cost relative to the analyses per 1 Mg d.m. Such relations were observed for Tur and UWM 035 varieties, which achieved the highest calorific values (Tur, UWM 035); in the varieties of lower calorific value, like UWM 155, Turbo and Star, the share of the external costs diminished.

**Table 5.** Production cost of willow variety per energy unit (€$GJ^{-1}$).

| Willow Variety | Cost (€$GJ^{-1}$) | | |
|---|---|---|---|
| | Internal | External | Total |
| Start | 3.91 | 1.78 | 5.69 |
| Tur | 4.31 | 2.50 | 6.81 |
| Turbo | 4.11 | 1.83 | 5.94 |
| Żubr | 3.41 | 1.26 | 4.67 |
| UWM 035 | 4.11 | 2.09 | 6.19 |
| Ekotur | 3.51 | 1.38 | 4.89 |
| UWM 155 | 5.71 | 3.35 | 9.06 |
| Average | 3.81 | 1.72 | 5.53 |

The comparison of the production cost of 1 GJ from willow varieties and 1 GJ of polar chips (from our previous research) on mineral fertilization [56] indicates that the share of the external cost was similar among the highest yielding varieties, 26% for poplar and 27% for Żubr and Ekotur willow varieties. The share of the external cost for the other willow varieties was higher, 31% on average and 37% for Tur variety.

The results concerning the willow varieties indicate a relatively high average share of the total external cost in the total cost of producing 1 Mg d.m. in comparison with poplar chips presented in other research [56]. However, these values for the best yielding Żubr and Ekotur varieties were comparable. Also Panataleo et al. [49] investigated the impact of the external environmental effects of energy crops on the biomass, and calculated the external cost of forest biomass of short rotation to stand at 15%. Such significant differences may result from the lower internal costs of production than in other European countries [15] while the external cost for the EU28 is higher. In accordance with the Environmental Prices handbook the EU 28 version [46], the monetary Value Of Life Year (VOLY), or the endpoint impact category was adopted in line with the NEEDS project for the EU 15: €41,000, in 2005 prices, and then recalculated for €48,000 to correspond to the 2015 prices. In line with the calculations made by Desaigues et al. [57], the recommended VOLY value for Poland and other countries outside the EU 15 for 2015 should amount to €38,635. Following the recommendation that the VOLY values for countries outside the EU 15 should be lower by 24%, the values obtained by the authors perhaps should have been decreased accordingly. Another solution could be to adopt the environmental prices for midpoints for the monetary evaluations in countries outside the EU 15, based on the individualist characterization perspective at a lower value rather than the central value.

The analysis of the external production cost of willow varieties relative to the production phases per 1 hectare (in the whole life cycle of the plantation) indicated that the highest external cost, depending on the variety, was incurred by harvesting (Figure 1). For example, it came up to €2800 for the Żubr variety. The cost of fertilization was also high (over €1800) and the same for all of the varieties. Transport was also expensive, for instance nearly €1250 for Żubr and over €1000 for Ekotur. Similarly, in the structure of the internal cost analysed in previous studies [18], harvesting (26% share) and fertilization (33% share) made a major contribution; according to Havličjova [58], they had the largest impact on the minimal price of the produced biomass. Soil carbon sequestration was estimated as a value that reduced the cost, and its amount did not differ much between the varieties. The value of sequestration C was between €−873 for the Żubr variety to €−502 for Tur, with the average of €−622. The external cost of over €100 per 1 ha was also incurred for plantation re-establishment, tractor transport, loading chips (only for the Żubr variety).

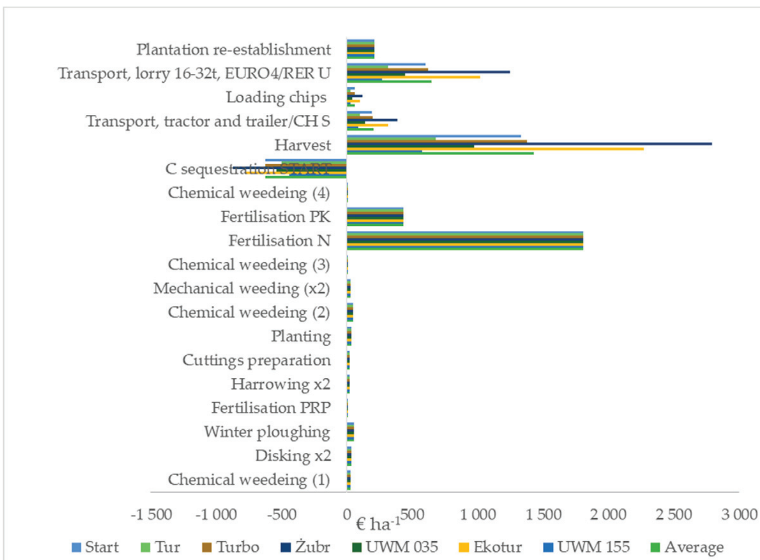


**Figure 1.** External cost for willow chips production depending on variety per 1 ha.

The analysis of the external cost of producing willow chips with reference to the agrotechnical operations per 1 Mg d.m. (Figure 2) and 1 GJ (Figure 3) suggested that nitrogen fertilization generated the highest external cost, particularly for the low yielding varieties (UWM 155—over €30 Mg$^{-1}$ d.m. and €1.86 GJ$^{-1}$, and for Tur over €23 Mg$^{-1}$ d.m. and €1.35 GJ$^{-1}$), unlike for the high yielding varieties (Żubr, Ekotur), where these values were €6 i €7 Mg$^{-1}$ d.m, and €0.36 and €0.44 GJ$^{-1}$. PK fertilization yielded a similar structure of the external cost, but the values were smaller by over €7 Mg$^{-1}$ d.m, €0.45 GJ$^{-1}$ for UWM 155 to €1.4 Mg$^{-1}$ d.m. and €0.32 GJ$^{-1}$ for Żubr.

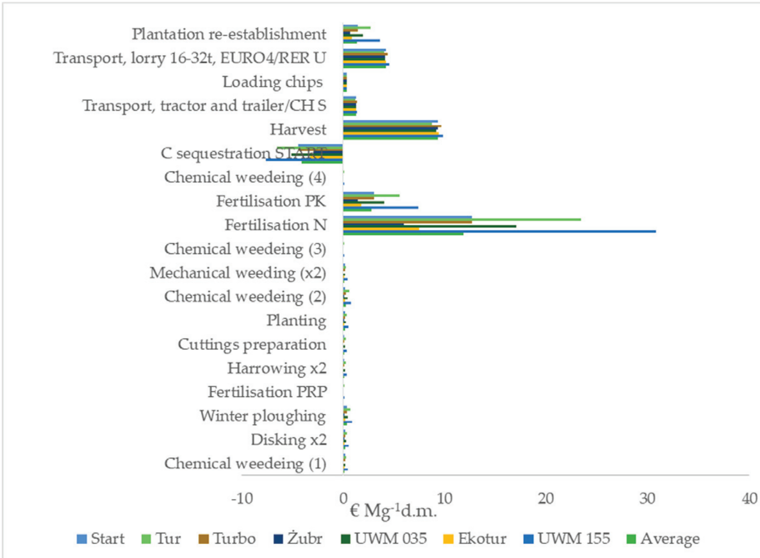


**Figure 2.** External cost for willow chips production depending on variety per 1 Mg d.m.

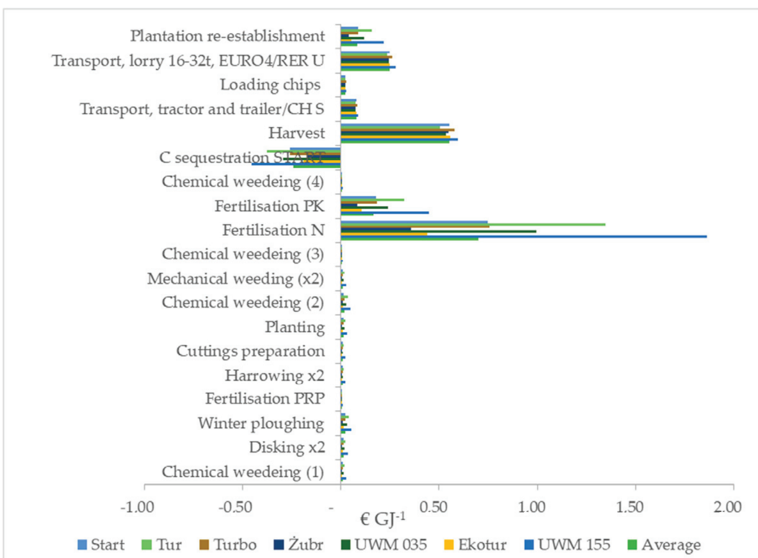


**Figure 3.** External cost for willow chips production depending on variety per 1 GJ.

Like the external cost per hectare, the other phases of production generating high external cost per unit of mass (Figure 2) and energy (Figure 3) were harvest and transport. The values were similar, at approximately €9 and €1.3 $Mg^{-1}$ d.m. and €0.55 $GJ^{-1}$ i €0.08 $GJ^{-1}$, respectively. With regard to C sequestration, which reduced the external cost, the highest negative value was calculated for UWM 155 (€−7.56 $Mg^{-1}$ d.m and €−0.46 $GJ^{-1}$) and for Tur (€−6.52 $Mg^{-1}$ d.m; €−0.37 $GJ^{-1}$); the lowest was computed for Żubr (€−2.92 $Mg^{-1}$ d.m and €−0.19 $GJ^{-1}$) and for Ekotur (€−3.22 $Mg^{-1}$ d.m; €−0.17 $GJ^{-1}$). Also, the internal cost of biomass production increased along with the increase in yield per 1 ha. This was due to the longer working time and the use of fuel, machines, and devices for harvest and transport. On the other hand, the cost of the establishment of plantation, fertilization, and plant protection was the same for all of the varieties, and its share in the total cost diminished as the willow yield increased. This is why the improvement in the economic effectiveness in both internal and external biomass production cost must be attained through the selection of varieties and the optimization of the willow harvesting technology [18]. Tharakan et al. [59] demonstrated that an increase in production may reduce the unit cost (per Mg d.m.) of delivering biomass to the end user by 13%. LCA analyses carried out by other authors [11] also indicated that nitrogen fertilization and diesel fuel in willow production had a significant environmental impact; in their view, the introduction of biodiesel to agriculture could reduce its negative impact on the environment.

An investigation into the categories of environmental impact of willow chips production singled out particulate matter formation as the one which involved the highest external cost. The cost in this category was between €1792 ha$^{-1}$ for UWM 155 and €3935 ha$^{-1}$ for Żubr (on average €2615 ha$^{-1}$) during the lifetime of the plantation (Figure 4). The external cost in the range of €180 ha$^{-1}$ to €600 ha$^{-1}$ followed from the categories: terrestrial acidification, human toxicity, climate change, photochemical oxidant formation, marine eutrophication. The external cost related to other impact categories in the whole period of the plantation's use amounted to less than €50 ha$^{-1}$. In our previous research the highest external cost for the poplar on mineral fertilization was also particulate matter formation, but terrestrial acidification came close second, at €1614 ha$^{-1}$ and €1519 ha$^{-1}$ respectively [56]. In other study the analysis of the external cost of electricity production from various biomass materials indicated that emissions of $PM_{10}$, $NO_X$ i $PM_{2.5}$ were one of the most significant factors contributing to this cost, and followed from the combustion of fossil fuels in the production of fertilizers [60].

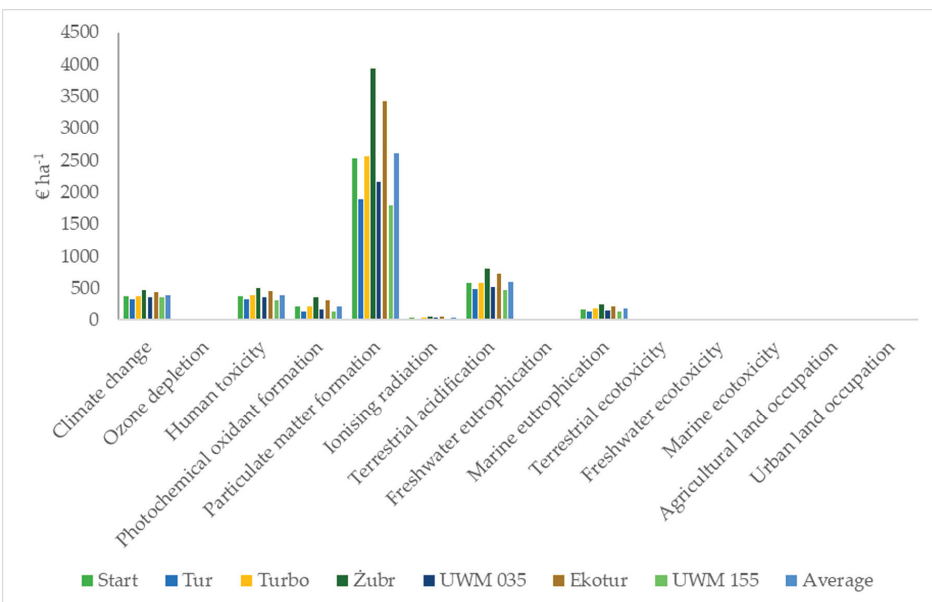


**Figure 4.** External cost of willow varieties production per 1 ha depending on impact category.

The analysis of the external cost of willow chips production per 1 Mg d.m. (Figure 5) and 1 GJ (Figure 6) also confirmed the highest cost of particulate matter formation, €17.17 Mg$^{-1}$ d.m., €1 GJ$^{-1}$ on average. The highest cost per 1 Mg d.m. and 1 GJ was generated by the lowest yielding varieties, namely UWM 155, while the lowest cost was generated by the best yielding varieties, like Żubr.

The external cost related to particulate matter formation was €13.17 $Mg^{-1}$ d.m and €0.77 $GJ^{-1}$ for Żubr, and €30.58 $Mg^{-1}$ d.m. and €1.84 $GJ^{-1}$ for UWM 155. The second group was composed of the categories: terrestrial acidification (from €2.69 $Mg^{-1}$ d.m. to €7.93 $Mg^{-1}$ d.m. and from €0.16 $GJ^{-1}$ to €0.48 $GJ^{-1}$), and climate change and human toxicity at similar levels (from ok €1.5 $Mg^{-1}$ d.m. to approximately €6 $Mg^{-1}$ d.m. and from approximately €0.1 $GJ^{-1}$ to approximately €0.35 $GJ^{-1}$). Emissions in the category of photochemical oxidant formation generated the cost of from €1.2 $Mg^{-1}$ d.m. to €2.23 $Mg^{-1}$ d.m. and from €0.07 $GJ^{-1}$ to €0.13 $GJ^{-1}$) for Żubr and UWM 155 varieties, respectively. Particulate matter formation was an impact category of the highest weight in the procedure suggested by Hafizan et al. [61], while the second highest category was fossil depletion. In LCA studies over willow production, the highest environmental impact was determined in the range of 51–67% in the following categories: global warming, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity [24,62]. Besides, a high impact of willow production on the environment in terms of acidification was also noted by Borzecka-Walker et al. [63].

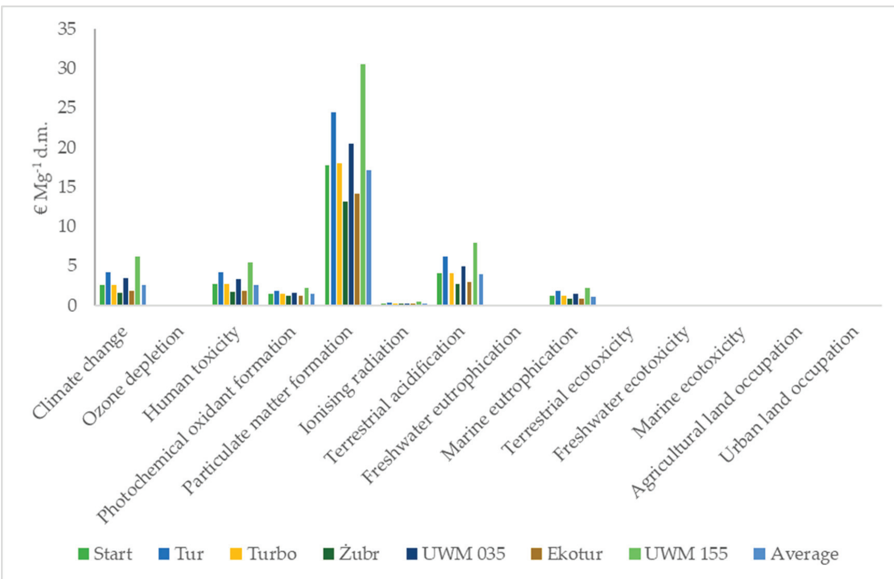


**Figure 5.** External cost of willow varieties production per 1 Mg d.m. depending on impact category.

In the analysis of the structure of external costs generated in willow chips production (Figure 7), it is noteworthy that the share of particulate matter formation exceeded half of the cost for every variety, namely from 55% for UWM 155 (a low yielding variety [53]) to 61% for Żubr (a high yielding variety [53]); the average was 59%. Another cost-intensive impact category was terrestrial acidification. The share of this cost was different, from 13% for Żubr to 14% for Tur (low yield varieties [53]). The share of the other impact categories in the cost usually did not exceed 10% (with the exception of 11% for climate change in the case of UWM 155). The other impact categories whose share in the external cost was at 8–9% were human toxicity and climate change. The share of photochemical oxidant formation and climate change was 4–5%, while the share of the remaining categories did not reach 1%. An LCA analysis [24] of the production of 1 Mg willow chips for indicated a significant contribution of mineral fertilization to global warming. Another phase of production, harvesting, also significantly contributed to global warming through its acidifying impact. The LCA also showed the positive influence of carbon sequestration in the soil under the willow plantation, mitigating global warming. The normalization value for average yield (chips transporting distance of 25 km) indicated that freshwater toxicity had the largest impact on the environment.

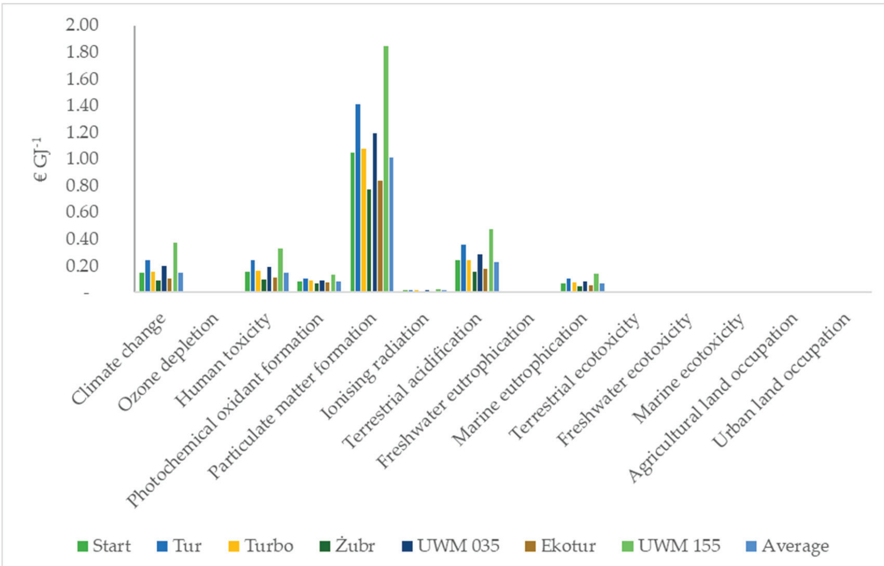


**Figure 6.** External cost of willow varieties production per 1 GJ depending on impact category.

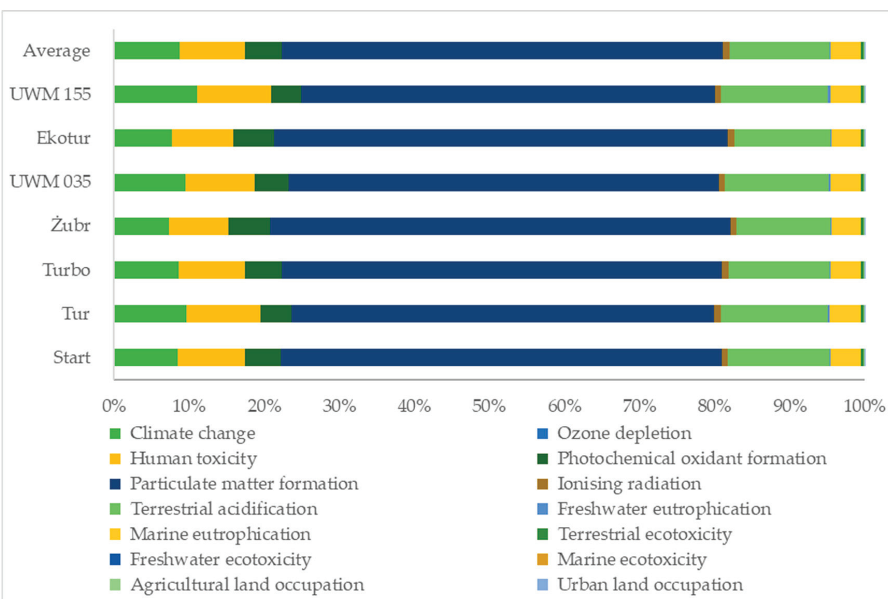


**Figure 7.** Contribution to the sum of external cost of field operation depending on impact category.

Both the analysis of the external environmental cost and the economic and energy research results presented in previous works [18,53] demonstrated that the selection of willow varieties is of utmost importance. The cost of fertilizers was the dominant variable for the lowest yielding varieties, whereas for the high yielding varieties it was the cost of diesel fuel. It was determined that the cultivation of high-performance willow varieties may lead to a significantly reduced energy consumption in the willow chips production and a higher energy ratio in comparison with the varieties of lower productivity. The analysis of the energy consumption and the energy ratio in the production of chips of new willow varieties also defined the optimal transporting distance to the end user. The lowest energy consumption was noted for the Żubr variety. When the yield exceeded 86 Mg $ha^{-1}$ of fresh biomass, the energy intensity amounted to 0.35 GJ $Mg^{-1}$ f.m. [6]. Although it is often recommended that biomass should not be transported further than 30–50 km, the LCA analysis and the profitability studies of willow chip production indicate that for high-yielding varieties, like Żubr, willow chips can be transported for up to 100 km [18,53]. Transport is an important issue as the external cost they generate may reach 26–37% [64].

Woody plants of short rotation, like willow, have a lower or similar impact on the environment to other perennial energy crops. Their impact is 2- to 3-fold lower than that of annual crops, which is true for food, energy or industrial crops [63]. The evaluation of the impact on the environment resulting from the production of 1 MJ thermal energy from short rotation willow (SRC) compared to fossil fuel (heating oil and gas) indicated that the direct combustion of the SRC chips reduced the global warming potential (GWP) by nearly 85% against fossil fuels, and the carbon sequestrated by the SRC biomass reduced the GWP by 23% [7]. Similar results related to the reduction of the GHG can be found in the literature [27,65–67]. However, in comparison with fossil fuels, the energy generated from SRC had a larger share in such categories as eutrophication, due to the use of mineral fertilization in the production of biomass [7]. The production of energy from fossil fuels involves three key environmental strains, and in consequence, an environmental cost. These are land use, depletion of non-renewable resources and air pollution from the emissions of $CO_2$, $CH_4$, $N_2O$, CO, $NO_X$, $SO_2$, VOC i $PM_{10}$. It was determined that the environmental cost they involve constitute as much as 34% of the total production cost of conventional diesel fuel [68]. An equal value of external cost, namely 33.6%, was obtained for the production of 1 $dm^3$ of diesel fuel [69]. A shift from fossil fuels to willow for the production of electricity was estimated to reduce the external cost of air pollution in the range of \$0.02–0.06 $kWh^{-1}$ [70]. The study by Wang et al. [71] confirms that the external cost of using coal for the production of electricity amounted to \$0.072 $kWh^{-1}$, while the same cost for the production of electricity from biomass was \$0.00012 $kWh^{-1}$. In China, the direct internal cost of energy from biomass reached CNY 0.44 per 1 kWh (approx. \$0.0678 $kWh^{-1}$); this figure for coal was higher by 25–37%. However, due to significant emissions of the GHG and $PM_{2.5}$ pollution during coal combustion, the external cost of coal energy is estimated at CNY 0.17 $kWh^{-1}$ (approx. \$0.0262 $kWh^{-1}$) and from biomass at CNY 0.06 $kWh^{-1}$) (approx. \$0.0092 $kWh^{-1}$), on average. What follows from estimations is that if the external environmental cost were included in the cost or electricity production, the production of electricity from biomass would be less expensive than from coal [71]. Owen [72] suggested that the inclusion of the external cost to the price of production of electricity would render some of the renewable technologies financially competitive against the energy generated in coal power plants.

Cultivation of crops for energy purposes, like willow, generates not only cost but also several environmental benefits. Nitrogen remains a key element in today's agriculture [73]. The positive nitrogen-binding impact of willow plantation, which eliminates fertilizer-derived nitrogen compounds from the soil of the neighbouring plantations was estimated at \$1.8–37.0 kg $year^{-1}$ N [74,75]. Brink et al. [76] analysed the cost of nitrogen in the environment and concluded that the annual damage resulting from the presence of nitrogen in waters and soils of the European countries varied between €70 and €320 billion (€150–750 per resident), of which 75% was related to harm to the human health and air pollution. Jongeneel et al. [77] presented an analysis of the Dutch agricultural sector in terms of the cost and benefits of externalities. The authors estimated the annual external cost related to agriculture at €1857 million, while the revenue from positive externalities was estimated at €186.2 million.

Another group of environmental benefits derived from willow cultivation is the enhanced biodiversity. A well-managed SRC plantation can enrich biodiversity in a landscape dominated by agriculture [78]. It has also been found that willow plantations grown for energy purposes increase the biodiversity of earthworms and add to landscape diversity [79]. An SRC plantation has also been identified as a habitat for many microorganisms, soil organisms and insects [80].

## 4. Conclusions

The external cost of willow chip production varied between varieties; in other words, the value and share of the cost depended on a crop yield. The highest external cost (per 1 Mg d.m. and 1 GJ) of a willow plantation was obtained for the lowest yielding varieties, like UWM 155 and Tur, whereas the lowest cost was determined for the highest yielding varieties, such as Żubr and Ekotur. The external environmental cost of willow chip production amounted to €212 $ha^{-1}$ $year^{-1}$ which constituted 23% of the total production cost of willow chips. The average total cost of production per 1 Mg d.m. of willow chips was €94.0, of which €29.2 was the external cost.

Among the agrotechnical operations, nitrogen fertilization generated the highest external cost, particularly for the low yielding varieties (UWM 155—€1.86 $GJ^{-1}$, and for Tur—€1.35 $GJ^{-1}$), unlike for the high yielding varieties (Żubr, Ekotur), where these values were €0.36 and €0.44 $GJ^{-1}$. The research demonstrated that a proper selection of an optimal variety may lead to the reduction of the external cost. The highest external cost was generated in categories of particulate matter formation (from €0.77 to €1.84 per 1GJ) and terrestrial acidification (from €0.16 to €0.48 per 1GJ), which followed from the use of mineral fertilizers. Such high values of the external cost indicate the need to seek production residues, which could be used for fertilizing plants, enriching the soil, and enhancing the productivity of biomass, in particular in the areas with poorer soils. Willow harvesting also involved a significant external cost, which points at harvesting technologies, machine capacity, and energy intensity of this phase as key elements of the process.

Determination of the external environmental costs involved in the production of energy from biomass is an extremely important step in any discussion on profitability of energy generation, especially from such non-renewable resources as coal. When the price of raw material for energy generation does not include such aspects as depleting non-renewable energy sources or $CO_2$ emission, then an image of the estimated production costs is erroneous and therefore an estimate of the energy production profitability is incorrect as well. Whenever external environmental costs are not included, the consequence is the omission of costs borne by the society, that is by consumers, who make buying decisions based on the price usually reflecting only internal costs, and neglecting the costs that need to be covered in order to restore or maintain the quality of the natural environment in at least non-deteriorated condition.

To sum up, our research has shown that a comprehensive evaluation of the economic effectiveness, beside the internal and external cost, will also require studies of the environmental benefits of willow cultivation and its cascading use for energy and industrial purposes. It is worth adding that the literature provides information about other methods and values applied to estimate the monetary value of pollutants, with results different from the ones employed in this study. Moreover, the subject raised in this paper is relatively new and submitted to ongoing investigations, therefore it cannot be excluded that results of current analyses will need to be verified in the future. Moreover, social aspects have not been discussed in this article, as they fall outside the scope of this study. The importance of social issues related to the production and use of bio-materials for renewable energy and other bio-products cannot be stressed enough, which is why these considerations will be the subject of our future research.

**Author Contributions:** Conceptualization, E.O.-Z.; methodology, E.O.-Z., M.J.S., M.K.; software, E.O.-Z., M.K.; validation, E.O.-Z., M.J.S., M.K., K.W.; formal analysis, E.O.-Z., M.K.; investigation, E.O.-Z., M.J.S.; resources, E.O.-Z., M.J.S.; data curation, E.O.-Z., M.K., M.J.S.; writing—original draft preparation, E.O.-Z.; writing—review and editing, E.O.Z., M.J.S., M.K., K.W.; visualization, E.O.-Z.; project administration, E.O.Z., M.J.S. All authors have read and agreed to the published version of the manuscript.

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# Potential of Straw for Energy Purposes in Poland—Forecasts Based on Trend and Causal Models

**Piotr Gradziuk [1,*], Barbara Gradziuk [2], Anna Trocewicz [3] and Błażej Jendrzejewski [1]**

1. Economic Modelling Department, Institute of Rural and Agricultural Development, Polish Academy of Sciences, Nowy Swiat 72, 00-330 Warsaw, Poland; bjendrzejewski@irwirpan.waw.pl
2. Department of Management and Marketing, Faculty of Agrobioengineering, University of Life Sciences in Lublin, Akademicka 13, 20-950 Lublin, Poland; barbara.gradziuk@up.lublin.pl
3. Department of Economy, Faculty of Economic Sciences, Pope John Paul II State School of Higher Education, Sidorska 95/97, 21-500 Biała Podlaska, Poland; usanna@op.pl

* Correspondence: pgradziuk@irwirpan.waw.pl

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**Abstract:** The mitigation of climate change poses a major challenge to the legal framework which aims to stimulate the development of renewable energy sources. The European Union's direction for the use of renewable energy is distributed generation and an increased use of by-products and organic waste, especially in the production of next-generation biofuels. The main aim of this study is to evaluate the production potential of straw in Poland and the possibility of its use for energy purposes, including a forecast for 2030, on the assumption that the management of this resource is in accordance with the provisions of the Polish Code for Good Agriculture Practice. In Poland, in the years 1999–2018, the average annual surplus of straw harvested over agricultural consumption equalled 12.5 million tons (4.2 Mtoe). Its largest surpluses were in the Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Wielkopolskie, and Zachodniopomorskie voivodeships (NUTS2). Based on the developed panel models, forecasts for straw surpluses in Poland are presented in three perspectives: realistic, pessimistic, and optimistic. The forecasts show regional differentiation until 2030. Each of the three perspectives indicate a slow increase in these surpluses, and depending on the adopted version, it will range from 10.6% to 21.9%.

**Keywords:** renewable energy sources; straw; biofuels; agriculture residues; forecasting; modelling; Poland

## 1. Introduction

The production of biofuels has led to many controversies. It has been undermined for ethical [1–4], economic [5–7], and environmental [8,9] reasons. Its production has become a subject of numerous discussions, polemics, comments, and contradictory judgments which vary from extreme negations and objections [10,11] to equally extreme affirmations and approvals [12,13]. Therefore, frequent changes in the legislations related to this market can be observed [14,15]. In 2019, the European Parliament and the European Council adopted the climate package [16] in which the European Union is obligated to reduce greenhouse gas emission by 20% (in $CO_2$ equivalent) by the year 2020 (if similar commitments are made by other developed countries, this reduction may be as high as 30%). In the same period, the EU is supposed to increase its share of renewable energy in total energy production from 8.5% to 20%, increase the share of biofuels in transport fuels to at least 10%, as well as reduce energy consumption by 20%.

The European Union's Renewable Energy Directive (EU-RED) [17] is the main document regulating the biofuels sector. Implementing these plans would result in very significant increases in global land use for biofuels and thus greenhouse gas (GHG) emissions due to the effects of both direct and indirect land-use changes. Various studies now conclude that quite a large share of these biofuels is not sustainable and is not likely to meet the sustainability criteria once Indirect Land Use Change (ILUC) is included [18–20]. Ongoing discussions and numerous analyses of the biofuels market resulted in modifications of existing solutions and changes in directives of the European Parliament and the European Council (EU) 2015/1513 [21] and (EU) 2018/2001 [22]. Among the key changes within the new directives is the limit for the first-generation biofuels (generated mainly from crops—grains, sugar cane and vegetables oils). The limit applied restricts their level at 7% in 2020. The other 3% (at minimum) are to consist of the second-generation biofuels. These, in turn, are to be produced from cellulose, hemicellulose (e.g., crop residues, leftovers in forestry), lignocellulosic crops, as well as third-generation biofuels derived from aquatic autotrophic organisms (e.g., algae).

The Renewable Energy Directive proposal for the period 2021–2030 presented by the EU Commission in November 2016 included the following 2030 targets concerning the transportation: decrease the limits on food and feed-based biofuels down to 3.8% and introduce a requirement for fuel suppliers requiring to blend 6.8% of advanced fuels [23]. To achieve them, the fuel industry entities are focusing their research and development (R&D) efforts to define and substantiate possible development pathways and improved fuel production technologies [24]. Among the key inputs for the production of new generation fuels is ordinary straw, being a crop by-product (residue) left in the fields after the primary crop (e.g., cereals, rapeseed, sunflowers) is harvested. The straw includes stalks, leaves, and empty ears and corncobs, which are the leftovers separated from the grains. Straw serves several functions as it can be used as lignocellulosic feedstock for the production of biofuels and chemicals while being a nitrogen-fixing element beneficial for the climate change mitigation. Theoretical advances [25–27] in regard to production of advanced biofuels based on straw inputs have been confirmed in practice [28–30] as well.

High investment costs (ca. €40 million for 50 Gg y-1 yield) [31] predefine the need for a long-term and stable supply of raw materials. Biomass has become one of the most globally studied directions to ensure renewable energy generation based on low-emission sources. There are also varied strategies [31–33] in regard to the biomass utilization as the renewable energy source. More in-depth analyses of straw use for bioenergy generation are also being conducted on regional and local levels [29–37]. One of them [38] reveals that total UK crop residues equal 20.4 Mt of dry matter (including 8.37 Mt collectable and 4.2 Mt available). Intensifying trend of the past several years is utilization of straw as the basis for second-generation biofuels (produced from agricultural non-food produce). Second-generation bioethanol is a liquid biofuel used for transportation purposes, which is in line with the sustainable development goals, since both the generation of ethanol and its combustion in engines contribute to diminishing the emission of $CO_2$ to the atmosphere [39–42]. The research conducted in Sweden shows that GHG emissions from biofuels produced from straw were significantly lower than those produced from cereal grains [43].

The issue of straw usage for energy purposes, including ethanol production, and analyses of its potential were also undertaken in Poland [16,32,44,45], but these studies were mainly retrospective and included only short-term forecasts [46–53]. This study fills the gaps in the literature because its main goal is the evaluation of the production potential of straw in Poland and the possibility of its use for energy purposes, including a forecast up to the year 2030, on the assumption that the management of this resource (straw) is in accordance with the provisions of the Polish Code for Good Agriculture Practice [54].

## 2. Materials and Methods

### *2.1. Overview*

Despite being a by-product, straw has a great economic importance, especially in agricultural production. It is mainly used as bedding, organic fertilizer or fodder. Such use of straw was proved in the early eighties by the research of Institute of Soil Science and Plant Cultivation (IUNG) in Puławy.

The research showed that ca. 58% of harvested straw was used for bedding, 36% for fodder and 6% for other uses (covering mounds, isolating mats in horticultural farms, insulating buildings). During periods of lower harvest, like in the years 1977–1980, there was even a deficit of straw. In the second half of the eighties, there was a shift in the structure of agricultural production resulting in a significant decrease of livestock (primarily cattle, sheep and horses) and increase in cereals and rapeseed sowing. Straw harvests began to exceed the demand, inducing theoreticians and practitioners to look for new uses such as production of energy [49,50,52].

### 2.2. Methodology and Material Sources for Estimation of Straw Surplus

In order to assess its quantity available for alternative use (energy production), the following formula was applied:

$$S_s = P_s - \left(D_I + D_f + D_{of}\right) \tag{1}$$

where:

$S_s$—surplus of straw for alternative use (energy production);
$P_s$—production of straw from basic cereals (including mixtures), rapeseed and corn;
$D_I$—straw demand for bedding;
$D_f$—straw demand for fodder;
$D_{of}$—straw demand for ploughing (organic fertilizer).

This selection of plants was based on the fact that the straw from basic cereals together with mixtures, rapeseed and corn constitute about 99% of total straw production in Poland and is suitable for energy production uses. The analysis is based on data received from the main office of the Statistics Poland (GUS) located in Warsaw. The data allowed the determination of the harvest of straw from cereals (including mixtures) in the years 1999–2019, divided by voivodeships NUTS2 (Nomenclature of Territorial Units for Statistics). The period was chosen due to administration changes introduced in 1 January 1999 which resulted in the creation of new voivodeship borders (NUTS2) [55]. The data mentioned above lacked information about the harvest of rapeseed and corn. The harvest of those plants was calculated based on the harvest of their seeds. The ratio of seeds to straw was assumed to be 1:1. In the data received from Statistics Poland, there was also no information about the distribution of straw. Straw demand for fodder and bedding was estimated on the basis of livestock population and annual norms for individual species and utility groups:

$$D_I = \sum_{i=1}^{n} q_i s_i \text{ and } D_f = \sum_{i=1}^{n} q_i p_i \tag{2}$$

where:

$D_I$—straw demand for bedding;
$D_f$—straw demand for fodder;
$q_i$—population $i$ of individual species and utility groups;
$s_i$ —straw demand norm for bedding by $i$ species and utility groups [56];
$p_i$ —straw demand norm for fodder by $i$ species and utility groups [56].

In recent years, the reduction in the area of grass and perennial legumes as well as a significant decrease in the animal population and the associated lower manure production resulted in a loss of organic matter in soil. In order to balance it, a proportion of the straw must also be allocated for the conservation of the soil's organic matter [50,57].

The increase or loss of organic matter can be measured with the use of coefficients which determine its reproduction or degradation [50,57]. Knowing the sown area of individual plant groups and the amount of manure produced (based on animal population and appropriate norms [$o_i$]), the balance of organic substance $B$ was determined based on to the following formula:

$$B = \sum_{i=1}^{n} a_{ri}c_{ri} + \sum_{i=1}^{n} a_{di}c_{di} + \sum_{i=1}^{n} q_i m_i \quad (3)$$

where:

$B$—balance of organic matter ($t$);
$a_{ri}$ —area of plant groups which increase the content of organic matter (ha);
$a_{di}$ —area of plant groups which decrease the content of organic matter (ha);
$c_{ri}$ —organic matter reproduction coefficient of given plant group (t·ha$^{-1}$);
$c_{di}$—organic matter degradation coefficient of given plant group (t·ha$^{-1}$);
$q_i$—livestock population by species and age groups (number of heads);
$m_i$—manure production norms by species and age groups (t·year$^{-1}$).

The occurrence of a negative balance of organic matter means that there is a need to plough a certain amount of straw to maintain a sustainable balance of humus. It was assumed that 1 ton of dry solid manure is equivalent to 1.54 tons of straw, hence the need for straw to be ploughed is calculated as follows:

$$D_{of} = 1.54\,B \quad (4)$$

where:

$D_{of}$—straw demand for ploughing (organic fertilizer);
$B$—balance of organic matter.

### 2.3. The Applied Statistical Methods

First, for each of the 16 voivodeships and for the whole of Poland, the best straw surplus trend model was searched for among linear (y = a0 + a1t) and non-linear models:

- $y = a_0 + a_1t^2$;
- $y = a_0 + a_1t^3$;
- $y = a_0 + a_1t + a_2t^2$;
- $y = a_0 + a_1t + a_2t^3$;
- $y = a_0 + a_1t^2 + a_2t^3$;
- $y = a_0 + a_1t + a_2t^2 + a_3t^3$.

The criterion for choosing the final model was the significance of the parameters as well as the value of the coefficient of determination, which were estimated using the Wolfram Mathematica software in addition, the selected model verified the hypothesis of the occurrence of autocorrelation residues based on the Box–Pierce and Ljung–Box tests [58]. Then, based on the 17 models, point projections for 2025 and 2030 were estimated along with 95% confidence intervals. Next, the selected models were subjected to further verification in order to determine (and confirm) their quality. Next, the selected model was subjected to further verification in order to determine (and confirm) its quality [59].

The amount of straw surplus was also estimated using a cause-effect model. The following variables were used to study the causes of changes in straw surplus:

$Y_1$—harvest of straw from basic cereals with mixtures (thousands of tons);
$Y_2$—harvest of straw from rapeseed (thousands of tons);
$Y_3$—harvest of straw from corn (thousands of tons);
$Y_4$—$Y_1$ + $Y_2$ $Y_3$;

$Y_5$—surplus of straw (thousands of tons);
$X_{11}$—sown area of basic cereals with mixtures (thousands of ha);
$X_{21}$—sown area of rapeseed (thousands of ha);
$X_{31}$—sown area of grain corn (thousands of ha);
$X_{12}$—straw yield from cereals with mixtures ($t \cdot ha^{-1}$);
$X_{22}$—straw yield from rapeseed ($t \cdot ha^{-1}$);
$X_{32}$—straw yield from corn ($t \cdot ha^{-1}$);
$X_{412}$—straw consumption for fodder and bedding (thousands of tons);
$X_{43}$—straw consumption for ploughing (organic fertilizer) (thousands of tons).

The procedure of finding the best set of variables consisted of the stepwise a posteriori elimination of statistically insignificant variables (at 0.05) from the model (which initially contained all potential variables) and the removal of non-coincident variables (which, if maintained, would cause difficulties in interpreting the estimated parameters of the model).

In order to estimate the forecasts based on the selected cause–effect models, it was required to obtain in advance the predicted values of explanatory variables. Such forecasts, broken down by individual voivodeships, were estimated based on the time series models from the ARIMA (p,d,q) (Autoregressive Integrated Moving Average) class models. Such models are relatively "universal" in that they consist of an autoregressive (AR) element and a moving average (MA), i.e., a random component with an extensive structure, and can additionally be built on different values (if necessary), which helps solve problems related to the modelling of non-stationary time series [58]. Moreover, these models are built only on the basis of statistical properties of modelled data—they do not require the search for any additional explanatory variables and automatically solve the problem of autocorrelation of residues, which is quite often found in "classic" models of linear or non-linear trend. The final step was the Granger causality test. According to this test, the variable X is a cause of the variable Y if current values of Y can be predicted with a greater probability based on former values of X than without them (with the rest as a constant), thus, when the coefficients of the delayed variables X are statistically significant.

Next, based on the 17 models, point projections for 2025 and 2030 were estimated along with 95% confidence intervals. As an additional method of verifying the quality and acceptability of forecasts estimated using these two types of models (i.e., trend and cause–effect), the straw surpluses forecast for individual voivodeships were summed and compared with the forecasts obtained for the whole of Poland.

## 3. Results

### *3.1. Statistical Characteristics of Variables*

One of the main factors determining the possibility of the use of straw in the energy sector is the volume and stability of its production. In the analysed years, the average annual total straw harvest ($Y_4$) in Poland amounted to 29.5 million tons. In terms of weight, it was similar to cereal grain harvests, which confirms the thesis put forward by V. Smil [60] that a significant part of the global production produced in agriculture are by-products. In countries with similar soil-natural conditions to Poland, straw is the most important among all by-products [61]. The highest harvests of straw in Poland, reaching 35.8 million tons, were recorded in 2014, and the lowest in 2000, 2003, and 2006 (respectively: 22.9, 24.0, and 23.4 million tons), which shows that they were characterized by significant fluctuations. In the harvest structure, the largest share had basic cereal straw with mixtures (84.8%), the production of which oscillated around an average of 25.1 million tons. Rapeseed had the lowest share (6.5%). Rapeseed straw ($Y_2$) harvests were characterized by a slow upward trend until 2003 and a significant increase from 2004. The lowest harvests occurred in 2003 and amounted to 793 thousand tons, after which they increased relatively quickly and reached the highest value in 2014 (3.4 million tons). The corn ($Y_3$) straw harvest was relatively small in 1999 (599 thousand tonnes) but began to increase very rapidly. In 2001, the corn straw harvest exceeded the level of the rapeseed straw harvest and in 2013 amounted to 4 million tonnes.

In the years 1983–1990, the average annual surplus over agricultural consumption ($Y_5$) amounted to 5119 thousand tons, which in 2007–2013 rose, on average, to 17047 thousand tons [50]. Using them for energy purposes would meet 5% of primary energy demand. An increasing surplus of straw is caused by a decrease in the number of livestock and thereby a decreasing demand for (mainly) bedding. An unfavourable phenomenon, although characteristic to agriculture, were fluctuations in the straw harvest, which had a direct impact on the level of its surpluses. In the year 2000, the straw surplus amounted to only 6348 thousand tons, and in following year, they amounted to more than twice as much at 15,042 thousand tons. Such significant fluctuations, although occurring every few years, are one of the barriers that inhibit the use of straw outside agriculture.

The main factors determining the surplus straw were mainly the sown and crop area of cereals and oilseeds as well as its consumption. The area of sown basic cereals with mixtures ($X_{11}$) reached a maximum value of about 8.6 million ha in 1999–2001, after which it fell sharply by 602 thousand ha in 2002 and by 169 thousand ha in 2003, covering an area of 7.8 million ha (reaching the level of the second decade of the 1970s). The following years brought a slow increase to 8.2 million ha, followed by another sharp decrease in the sown area—in 2013–2019 it ranged from 6.7 to 7.1 million ha. The increase in the area of sown basic cereals with mixtures ($X_{11}$) in the initial years of the examined period was caused by the decrease in the animal population, and thus also the sown area of fodder plants, mainly grown for green matter. In addition, the animal nutrition model was changing, whereby concentrated feed was becoming increasingly more important. The reason for the decrease in the area of basic cereal sowing at the turn of the twentieth and twenty-first centuries was the preparation and implementation of the EU energy policy, which initially recommended and then obliged Member States to increase the production of biofuels, mainly biodiesel [17,21,22]. Hence, the area of rapeseed sowing increased from 426 thousand ha in 2003 to 952 thousand ha in 2014. The area of maize sowing, relatively small in 1999 (104 thousand ha), increased very rapidly and from 2013 oscillated between 562 and 678 thousand ha.

In the years 1999–2019, average yields of straw from basic cereal with mixtures ($X_{12}$), rapeseed straw ($X_{22}$) and maize straw ($X_{32}$) yields were, respectively, 3.3, 2.6 and 6.1 t·ha$^{-1}$. The highest yields of straw from basic cereal with mixtures were recorded in the 1980s, early 1990s and in 2010. The highest yields of rapeseed straw were observed in the late 1990s and in the years 2004–2009. A slow increase in total straw yields has been observed since 1975. Maize straw yields increased by about 50% in the analysed period (from 4 t·ha$^{-1}$ in the 1980s to 6 t·ha$^{-1}$ in the first decade of the 20th century) [50]. The highest corn straw yields were recorded in 2012 (7.4 t·ha$^{-1}$).

Straw consumption in agriculture depends primarily on the animal population and its structure. This is because it can be used as bedding material for raising all farm animals or as feed for ruminants. During the period under consideration, straw consumption in both cases decreased by approx. 60%. Demand for bedding ($X_{42}$) declined continuously throughout the entire period between 1999 and 2019. The consumption of straw for fodder ($X_{41}$) after years of decline, since 2002, has remained at the level of approx. 5.5 million tons. These trends are the result of a decrease in the total livestock population and stabilization of ruminant populations (mainly cattle) since 2002 [50]. Basic descriptive statistics of variables for Poland in total are presented in Table 1. The test was selected automatically by the Wolfram Mathematica software, based on the statistical properties of each variable. For all variables, with the exception of $X_{32}$, the non-parametric Kolmogorov-Smirnov test [62] was used to assess the compliance of an empirical distribution with a theoretical normal distribution. For the variable $X_{32}$, the algorithm of the software has selected Pearson's chi-square compatibility test [63].

Straw production and the possibilities to use it for energy purposes vary regionally. This strongly depends on the structure of land use, the structure of crops, the size of farms as well as the stocking density and method of breeding livestock. In 2019, the areas with the highest potential to use straw for energy purposes were in Wielkopolskie, Lublin, Lower Silesia, West and Kujawsko-Pomorskie.

The lowest potential was seen in Podlaskie and Podkarpackie voivodeships, which in some years even had a deficit of straw. The basic characteristics of variables by voivodeships are presented in Table 2.

**Table 1.** Basic statistics of variables determining the straw surplus (Y5) in Poland.

| Variables | Mean | Median | Minimum | Maximum | Standard Deviation (st.dev) | Prospensity | Kurtosis | *p*-Value |
|---|---|---|---|---|---|---|---|---|
| $Y_1$ | 25,069.6 | 24,855.7 | 20,449.5 | 29,194.5 | 2613.1 | −0.196 | 2.013 | 0.231 |
| $Y_2$ | 1926.9 | 2105.8 | 793.0 | 3276.0 | 684.9 | −0.070 | 2.142 | 0.480 |
| $Y_3$ | 2550.6 | 1994.2 | 599.4 | 4468.0 | 1221.0 | 0.238 | 1.675 | 0.026 |
| $Y_4$ | 29,546.9 | 30,002.0 | 22,885.6 | 35,847.0 | 3285.0 | −0.426 | 3.042 | 0.506 |
| $Y_5$ | 12,512.1 | 13,727.9 | 3520.9 | 20,563.7 | 4287.2 | −0.456 | 2.855 | 0.374 |
| $X_{11}$ | 7590.2 | 7769.7 | 6699.0 | 8599.9 | 656.4 | 0.059 | 1.586 | 0.125 |
| $X_{21}$ | 721.8 | 796.8 | 426.3 | 952.0 | 192.1 | −0.375 | 1.608 | 0.082 |
| $X_{31}$ | 414.5 | 339.3 | 104.2 | 678.0 | 181.5 | 0.139 | 1.738 | 0.031 |
| $X_{12}$ | 3.3 | 3.4 | 2.4 | 4.2 | 0.4 | −0.171 | 3.272 | 0.605 |
| $X_{22}$ | 2.6 | 2.6 | 1.9 | 3.4 | 0.4 | 0.013 | 2.758 | 0.355 |
| $X_{32}$ | 6.1 | 6.1 | 4.2 | 7.3 | 0.8 | −0.404 | 3.127 | 0.119 |
| $X_{412}$ | 13,592.1 | 13,409.8 | 12,026.1 | 16,560.7 | 1213.7 | 0.556 | 2.774 | 0.703 |
| $X_{43}$ | 2780.2 | 2884.8 | 1823.6 | 3463.1 | 510.9 | −0.495 | 2.120 | 0.406 |

### *3.2. Trend Models for Straw Surplus ($Y_5$) in Poland in the Years 1999–2019*

Table 3 and Figure 1 present trend models of total straw surplus in Poland and by individual voivodeships.

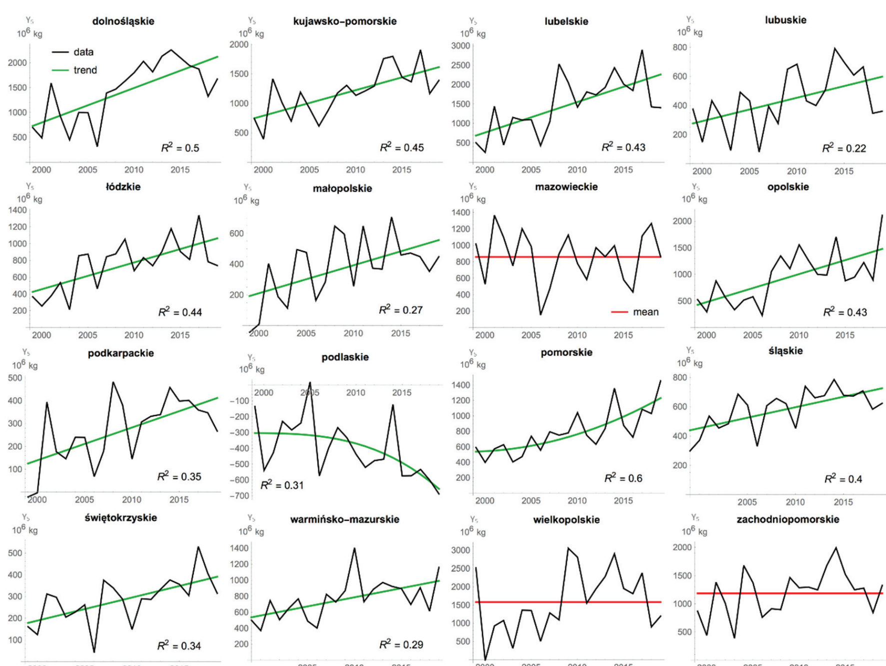


**Figure 1.** Observed values and trend models of straw surpluses ($Y_5$) in Poland by voivodeships.

**Table 2.** Basic statistics of variables determining the straw surplus (Y5) in Poland by voivodeships.

| Specification | | $X_{11}$ | $X_{21}$ | $X_{31}$ | $X_{12}$ | $X_{22}$ | $X_{32}$ | $X_{412}$ | $X_{43}$ | $Y_1$ | $Y_2$ | $Y_3$ | $Y_4$ | $Y_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dolnośląskie | median | 461.0 | 110.3 | 69.9 | 4.6 | 2.7 | 6.6 | 280.5 | 902.9 | 2148.3 | 271.5 | 449.4 | 2878.4 | 1591.8 |
| | mean | 455.8 | 101.0 | 71.0 | 4.7 | 2.6 | 6.5 | 299.1 | 903.2 | 2136.3 | 272.7 | 460.2 | 2869.2 | 1426.0 |
| | st.dev | 31.4 | 28.7 | 17.9 | 0.7 | 0.4 | 0.8 | 72.8 | 60.3 | 309.7 | 94.9 | 128.0 | 384.2 | 597.2 |
| Kujawsko-pomorskie | median | 599.2 | 83.5 | 33.5 | 3.2 | 2.7 | 5.7 | 1151.6 | 0.0 | 1853.1 | 210.1 | 179.4 | 2341.6 | 1190.0 |
| | mean | 594.5 | 82.3 | 46.9 | 3.1 | 2.8 | 5.8 | 1128.5 | 50.4 | 1852.8 | 227.7 | 280.3 | 2360.8 | 1181.9 |
| | st.dev | 54.7 | 28.1 | 30.9 | 0.5 | 0.9 | 0.8 | 79.9 | 73.3 | 210.4 | 99.4 | 197.2 | 372.7 | 389.9 |
| Lubelskie | median | 803.6 | 43.1 | 18.8 | 3.4 | 2.4 | 5.7 | 898.3 | 544.9 | 2782.1 | 96.9 | 104.0 | 2986.5 | 1426.7 |
| | mean | 811.7 | 48.0 | 22.3 | 3.5 | 2.5 | 5.8 | 973.2 | 493.2 | 2833.9 | 123.6 | 132.4 | 3089.9 | 1474.8 |
| | st.dev | 60.7 | 30.1 | 11.4 | 0.6 | 0.4 | 0.8 | 223.5 | 180.3 | 527.0 | 90.3 | 77.9 | 580.0 | 720.5 |
| Lubuskie | median | 207.3 | 27.7 | 15.3 | 3.4 | 2.4 | 5.6 | 172.3 | 195.7 | 714.1 | 68.0 | 88.6 | 832.8 | 431.7 |
| | mean | 197.2 | 26.8 | 15.6 | 3.4 | 2.4 | 5.6 | 173.8 | 204.7 | 678.9 | 69.9 | 88.5 | 837.4 | 437.8 |
| | st.dev | 24.9 | 8.9 | 4.5 | 0.9 | 0.6 | 1.3 | 19.6 | 60.5 | 143.2 | 31.8 | 34.9 | 177.8 | 197.3 |
| Łódzkie | median | 598.5 | 16.0 | 11.8 | 2.9 | 2.3 | 5.7 | 1095.5 | 0.0 | 1630.9 | 37.4 | 71.8 | 1825.5 | 812.1 |
| | mean | 598.7 | 14.6 | 16.5 | 2.8 | 2.4 | 5.7 | 1082.8 | 7.2 | 1697.1 | 36.8 | 93.9 | 1827.8 | 745.1 |
| | st.dev | 34.8 | 7.2 | 10.8 | 0.3 | 0.6 | 1.1 | 91.3 | 27.0 | 212.6 | 21.4 | 64.9 | 237.6 | 290.1 |
| Małopolskie | median | 241.7 | 4.5 | 13.4 | 3.5 | 2.8 | 6.2 | 528.6 | 0.0 | 866.5 | 12.5 | 81.9 | 938.9 | 404.8 |
| | mean | 227.5 | 5.2 | 15.9 | 3.8 | 2.7 | 6.2 | 584.4 | 13.1 | 855.4 | 15.0 | 102.4 | 972.8 | 375.3 |
| | st.dev | 32.5 | 3.2 | 6.6 | 0.5 | 0.5 | 0.8 | 202.5 | 24.6 | 190.2 | 9.9 | 51.6 | 161.5 | 204.5 |
| Mazowieckie | median | 973.8 | 33.2 | 26.8 | 3.0 | 2.4 | 5.8 | 2187.8 | 0.0 | 2714.9 | 77.2 | 170.2 | 3028.0 | 897.1 |
| | mean | 950.7 | 30.7 | 34.5 | 2.9 | 2.4 | 5.7 | 2176.6 | 0.0 | 2764.7 | 75.7 | 196.9 | 3037.2 | 860.6 |
| | st.dev | 99.7 | 13.8 | 21.9 | 0.3 | 0.5 | 0.6 | 115.4 | 0.0 | 358.9 | 37.3 | 125.3 | 322.0 | 309.9 |
| Opolskie | median | 297.7 | 71.2 | 46.2 | 3.6 | 2.9 | 6.7 | 342.9 | 315.5 | 1063.7 | 213.2 | 283.8 | 1682.7 | 950.2 |
| | mean | 294.7 | 65.7 | 44.1 | 4.2 | 2.9 | 6.8 | 339.5 | 314.5 | 1207.6 | 196.7 | 301.0 | 1705.4 | 955.2 |
| | st.dev | 16.2 | 15.6 | 8.5 | 1.1 | 0.6 | 1.3 | 55.2 | 85.6 | 301.7 | 62.8 | 86.9 | 348.7 | 482.6 |

**Table 2.** *Cont.*

| Specification | | $X_{11}$ | $X_{21}$ | $X_{31}$ | $X_{12}$ | $X_{22}$ | $X_{32}$ | $X_{412}$ | $X_{43}$ | $Y_1$ | $Y_2$ | $Y_3$ | $Y_4$ | $Y_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Podkarpackie | median | 244.1 | 16.2 | 12.6 | 2.9 | 2.2 | 5.8 | 370.9 | 136.5 | 629.0 | 33.2 | 69.4 | 831.2 | 307.3 |
| | mean | 239.8 | 15.2 | 16.6 | 2.9 | 2.2 | 6.1 | 396.4 | 147.3 | 680.7 | 35.4 | 106.6 | 822.7 | 268.7 |
| | st.dev | 38.9 | 7.0 | 8.1 | 0.4 | 0.3 | 1.0 | 195.1 | 98.1 | 137.5 | 18.8 | 66.1 | 111.5 | 144.1 |
| Podlaskie | median | 491.6 | 5.1 | 4.8 | 2.5 | 2.6 | 5.0 | 1640.0 | 0.0 | 1149.2 | 14.8 | 26.3 | 1198.7 | −437.4 |
| | mean | 473.1 | 6.9 | 9.9 | 2.4 | 2.5 | 5.2 | 1613.7 | 0.0 | 1138.9 | 19.4 | 55.5 | 1213.8 | −399.9 |
| | st.dev | 53.2 | 5.3 | 9.0 | 0.4 | 0.6 | 1.1 | 127.2 | 0.0 | 177.6 | 16.4 | 54.4 | 171.0 | 186.2 |
| Pomorskie | median | 401.5 | 54.6 | 5.0 | 3.0 | 2.6 | 5.0 | 532.9 | 97.5 | 1241.2 | 156.7 | 23.1 | 1397.8 | 749.9 |
| | mean | 404.6 | 56.7 | 5.6 | 3.2 | 2.6 | 5.0 | 549.0 | 100.5 | 1267.0 | 153.7 | 29.3 | 1449.9 | 785.0 |
| | st.dev | 24.4 | 17.0 | 3.4 | 0.6 | 0.5 | 1.1 | 50.1 | 39.6 | 195.4 | 65.9 | 21.8 | 256.8 | 281.6 |
| Śląskie | median | 201.6 | 18.2 | 14.9 | 4.1 | 2.6 | 6.7 | 302.2 | 39.6 | 807.4 | 48.4 | 102.9 | 967.9 | 621.5 |
| | mean | 200.7 | 16.9 | 15.3 | 3.9 | 2.6 | 6.7 | 321.1 | 34.8 | 792.5 | 44.4 | 103.0 | 939.8 | 583.0 |
| | st.dev | 13.5 | 4.7 | 4.1 | 0.5 | 0.4 | 0.9 | 59.7 | 32.9 | 92.8 | 14.6 | 31.8 | 118.6 | 135.8 |
| Świętokrzyskie | median | 268.1 | 6.3 | 3.3 | 2.8 | 2.3 | 5.2 | 408.6 | 11.6 | 707.1 | 15.6 | 15.1 | 742.6 | 296.9 |
| | mean | 258.1 | 6.3 | 3.6 | 2.7 | 2.3 | 5.2 | 430.6 | 27.2 | 711.1 | 14.8 | 19.2 | 745.2 | 285.2 |
| | st.dev | 31.9 | 3.2 | 2.0 | 0.3 | 0.4 | 0.7 | 118.5 | 29.4 | 111.4 | 7.7 | 11.8 | 106.9 | 108.1 |
| Warmińsko-mazurskie | median | 427.1 | 58.2 | 7.0 | 3.4 | 2.2 | 5.2 | 890.4 | 0.0 | 1447.0 | 131.8 | 38.9 | 1640.4 | 746.5 |
| | mean | 422.0 | 59.4 | 8.3 | 3.5 | 2.2 | 5.2 | 892.0 | 0.0 | 1472.8 | 139.9 | 44.1 | 1656.8 | 764.8 |
| | st.dev | 53.8 | 10.8 | 4.2 | 0.7 | 0.4 | 0.8 | 43.7 | 0.0 | 208.9 | 46.5 | 24.5 | 244.5 | 249.6 |
| Wielkopolskie | median | 1054.0 | 98.9 | 56.2 | 3.0 | 2.7 | 5.9 | 2328.9 | 0.0 | 2981.2 | 243.4 | 325.0 | 3752.8 | 1359.8 |
| | mean | 1016.2 | 94.8 | 80.2 | 3.1 | 2.7 | 6.0 | 2336.5 | 0.0 | 3165.3 | 259.7 | 493.4 | 3918.3 | 1581.9 |
| | st.dev | 75.3 | 24.2 | 50.1 | 0.7 | 0.6 | 1.1 | 92.2 | 0.0 | 734.8 | 91.9 | 335.4 | 855.6 | 861.6 |
| Zachodnio-pomorskie | median | 462.2 | 98.3 | 6.8 | 4.2 | 2.5 | 5.2 | 260.2 | 487.5 | 1765.5 | 240.9 | 37.5 | 2020.9 | 1279.2 |
| | mean | 444.9 | 91.3 | 8.3 | 4.2 | 2.5 | 5.4 | 295.1 | 484.2 | 1814.6 | 241.4 | 43.8 | 2099.8 | 1186.7 |
| | st.dev | 59.5 | 16.4 | 8.0 | 0.8 | 0.5 | 0.8 | 68.8 | 163.1 | 347.3 | 81.8 | 38.2 | 370.6 | 402.7 |
| **Poland** | **median** | **7769.7** | **796.8** | **339.3** | **3.4** | **2.6** | **6.1** | **13,409.8** | **2884.8** | **24,855.7** | **2105.8** | **1994.2** | **30,002.0** | **13,727.9** |
| | **mean** | **7590.2** | **721.8** | **414.5** | **3.3** | **2.6** | **6.1** | **13,592.1** | **2780.2** | **25,069.6** | **1926.9** | **2550.6** | **29,546.9** | **12,512.1** |
| | **st.dev** | **656.4** | **192.1** | **181.5** | **0.4** | **0.4** | **0.8** | **1213.7** | **510.9** | **2613.1** | **684.9** | **1221.0** | **3285.0** | **4287.2** |

**Table 3.** Surplus straw ($Y_5$) trend models in Poland by voivodeships.

| Specification | Constant | t | *p* | $t^2$ | *p* | $t^3$ | *p* | $R^2$ * |
|---|---|---|---|---|---|---|---|---|
| Dolnośląskie | 661.25 | 69.52 | <0.001 | | | | | 0.497 |
| Kujawsko-pomorskie | 704.30 | 43.42 | <0.001 | | | | | 0.450 |
| Lubelskie | 609.39 | 78.68 | <0.001 | | | | | 0.430 |
| Lubuskie | 261.01 | 16.07 | 0.019 | | | | | 0.216 |
| Łódzkie | 394.12 | 31.90 | <0.001 | | | | | 0.437 |
| Małopolskie | 175.37 | 18.18 | 0.010 | | | | | 0.267 |
| Mazowieckie ** | | | | | | | | |
| Opolskie | 376.66 | 52.59 | <0.001 | | | | | 0.429 |
| Podkarpackie | 111.07 | 14.33 | 0.003 | | | | | 0.348 |
| Podlaskie | −303.10 | | | | | −0.04 | 0.005 | 0.314 |
| Pomorskie | 536.89 | | | 1.57 | <0.001 | | | 0.597 |
| Śląskie | 425.38 | 14.33 | 0.001 | | | | | 0.399 |
| Świętokrzyskie | 168.10 | 10.64 | 0.003 | | | | | 0.340 |
| Warmińsko-mazurskie | 514.02 | 22.80 | 0.007 | | | | | 0.285 |
| Wielkopolskie *** | 2071.98 | −584.47 | 0.048 | 79.49 | 0.013 | −2.60 | 0.008 | 0.385 |
| Zachodniopomorskie ** | | | | | | | | |
| **Poland** | **7357.54** | **468.60** | **<0.001** | | | | | **0.432** |

* adjusted R-squared; ** none of estimated models has significant parameters; *** parameters significant, but model not acceptable due to sudden decrease of forecasted values.

In Poland, in total, for the surplus of straw ($Y_5$), the best model turned out to be the linear function. Non-linear models—with a square and cube of a time variable—either had irrelevant parameters or indicated that, already in 2024, the surplus straw would fall to zero and would continue to fall, which is unacceptable. Residual components of the linear model did not show autocorrelation and are characterized by normal distribution, as proven by Ljung–Box test (Statistic 7357.54, *p*-value 0.616) and by Kolmogorov–Smirnov test (Statistic 1.162, *p*-value 0.187). The trend model was fitted to the data in 43.2%.

For most voivodeships (11), linear trends were the best. The estimated trend parameters for these voivodeships indicated an upward trend in the surplus of straw ($Y_5$) in the years 1999–2019 (from 10.64 thousand tonnes on average a year in the Świętokrzyskie voivodeship, to 78.68 thousand tonnes on a yearly average in the Lubelskie voivodeship; on average, 33.86 thousand tonnes).

For the Pomorskie voivodeship the square trend turned out to be best suited, and for the Podlaskie voivodeship it was the cubic trend. At the same time, the Podlaskie voivodeship was the only voivodeship in which straw production was lower than demand.

In the case of the Wielkopolskie voivodeship, the non-linear trend turned out to be unacceptable due to generated forecasts, while the linear trend did not have a significant parameter of the time variable. Therefore, it was considered that no trend model could be obtained in this case. For the Mazowieckie and Zachodniopomorskie voivodeships, no trend model with significant parameters could be estimated. Therefore, for these three voivodeships, instead of the trend model, a constant level of straw surplus (with an average value) was adopted for the entire period considered.

The fitting of trend models to the data was not very high. The adjusted coefficients of determination $R^2$ for obtained equations ranged from 0.22 to 0.60 (average 0.39). Of course, this does not mean that trends did not correctly reflect development trends. The relatively low values of the coefficients of determination were due to quite large fluctuations in production, and thus also surpluses of straw.

### 3.3. *Cause-Effect Models of Surplus Straw ($Y_5$) in Poland in the Years 1999–2019*

Table 4 and Figure 2 show the cause-effect models of straw surpluses in Poland in total and by individual voivodeships in the years 1999–2019. Based on the tests of independence using Pearson's correlation, Spearman's correlation and Hoeffding's D statistics, it was found that the surplus of straw ($Y_5$) was significantly correlated with the following variables: sown area and yields of basic cereals with mixtures ($X_{11}$; $X_{12}$), rapeseed ($X_{21}$), and corn ($X_{31}$; $X_{32}$), as well as consumption for fodder and bedding ($X_{412}$) and ploughing ($X_{43}$). As expected, the relationships (correlations) are positive with variables describing straw harvests, cereals and rapeseed sown areas and yields. Also expected were negative relationships describing straw consumption for fodder and bedding.

Granger causality tests were also performed [64]. The tests show that the amount of surplus straw is affected (in terms of Granger causality) by straw yields of four cereals and straw consumption for feed, bedding, and ploughing. Due to the possibility of apparent regression, the degree of integration of the variables was also examined. For the original time series, the basic integration test was used, taking into account the possibility of a non-zero mean and deterministic trend for different series.

During the construction of cause-effect models, a set of independent variables that would best explain the changes in the level of surplus straw in the years 1999–2019, were searched for. Subsequently, the equation parameters with all possible combinations of these variables were estimated and equations with the highest corrected coefficient of determination and the lowest value of the Akaike information criterion (AIC) were selected. Then the insignificant variable ($X_{22}$) was removed from the model. For each voivodeship, models were finally estimated in which all parameters with explanatory variables were statistically significant (at the level of 0.05) and coincidental. No random component autocorrelation phenomenon was observed in the estimated models.

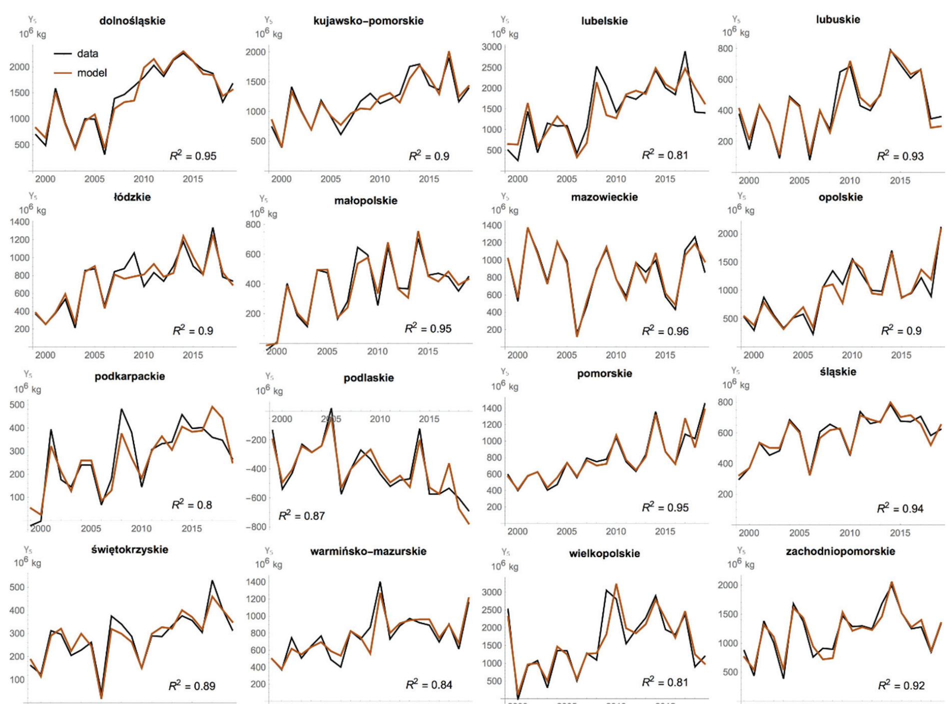


**Figure 2.** Observed values and cause-effect models of straw surpluses ($Y_5$) in Poland by voivodeships.

**Table 4.** Cause-effect models for surplus of straw (Y5) in Poland by voivodeships.

| Specification | Constant | $X_{11}$ | *p* | $X_{21}$ | *p* | $X_{31}$ | *p* | $X_{12}$ | *p* | $X_{32}$ | *p* | $X_{412}$ | *p* | $X_{43}$ | *p* | $R^2$ * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dolnośląskie | −2726.68 | | | 10.9 | <0.001 | 3.8 | 0.050 | 415.7 | <0.001 | 127.2 | 0.009 | | | | | 0.948 |
| Kujawsko-pomorskie | −1163.80 | | | 2.2 | 0.049 | | | 687.7 | <0.001 | | | | | | | 0.902 |
| Lubelskie | −1907.86 | | | | | | | 759.8 | <0.001 | | | | | 1.5 | 0.005 | 0.809 |
| Lubuskie | −429.93 | | | 4.7 | 0.009 | | | 162.0 | <0.001 | 32.4 | 0.007 | | | | | 0.933 |
| Łódzkie | −27.49 | | | | | | | 655.8 | <0.001 | | | −1.0 | 0.001 | | | 0.899 |
| Małopolskie | −307.20 | | | | | | | 277.5 | <0.001 | | | −0.6 | <0.001 | | | 0.952 |
| Mazowieckie | −3758.03 | 3.1 | <0.001 | | | 10.1 | <0.001 | 898.5 | <0.001 | 97.8 | 0.002 | −0.8 | <0.001 | | | 0.959 |
| Opolskie | 532.44 | | | 7.6 | 0.025 | | | 206.2 | <0.001 | 83.2 | 0.015 | −2.7 | 0.008 | −1.9 | 0.004 | 0.901 |
| Podkarpackie | −310.32 | | | | | | | 250.3 | <0.001 | | | −0.4 | <0.001 | | | 0.802 |
| Podlaskie | −423.40 | 1.1 | 0.016 | | | | | 408.6 | <0.001 | | | −0.9 | <0.001 | | | 0.869 |
| Pomorskie | −560.03 | | | 3.6 | 0.015 | | | 359.6 | <0.001 | | | | | | | 0.949 |
| Śląskie | −426.17 | | | | | 8.8 | 0.001 | 181.2 | <0.001 | 23.8 | 0.031 | | | | | 0.941 |
| Świętokrzyskie | −313.83 | | | | | | | 277.8 | <0.001 | | | −0.4 | <0.001 | | | 0.893 |
| Warmińsko-mazurskie | −313.96 | | | | | | | 311.5 | <0.001 | | | | | | | 0.842 |
| Wielkopolskie *** | 3351.16 | | | 9.9 | 0.029 | | | 924.1 | <0.001 | | | −2.40 | 0.019 | | | 0.809 |
| Zachodniopomorskie | −237.701 | | | | | | | 416.8 | <0.001 | | | −1.0 | 0.022 | | | 0.916 |
| **Poland** | **−18,335.00** | | | **5.5** | **0.004** | | | **8111.9** | **<0.001** | | | | | | | **0.940** |

* adjusted R-squared; *** parameters significant, but model not acceptable due to sudden decrease of forecasted values.

All received models contained at least two explanatory variables. The obtained models were very well fitted to the empirical data (Figure 2 and Table 4). The adjusted determination coefficients had values from 0.80 to 0.96, which means that the models explained at least 80% of the changes in the surplus of straw by voivodeships in the examined period.

The amounts of straw surpluses vary regionally because they depend on the land use, the structure of crops, the size of farms, as well as the stocking density and method of raising livestock. The greatest possibilities for straw use for energy production purposes were characterized in the following voivodeships: Wielkopolskie, Kujawsko-Pomorskie, Lubelskie, Zachodniopomorskie, Dolnośląskie, and Mazowieckie. The results obtained are close to the estimates presented by other authors [46–53,56].

### *3.4. Straw Surplus Forecasts*

Long-term forecasts require that models meet certain prediction assumptions [65] in regard of stability over time of, among others, (i) economic regularity, (ii) model parameters, and (iii) random component distribution.

Therefore, obtained models for the $Y_5$ variable were subjected to additional analysis to check their structural stability over time. The forecast based on this model required prior obtainment of the forecast values of the above seven explanatory variables.

The models in Table 3 and Figure 1 were used to forecast the straw surpluses based on the trend; their properties are described in Section 3.2. Based on the estimated trend models, point and interval forecasts were calculated for the lower and upper limits of the confidence interval (95%). The numerical results are shown in Table 5, and the visualization of forecasts in Figure 3.

**Table 5.** Point and interval forecast of Surplus of straw ($Y_5$) on the basis trend models (thous. t).

| Specification | 2025 | | | 2030 | | |
|---|---|---|---|---|---|---|
| | Lower Endpoint | Forecast | Upper Endpoint | Lower Endpoint | Forecast | Upper Endpoint |
| Dolnośląskie | 1497 | **2538** | 3580 | 1757 | **2886** | 4015 |
| Kujawsko-pomorskie | 1166 | **1877** | 2587 | 1323 | **2094** | 2864 |
| Lubelskie | 1397 | **2734** | 4071 | 1679 | **3127** | 4576 |
| Lubuskie | 266 | **695** | 1124 | 310 | **775** | 1241 |
| Łódzkie | 720 | **1256** | 1791 | 835 | **1415** | 1995 |
| Małopolskie | 236 | **666** | 1097 | 290 | **757** | 1223 |
| Mazowieckie | lower = 719 | | mean = **860** | | upper = 1001 | |
| Opolskie | 900 | **1797** | 2694 | 1088 | **2060** | 3031 |
| Podkarpackie | 212 | **498** | 784 | 259 | **570** | 880 |
| Podlaskie | −1594 | **−1053** | −511 | −2376 | **−1551** | −726 |
| Pomorskie | 1172 | **1684** | 2197 | 1506 | **2149** | 2791 |
| Śląskie | 553 | **812** | 1071 | 603 | **884** | 1165 |
| Świętokrzyskie | 240 | **455** | 671 | 275 | **509** | 743 |
| Warmińsko-mazurskie | 611 | **1130** | 1648 | 681 | **1244** | 1806 |
| Wielkopolskie | lower = 1189 | | mean = **1581** | | upper = 1974 | |
| Zachodniopomorskie | lower = 1003 | | mean = **1186** | | upper = 1370 | |
| **Poland** | 12,062 | **20,010** | 27,958 | 13,740 | **22,353** | 30,965 |

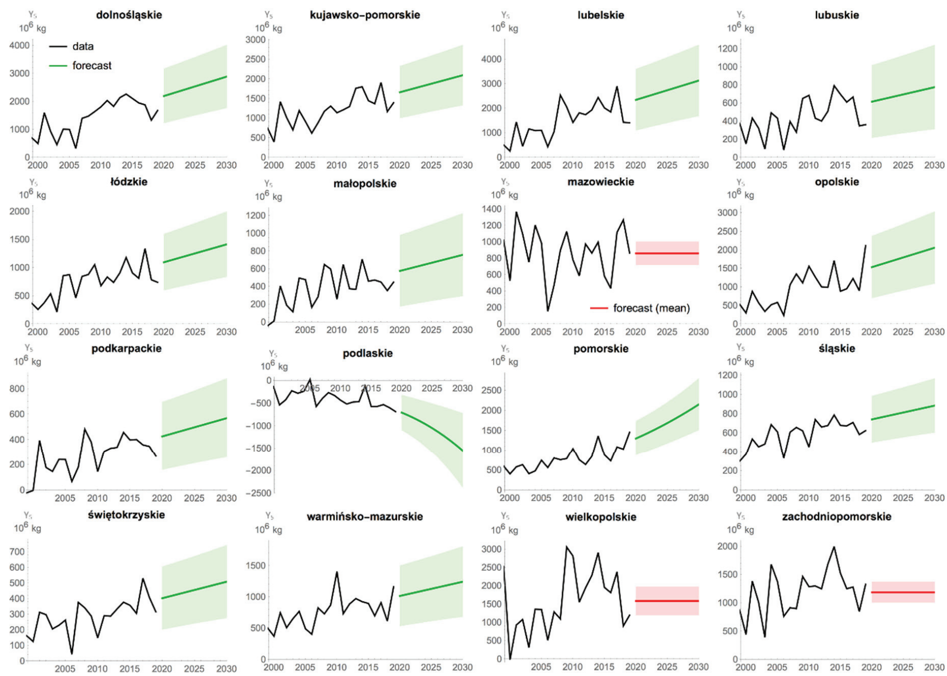


**Figure 3.** Point and interval forecast of Surplus of straw ($Y_5$) on the basis trend models (thous. t).

The presented forecast of surplus straw built on the basis of trend models shows that in most voivodeships growth of the straw surplus will be steady. In 2030, these surpluses will amount to over 22 million tons, the highest will be in the Lubelskie, Dolnośląskie, Pomorskie, Kujawsko-Pomorskie and Zachodniopomorskie voivodeships, and the lowest in Lubuskie, Małopolskie, Podkarpackie, and Świętokrzyskie voivodeships. Straw deficit in the Podlasie voivodeship will continue, due to the low share of cereals and rapeseed in the structure of sown crops and large-scale cattle breeding.

To prepare the straw surplus forecast based on cause-effect models, the equations given in Table 4 and Figure 2 were used; their properties are described in Section 3.3. Based on the estimated models, the point and interval forecasts were calculated for the lower and upper limits of the confidence interval (95%). Numerical results are presented in Table 6, and forecast visualization in Figure 4.

**Table 6.** Point and interval forecast of Surplus of straw ($Y_5$) based on cause-effect models (thous. t).

| Specification | 2025 | | | 2030 | | |
|---|---|---|---|---|---|---|
| | Lower Endpoint | Forecast | Upper Endpoint | Lower Endpoint | Forecast | Upper Endpoint |
| Dolnośląskie | 1454 | **1759** | 2065 | 1575 | **1890** | 2205 |
| Kujawsko-pomorskie | 1400 | **1678** | 1956 | 1518 | **1804** | 2090 |
| Lubelskie | 1311 | **2103** | 2895 | 1433 | **2297** | 3162 |
| Lubuskie | 283 | **397** | 511 | 272 | **388** | 504 |
| Łódzkie | 665 | **871** | 1076 | 920 | **1133** | 1346 |
| Małopolskie | 519 | **624** | 729 | 612 | **724** | 837 |
| Mazowieckie | 797 | **965** | 1134 | 802 | **983** | 1165 |
| Opolskie | 986 | **1388** | 1790 | 1094 | **1550** | 2006 |

**Table 6.** *Cont.*

| Specification | 2025 | | | 2030 | | |
|---|---|---|---|---|---|---|
| | Lower Endpoint | Forecast | Upper Endpoint | Lower Endpoint | Forecast | Upper Endpoint |
| Podkarpackie | 203 | **345** | 486 | 158 | **296** | 435 |
| Podlaskie | −864 | **−703** | −542 | −963 | **−793** | −623 |
| Pomorskie | 1306 | **1462** | 1617 | 1471 | **1637** | 1802 |
| Śląskie | 581 | **665** | 750 | 603 | **698** | 794 |
| Świętokrzyskie | 294 | **378** | 462 | 325 | **417** | 508 |
| Warmińsko-mazurskie | 987 | **1218** | 1449 | 1148 | **1396** | 1644 |
| Wielkopolskie | 685 | **1500** | 2316 | 708 | **1522** | 2336 |
| Zachodniopomorskie | 1043 | **1316** | 1589 | 1079 | **1375** | 1672 |
| **Poland** | 11,467 | **13,887** | 16,307 | 11,798 | **14,337** | 16,875 |

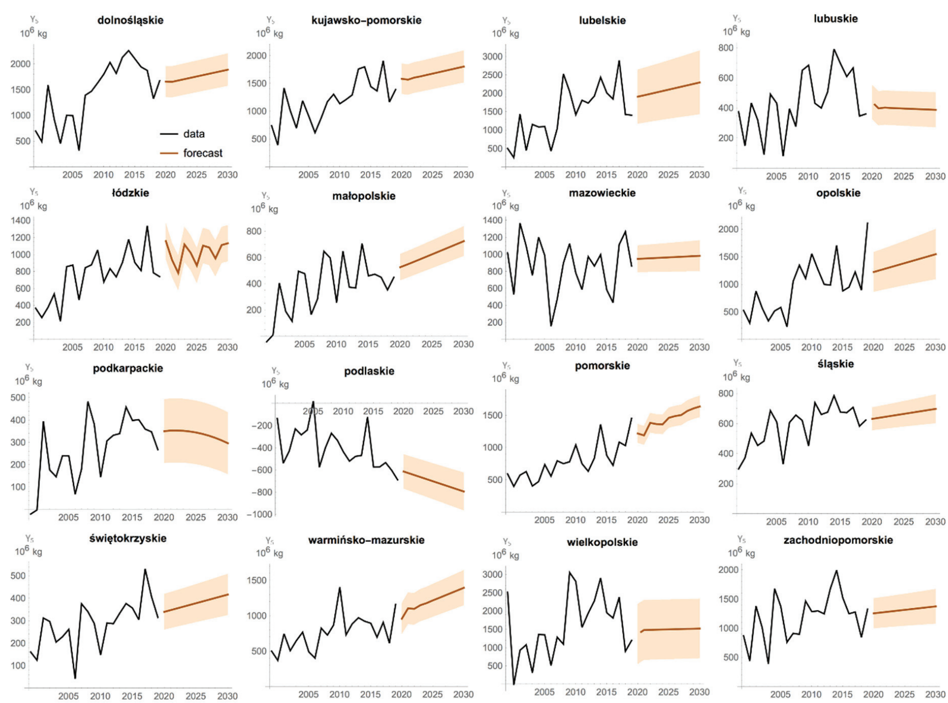


**Figure 4.** Point and interval forecast of Surplus of straw ($Y_5$) based on cause-effect models (thous. t).

For all voivodeships (except for Podlaskie and Warminsko-Mazurskie voivodeships), forecasts based on the trend are higher than forecasts resulting from the cause-effect model. Considering the values of determination coefficients, forecasts estimated on basis of cause–effect models are more reliable.

## 4. Discussion

Poland is perceived within the EU as having a substantial biomass production potential that could be used for energy generation purposes. One of the factors is the level of availability of agricultural areas (AA), which calculated per capita equals 0.41 ha and is higher compared to the EU-15 average. Studies [66,67] show that areas between 1.0 and 4.3 million hectares of Polish land are available for production of biomass suitable for energy generation purposes.

The 2019 statistical data reveals that out of 14.6 million hectares of land in Poland 10.9 million hectares are utilized for crop production. Within this area up to 8.787 million hectares could be utilized for cultivation of crops providing the straw as its by-product (primarily cereals, corn, and rapeseed). Currently the cereals and rapeseed show the largest shares in the crops' structure (72.4% and 8.0% respectively). At the same time regional differences are present in regard to the crop structure, yet cereals are typical for all regions (reaching share of 75%). Therefore, the potential for removal of straw for the bioenergy generation purposes is highly probable and feasible, especially taking into account the current EU's renewable energy policy targets [21,22]. Poland too aims to increase the renewable energy generation with the key national policies defining or regulating the use of straw for bioenergy purposes being the biomass energy law [68], Energy Policy of Poland until 2040 [69] and Renewable Energy Sources Act [70].

Numerous independent scientific projects as well as the Joint Research Centre [46] have conducted research aimed at assessment straw's potential for bioenergy generation in Europe. France is the country with largest biomass potential due to highly spread production of cereals and declining trend of livestock production [71]. Significant possibilities of using straw for energy purposes are also possible in such countries as Poland, Germany, Great Britain, Romania, and Slovakia. However, the Danes have the greatest experience in the field of energy use of straw, where about 20% of the crop is allocated to this purpose [72]. Countries which show particularly large increases in use of straw for energy purposes towards 2020 and 2030 are Polish, France, UK, Romania, Hungary, and Denmark.

The interviews with companies interested in obtaining straw for energy purposes show that, these analyses do not seem to be sufficiently comprehensive. This applies especially in case studies conducted for larger countries such as Germany, France, UK, and Poland, which have a high theoretical potential for this resource. The report prepared for the World Bank [73] predicts that in the coming years straw will become most important of RES in Poland.

This study has confirmed the widely proclaimed thesis about significant surpluses of straw in Poland that can be used for energy purposes. In the years 1999–2019, the average annual surplus of harvested straw amounted to 12.5 million tons (4.2 Mtoe). The study presents those estimates by voivodeships. The largest straw surpluses were available in the following voivodeships: Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Wielkopolskie, and Zachodniopomorskie.

The main problem is the real availability of straw surplus. The area structure of farms in Poland is very unfavourable as it is dominated by small farms. This reduces substantially the possibility of using high-performance, large-sized presses, which in turn determines an economic feasibility of biomass supply. Hence, the presented study assessed the economic potential of the supply system which would guarantee its economic feasibility based on the system of collection, storage, and transport. It was assumed that potential suppliers of straw should be sought in regions which, in prediction, will have a significant straw surplus to at least 2030 and have a favourable agricultural structure with farms over 50 ha.

As was mentioned above, Polish agriculture is characterized by unfavourable area structure of farms dominated by small farms. From the total number of farms (1.4 million) 85.5% have farmland smaller than 15 hectares. However, farms with the area over 50 hectares (32.1 thousand) operate on total area over 3.4 million hectares. For the calculation purposes it was assumed that economic potential of straw used for energy production depends on the average size of farms. Averaged coefficients for each voivodship were used. For voivodship with a favourable structure of the area (e.g., Zachodnipomorskie Voivodship) the rate stands at 60%, which means that the economic potential is 60.1% of the technical potential.

The results show that in 2030 the economic potential of straw for energy production will account up to 5.4 million tons (1.8 Mtoe). The most promising areas were found in the north and south-west of the country. Limited possibilities of straw use for energy production were found in the Małopolskie, Podkarpackie, and Świętokrzyskie voivodships, whereas Podlaskie Voivodship showed absence of straw surplus. A regional differentiation of straw surplus for alternative use in Poland in the 2030 is illustrated in Figure 5.

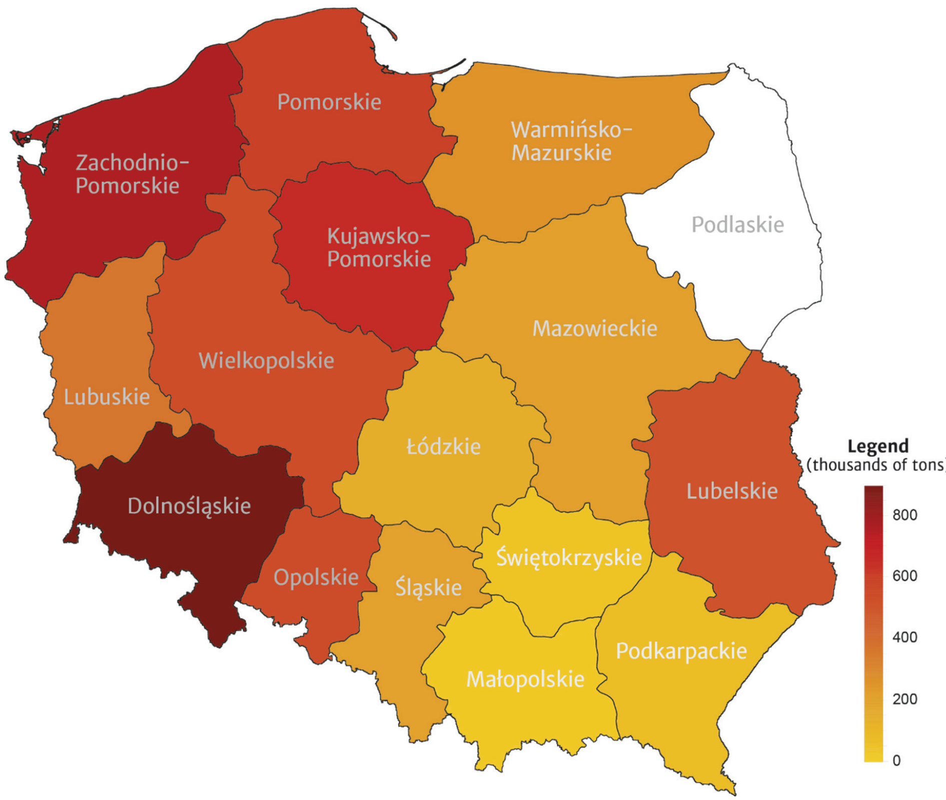


**Figure 5.** Straw surplus for energy production in Poland.

So far, the surplus of straw has been used in the following sectors: composting plants, power plants, heating plants, processing plants (briquetting and pelleting plants). According to the author's estimates, conducted in cooperation with Agricultural Advisory Centres, 600 thousand tons of straw have been earmarked for composting purposes in 2019. The following entities from the energy sector which use straw for energy production have been identify, not only in the studied region, but also in other parts of Poland: Fortum Power and Heat Polska Sp. z o.o.; EDF, which includes Kogeneracja Wrocław and Elektrownia Rybnik, EC Wybrzeże, EC Kraków; ZE PAK, which consists of El. Patnów—Adamów—Konin; GdF Suez Elektrownia Połaniec, The Tauron Group - branches: Elektrownia Jaworzno II, Elektrownia Jaworzno III, Elektrownia Siersza, Elektrownia Łaziska, Zespół Elektrociepłowni Bielsko Biała; PGE, including power plants in Bełchatów, ZE Dolna Odra and EC Szczecin, EL Turów, EL Opole, EC Gorzów Wielkopolski; Thermal power plants of the Veolia Polska Group in Łódź and in Poznań. According to information obtained from the Polish Chamber of Biomass, the studied enterprises acquired approximately 900 thousand tons of straw in the studied region in 2019. Pelleting and briquetting plants, as well as local heat plant are also significant straw users. In 2019, enterprises from this sector acquired approximately 400 thousand tons of straw.

## 5. Conclusions

The mitigation of climate change is a major challenge for the legal framework which aims to stimulate the development of renewable energy sources. The European Union direction for the use of renewable energy is distributed generation and an increase in the use of by-products and organic waste – particularly in the production of next-generation biofuels. This creates a huge opportunity for rural areas and agriculture where more than half of global production is unfit for consumption. Despite those possibilities, the current production of biofuels used in transportation are from cereals and rapeseed. Such policies are criticized by many as they cause increases in the prices of agricultural raw materials and food. At the same time, their ecological effects in terms of $CO_2$ emission reduction are much lower than assumed.

However, due to the decision of the European Parliament and the European Council, the share of energy from first-generation biofuels is to be gradually reduced; they will be replaced by energy from advanced biofuels and biogas produced from waste materials, renewable nonbiological fuels and electricity from renewable sources [21,22]. There are significant resources of biomass waste in Poland (listed in parts A and B of Annex IX to Directive 2015/1513) that can be used for the production of second-generation biofuels. Such raw materials include straw, but the possibilities of using it for energy should be consistent with the provisions in the Code for Good Agricultural Practice [54].

Cause–effect models based on data for 16 voivodships from the period 1999–2019 were used to estimate the surplus straw. The estimated straw surplus in the studied years was significantly correlated with the following explanatory variables: sown area of the analysed crops ($X_{11}$, $X_{21}$, $X_{31}$), straw yields from four cereals with mixtures ($X_{12}$), corn $X_{32}$) and straw consumption for fodder and bedding ($X_{412}$). The obtained model was very well matched to the empirical data; the corrected coefficient of determination equalled 0.90. Based on the developed panel models (which were characterized by the ability to explain the described phenomena), forecasts for straw surpluses in Poland were presented in three perspectives: realistic, pessimistic, and optimistic. The forecasts show regional differentiation until 2030. Each of three perspectives indicate a slow increase in these surpluses; depending on the adopted version, it will range from 10.6% to 21.9%.

The basic problem, however, is the real availability of surpluses of straw. The area structure of farms in Poland is very unfavourable because of the domination of small farms. This significantly limits the possibility of using high-performance, large-scale straw harvesting presses and determines the success of the supply of biofuel (the organization of an efficient harvesting, storage, and transport system). Potential suppliers of straw for the biofuel sector should be sought in regions which will have significant surpluses of straw over the needs arising from agricultural production until at least 2030 and are characterized by a favourable area structure of farms (a significant number of large-scale farms, i.e., above 50 ha). These conditions are met by three regions: the southeastern (covering the eastern part of the Lubelskie and Podkarpackie voivodeships), the southwest (Dolnośląskie and Opolskie voivodeships), and the northwest (Pomorskie and Zachodniopomorskie voivodeships).

However, this does not mean that, on a local scale (township or county) in these regions, straw could not be employed for energy-related purposes. This would however require making calculations on a micro-scale, and it would then be possible to define the requisition of straw for agricultural purposes with greater accuracy, at the same time taking into account various methods of animal husbandry (litter and non-litter systems) and nutrition (nutritive or bulky fodder).

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# Mechanical Harvesting of Camelina: Work Productivity, Costs and Seed Loss Evaluation

**Walter Stefanoni [1], Francesco Latterini [1], Javier Prieto Ruiz [2], Simone Bergonzoli [3,*], Consuelo Attolico [1] and Luigi Pari [1]**

1 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, Italy; walter.stefanoni@crea.gov.it (W.S.); francesco.latterini@crea.gov.it (F.L.); consuelo.attolico@crea.gov.it (C.A.); luigi.pari@crea.gov.it (L.P.)
2 Camelina Company Espana, Camino de la Carrera, 11, Fuente el Saz de Jarama, 28140 Madrid, Spain; j.prieto@camelinacompany.es
3 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano 43, 24047 Treviglio, Italy
* Correspondence: simone.bergonzoli@crea.gov.it

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**Abstract:** Camelina is a low input crop than can be cultivated in rotation with cereals to provide vegetable oil suitable for bioenergy production, industrial applications and even as source of food for livestock. At large scale farming, camelina seeds are currently harvested using a combine harvester, equipped with a cereal header, but the literature still lacks the knowledge of the performance of the machine, the harvesting cost and the related loss of seeds. The present study aims to fulfill that gap by reporting the results obtained from an ad hoc harvest field test. Camelina seed yield was 0.95 Mg ha$^{-1}$ which accounted for the 18.60% of the total above ground biomass. Theoretical field capacity, effective field capacity and field efficiency were 3.38 ha h$^{-1}$, 3.17 ha h$^{-1}$ and 93.7% respectively, albeit the seed loss was 80.1 kg ha$^{-1}$ FM (7.82% *w/w* of the potential seed yield). The presence of material other than grain was rather high, 31.77% *w/w*, which implies a second step of cleaning to avoid undesired modification of the seed quality. Harvesting cost was estimated in 65.97 € ha$^{-1}$. Our findings provide evidence on the suitability to use a conventional combine harvester equipped with a cereal header for the harvesting of camelina seeds, although some improvements are required to reduce both seed loss and impurities.

**Keywords:** bioenergy; oil crops; work performance; harvesting loss

## 1. Introduction

The European Community has been facing ambitious challenges concerning the reduction of nonrenewable sources for energy production during the last decades. The new Renewable Energy Directives REDI and RED II aim to promote the exploitation of natural feedstocks while avoiding competition with food production, as for instance, the set target of 3.5% production of advanced biofuels in 2030 using either lignocellulosic residues or non-food crops [1]. Agriculture can significantly contribute to tackle the issue [2] providing a large spate of lignocellulosic residues [3–5] as well as energy crops for biofuel production [6,7]. Furthermore, biomolecules synthetized by energy crops can surrogate oil-derived compounds in several industrial sectors [8] to feed the so-called "green chemistry" which encompasses the production of many products, as solvents, cosmetics, building materials and biodegradable plastics [9]. Herbaceous crops are gaining interest across Europe as their biomolecules find many applications in the energy and industrial sectors [10]. Among them, camelina (*Camelina sativa* L.) is an attractive one since the seeds exhibit high oil content (30–49%) which is suitable for several industrial applications. Some studies investigated the possibility to exploit the camelina oil as valid alternative to fossil fuels and petroleum derivate compounds [11,12]. The critical aspects of using vegetable oil for fuel production are mainly linked to cost competitiveness of such industrial process [13,14]. In fact, Keske et al. (2013) reported the cultivation of camelina seeds for biodiesel production to be convenient for diesel fuel price higher than 1.31 $ $L^{-1}$ [15]. Moreover, Yang et al. 2015 investigated the quality of the biodiesel fuel derived from the transesterification of camelina oil and found the fuel properties being in compliance with both American and European standards (e.g., ASTM D6751 and EN 14214) although the poor oxidative stability [16]. Jet fuel production is also possible from camelina oil [17,18] and Natelson et al. (2015) reported a break-even selling price of 0.80 $ $kg^{-1}$ [19].

Moreover, camelina seeds are also suitable as a source of food for livestock [20–22], aquaculture [23,24] and feedstock for agrochemical, medical and veterinary products [25–27]. Additionally, the meal obtained from the oil extraction contains a high level of α-linolenic and for this reason, it can be used in animal diets resulting in an increase in the market value of the crop [28]. In facts, the same authors have recently reported that camelina meal can be incorporated into the poultry diet as a source of energy, protein, and essential *n*-3 and *n*-6 fatty acids and provided at low levels (5 up to 10%) no changes in egg production or egg quality were found. Thus, the multiple usage of camelina seeds makes it interesting for biorefinery industries [29]. Another key issue which makes camelina particularly interesting is its adaptability to different environmental conditions [30]. Camelina can be indeed cultivated as a low input crop and on poor or marginal soils [31,32] and even in double cropping regime with cereal and other agricultural species [33–38] thus, showing interesting features as a sustainable crop as well [18,39]. According to Lohaus et al. (2020), in semi-arid regions of North America, 86.4 L $ha^{-1}$ of biodiesel (9.45% v/w of the seeds yield) can be derived from camelina cropping [40].

However, the main concerns arising with camelina cropping for biofuel production are linked the high costs of the supply chain, which currently makes it 30% more costly than petroleum derived fuels [41]. Moreover, the competition for land between food and non-food crops it is also nourished, particularly if considering that more than 95% of the current biodiesel production worldwide relies on the use of edible vegetable [42,43]. Although the possibility to cultivate camelina on marginal lands can make its supply chain ethically acceptable, costs of harvesting and logistic must be investigated to make the camelina cropping economically sustainable too. Most of the costs related to the production of biodiesel are related to the feedstock [44] and the development of new technologies in the agriculture sector can lower them significantly, particularly at the harvesting stage [45]. Camelina seeds can be mechanically harvested to keep costs lower, by using a combine harvester equipped with cereal header [46]. However, seeds loss can be high since they are very small and light in weight (1000-seed weight ranges between 0.8 and 1.8 g [47,48] and the proper setting of the combine harvester is fundamental to keep such loss as low as possible [49]. The presence of weeds among camelina plants can further contribute to increase that loss [50]. The lack of knowledge of such important aspects leaves profound uncertainty on the practical outcomes of camelina cropping.

Notwithstanding the growing importance of camelina as a multipurpose oil crop, few studies have focused on the evaluation of work productivity, costs, and seeds loss in mechanical harvesting. For instance, Sintim et al. (2016) found 11.60% *w/w* of seed loss using a plot combine harvester [51], while Stolarski et al. (2019) recently reported the harvesting cost per surface unit of 46.70 € $ha^{-1}$ when using a New Holland (New Holland, PA, USA) combine harvester [52]. However, the performance and the harvesting costs of conventional combine harvester have not been tested yet although such information plays an important role in the decision making of farmers and other stakeholders.

Therefore, this study represents the first comprehensive investigation of camelina seeds harvesting in Spain reporting the work productivity, harvesting costs and seed loss related to the use of a conventional combine harvester, and it aims to provide the literature with relevant information for farmers and large enterprises.

## 2. Materials and Methods

### 2.1. Field Site

The test was carried out in the village of Villafruela, Burgos (Castilla y Leon, Spain) during the 27th week of 2020 (Figure 1). The field area was 3.82 ha, the altitude 912 m a.s.l. with a negligible slope value.

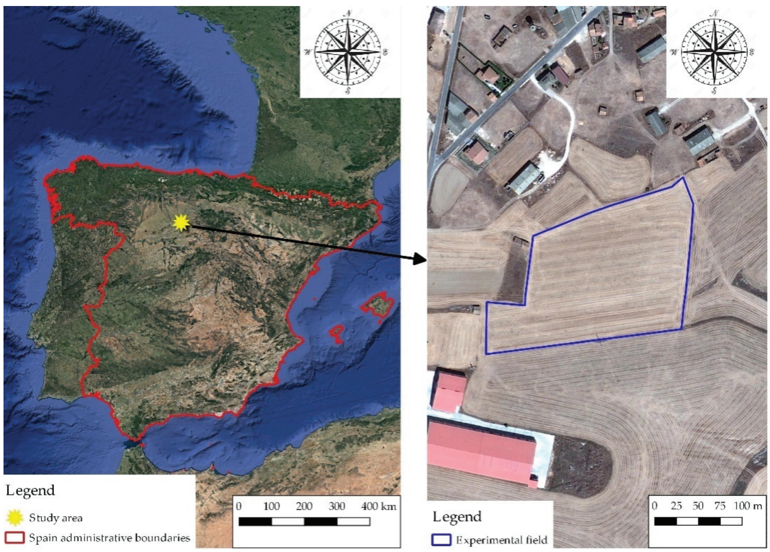


**Figure 1.** Map of the experimental field in Castilla y Leon region of Spain.

The cultivar Alba, variety suitable for cultivation in Mediterranean climate, was sown in early December 2019 at the rate of 8 kg ha$^{-1}$ and grown under conventional farming regime. Fertilizer was provided twice at the rate of 250 kg ha$^{-1}$ of NPK 8-15-15 and 250 kg ha$^{-1}$ of liquid Nitrogen fertilizer (32%) in winter and April, respectively. Successively, herbicide was applied for weed control.

The edge effect on the crop was excluded by selecting a 2 hectares homogeneous area within the field. The rest was preventively harvested but not included in the calculations.

### 2.2. Pre-Harvest Tests: Theoretical Biomass Assessment

Before harvesting, 10 sample plots of 1 m$^2$ each were randomly selected to evaluate the whole aerial biomass (i.e., straw, siliques, and seeds). Plants were cut at collect level and shipped outside the field, then counted and measured in weight and height. Siliques and seeds were removed manually from the plants and weighed separately. Successively, siliques, seeds and a sample of straw form each sample plot were put in plastic sealed bags and shipped to the laboratory of Research Centre for Engineering and Agro-Food Processing (CREA-IT) for further measurements as: theoretical yield of seed, dry weight (DW), bulk density and moisture content. Dry weight and moisture content were measured according to the EN ISO 18134-2:2017 standard [53]. The bulk density and 1000 seed-weight were also measured; seeds bulk density (kg m$^{-3}$) was assessed according to ISO 17828:2015 [54] in 10 randomly selected samples.

### 2.3. Combine Harvester

The contractor provided the combine harvester, a John Deere W650 (Figure 2) equipped with a conventional cleaning shoe and a 6.7 m wide cereal header. The machine was driven by 240 kW diesel engine and the setting applied (Table 1) was kept constant throughout the test.


**Figure 2.** John Deere W650 combine harvester equipped with a cereal header.

**Table 1.** Combine harvester (John Deere W650) settings used during harvesting of camelina.

| Parameter | Setting |
|---|---|
| Rotor speed (rpm) | 800 |
| Cleaning Fan Speed (rpm) | 700 |
| Openings of Upper Sieve (mm) | closed |
| Openings of Lower Sieve (mm) | 5 |
| Straw treatment | threshed |

### 2.4. Harvesting Performance

Five sample plots were randomly chosen within the selected area to test the performance of the combine harvester. The surface of each plot ranged between 1000 a 2500 $m^2$, and the study of the working times was carried out according to methodology proposed by *Comité International d'Organisation Scientifique du Travail en Agriculture* (CIOSTA) methodology and the recommendations from the Italian Society of Agricultural Engineering (A.I.I.A.) 3A R1 [55]. The assessment evaluation of the working speed allowed to identify the Theoretical Field Capacity (TFC, ha $h^{-1}$), the Effective Field Capacity (EFC, ha $h^{-1}$) and Material Capacity (MC, Mg $h^{-1}$). The ratio between EFC and TFC is named Field Efficiency (FE). The time required for discharge operations was recorded and considered as accessory time.

At the end of the harvesting operation the material collected was discharged onto a trailer and weighted for the determination of the seed yield at the farm scale. A sample of the collected material was taken and put in sealed bag in order to determine the moisture content, the percentage of MOG (Material Other than Grain, e.g., weed seeds, threshed siliques, part of weed plants) and the 1000-seeds weight.

### 2.5. Costs Analysis

The contractor, via interview, provided purchase and operating costs of the combine harvester, whilst the working performance of the machine was taken from the results of field tests and used as primary data. Finally, standard values for calculation were taken from CRPA (Research Centre on Animal productions) methodology [55].

Hourly costs of combine harvester were calculated considering the market value of the agricultural machinery [56]. The price of the machine was discounted to 2019, using the lending rate of 3% provided by Banca d' Italia Institute [57]. Applied parameters for economic evaluation are given in Table 2.

**Table 2.** Parameters for cost analysis.

| | Parameter | Measure Unit | Value |
|---|---|---|---|
| Machine | Power | kW | 240 |
| Financial costs | Investment | € | 380,000.00 |
| | Service life | year | 10 |
| | Service life | H | 3000 |
| | Resale | % | 19.00 |
| | Resale | € | 72,200.00 |
| | Depreciation | € | 307,800.00 |
| | Annual usage | h $year^{-1}$ | 312 |
| | Interest rate | % | 3 |
| Fixed costs | Ownership costs | € $year^{-1}$ | 30,780.00 |
| | Interests | € $year^{-1}$ | 6783.00 |
| | Machine shelter | $m^2$ | 30.82 |
| | Value of the shelter | € $m^{-2}$ | 100.00 |
| | Value of the shelter | € $year^{-1}$ | 61.64 |
| | Insurance | € $year^{-1}$ | 950.00 |
| Variable costs | Repair factor | % | 40 |
| | Repairs and maintenance | € $h^{-1}$ | 52.69 |
| | Fuel cost | € $L^{-1}$ | 0.57 |
| | Fuel consumption | L $h^{-1}$ | 37.37 |
| | Fuel cost | € $h^{-1}$ | 21.30 |
| | Lubricant cost | € $L^{-1}$ | 3.03 |
| | Lubricant consumption | L $h^{-1}$ | 0.36 |
| | Lubricant cost | € $h^{-1}$ | 1.08 |
| | Worker salary | € $h^{-1}$ | 11.5 |

### *2.6. Post-Harvesting Test: Seed Losses*

The total seed loss (TSL) was calculated as the mere difference between the theoretical biomass assessed during the pre-harvest and the effective quantity of seeds collected and weighted at the farm scale. This includes the seed loss due to the impact of the combine header and the ineffectiveness of the cleaning shoe of the machine to discriminate the seeds from the rest of the biomass processed. Therefore, a tarpaulin was installed at the end of two sample plots to collect the seeds lost by the combine harvester from the sieves and straw walkers. The entire amount of biomass expelled by the machine was thus collected by the tarpaulin laying on the ground. The biomass was shipped to the laboratory, then weighted and sieved for assessing the amount of seeds lost by the combine harvester (CSL). The weight of the seeds found was referred to a surface of 13.4 $m^2$ given by the width of the combine header (6.4 m) multiplied by the length of the tarpaulin (2 m). Furthermore, the 1000 seed-weight was recorded in order to compare it with the 1000 seed-weight of the harvested camelina seeds. The loss of seeds due to the impact (ISL) of the combine harvester with the siliques is calculated as TSL-CSL.

### *2.7. Statistical Analysis*

Statistical analysis was performed to investigate the difference between the 1000 seed-weight of harvested seeds and not-harvested ones. Normality and Homoscedasticity were tested with Shapiro test and F test, respectively. Considering that Shapiro test revealed that the distributions of the data could not be considered normal, the investigation of the presence of statistically significant differences between 1000 seed-weight of harvested seeds and not harvested ones was carried out through Kruskal-Wallis test. The analysis was performed with Statistica 7.0 software [58].

## 3. Results

### 3.1. Biomass Characterization

Results of the pre-harvest tests are given in Table 3.

**Table 3.** Results of pre-harvest tests.

| Parameter | Measure Unit | Average | St.Dev. |
|---|---|---|---|
| Harvested surface | ha | 3.82 | - |
| Number of plants | N $m^{-2}$ | 311 | 43 |
| Plant height | cm | 70.53 | 6.27 |
| Straw weight | Mg $ha^{-1}$ FM | 3.31 | 0.25 |
| Straw moisture content | % | 10.46 | 0.14 |
| Siliques weight | Mg $ha^{-1}$ FM | 1.20 | 0.05 |
| Siliques moisture content | % | 7.27 | 0.59 |
| Potential seed yield | Mg $ha^{-1}$ FM | 1.03 | 0.01 |
| Harvest Index (HI) | - | 0.186 | 0.013 |
| Seed moisture content | % | 5.18 | 0.58 |

At the harvesting, 311 plants per $m^2$ were standing on field and the plants measured 71 cm in height on average. Straw, siliques and seed moisture were 10.46%, 7.27% and 5.18% respectively.

As shown on Figure 3, the most abundant aboveground biomass was represented by straw which accounted for the 59.67% of the total, then siliques and seeds accounted for the 21.73% and the 18.60% respectively. Harvest Index (HI) resulted in 0.186.

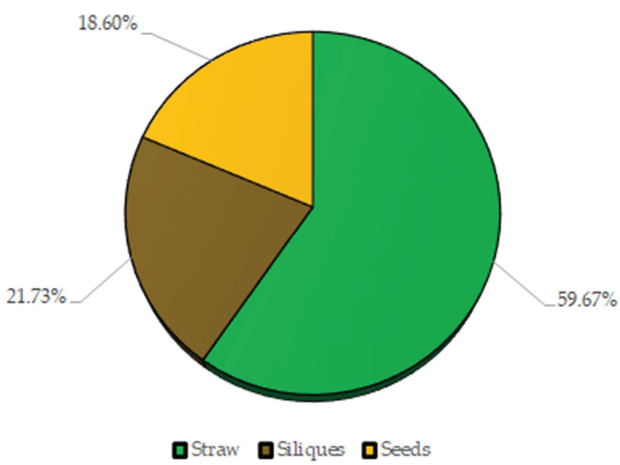


**Figure 3.** Percentage of straw, siliques and seeds of the aboveground biomass.

### 3.2. Work Performance and Costs Analysis

The performance of the combine harvester is given in Table 4.

The working speed of 5.05 km $h^{-1}$ allowed to reach a TFC and EFC values as high as 3.38 ha $h^{-1}$ and 3.17 ha $h^{-1}$, respectively. Since the seed yield was 0.95 Mg $ha^{-1}$ fresh matter (FM), the MC was 3.01 Mg $h^{-1}$ FM while the FE reached the value of 93.7%.

**Table 4.** Work performance analysis results.

| Parameter | Measure Unit | Average | St.Dev. |
|---|---|---|---|
| Seed yield | Mg ha$^{-1}$ FM | 0.95 | - |
| Working speed | km h$^{-1}$ | 5.05 | 0.35 |
| Theoretical Field Capacity (TFC) | ha h$^{-1}$ | 3.38 | 0.24 |
| Effective Field Capacity (EFC) | ha h$^{-1}$ | 3.17 | 0.20 |
| Field Efficiency (FE) | % | 93.7 | 0.83 |
| Material Capacity (MC) | Mg h$^{-1}$ FM | 3.01 | 0.19 |

The working performance allowed to calculate the harvesting costs (Table 5) of 210.21 € h$^{-1}$, 65.97 € ha$^{-1}$ and 69.42 € Mg$^{-1}$ FM.

**Table 5.** Results of costs analysis.

| Parameter | Measure Unit | Value |
|---|---|---|
| Costs per time unit | € h$^{-1}$ | 210.21 |
| Costs per surface unit | € ha$^{-1}$ | 65.97 |
| Costs per biomass unit | € Mg$^{-1}$ FM | 69.42 |

### *3.3. Seed Loss and Presence of MOG*

Results about seed loss and MOG analysis are given in Table 6.

**Table 6.** Seed loss and MOG analysis. Weights are given in FM.

| Parameter | Measure Unit | Average | St.Dev. |
|---|---|---|---|
| Total Seed loss (TLS) | Mg ha$^{-1}$ | 0.0806 | - |
| Total Seed loss (TLS) | % *w/w* | 7.82 | - |
| Combine Seed Loss (CSL) | Mg ha$^{-1}$ | 0.0598 | - |
| Combine Seed Loss (CSL) | % *w/w* | 5.80 | - |
| Impact Seed Loss (ILS) | Mg ha$^{-1}$ | 0.0208 | - |
| Impact Seed Loss (ILS) | % *w/w* | 2.02 | - |
| Bulk density of collected material | kg m$^{-3}$ | 439.947 | 43.064 |
| Bulk density of cleaned seed | kg m$^{-3}$ | 642.332 | 7.435 |
| Material Other than Grain (MOG) | % *w/w* | 31.77 | 3.10 |
| Moisture content of harvested seeds | % | 15.71 | 0.53 |
| 1000 seed-weight of harvested seeds | g | 1.1925 | 0.0168 |
| 1000 seed-weight of not-harvested seeds | g | 1.2074 | 0.0113 |

The TSL resulted in 80.1 kg ha$^{-1}$ FM (7.82% *w/w*), whilst CSL was 59.8 kg ha$^{-1}$ FM (5.80% *w/w*). Therefore, the ISL calculated as the difference between TSL and CSL, was 20.8 kg ha$^{-1}$ FM (2.02% *w/w*). The percentage of MOG found in the trailer was 31.77% *w/w*. That high value triggered by the presence of poppy seeds (*Papaver rhoeas* L.) and fine biomass residues caused the decreasing of the bulk density measured in the harvested camelina seeds, if compared with the value found in the laboratory for sieved seeds. Moreover, the presence of green parts of weeds and camelina plants increased seed moisture by 10.53%.

Finally, the means of 1000-seed weight recorded for the harvested seeds and CSL were not statistically different for the Kruskal Wallis test ($p$ value 0.2482).

## 4. Discussion

### *4.1. Biomass Characterization*

The average value of camelina seed yield (1.03 Mg ha$^{-1}$ FM) is in line with the values provided by other authors in Spain [59]. Schillinger (2019) reported values ranging from 0.34 to 1.18 Mg ha$^{-1}$

FM for cv. Calena in 8 years field experiment carried out in North-West USA [60]. Higher yield was experienced by Royo-Esnal et al. (2018) in Eastern Spain which reported values ranging from 0.92 to 2.31 Mg ha$^{-1}$ FM for cv. GP204 [36]. Imbrea et al. (2011) reported an average value of camelina seed yield for non-fertilized and fertilized fields of 0.93 Mg ha$^{-1}$ FM and 1.81 Mg ha$^{-1}$ FM, respectively [61]. These findings suggest that camelina is sensitive to the nutrient availability in the soil, although it is widely accepted that this species is suitable for marginal land cropping. High variability was also highlighted by Zanetti et al. (2020) suggesting a mindful approach when it comes to cultivate camelina as rotation crop with cereals [32]. Currently, other herbaceous oil crops are gaining interest through Europe, sometimes exhibiting higher seed yield, like canola (*Brassica napus* L.) and sunflower (*Heliantus annuus* L.) which yield 2.19 Mg ha$^{-1}$ FM and 1.97 Mg ha$^{-1}$ FM of seeds on average, respectively. On the other hand, the global average seed yield for safflower (*Carthamus tinctorius* L.) is 0.99 Mg ha$^{-1}$ FM [62].

The quantity of residual biomass found in the present study (i.e., straw and siliques) accounted for the 71.40% of the total biomass, whilst Stolarski et al. (2019) reported only 44% [52]. Camelina residues were not collected but chopped and left on the ground as a common practice. This would contribute to the accumulation of organic carbon in the soil. Findings in recent studies highlight the suitability of camelina residues for bioenergy production [63–65]. However, the exploitation of agricultural residues as a source of bioenergy, encompasses a comprehensive study of all the costs generated during collection and transportation. This is fundamental to provide reliable clues on the feasibility of a given supply chain. Nevertheless, further investigations are encouraged since it could represent a valid alternative to the already known agricultural residue supply chains.

### 4.2. Work Performance and Cost Analysis

The working performance of the combine harvester resulting from this study is similar to that found in other crops where the same machine is used, moreover with similar setting. Unfortunately, the lack of knowledge found in literature regarding the mechanical harvesting of camelina seeds does not allow a direct comparison of our results with other's ones.

In wheat harvesting, for instance, the TFC of the combine harvester ranges from 2.61 ha h$^{-1}$ to 3.72 ha h$^{-1}$, the EFC is in the range of 1.92–2.28 ha h$^{-1}$ while the FE lays between 67% and 83% [5,66,67]. In our findings TFC, EFC and FE were 3.38 ha h$^{-1}$, 3.17 ha h$^{-1}$, and 93.7% respectively. In harvesting camelina seeds, it seems that the combine harvester would perform better than in wheat grains harvesting. However, this difference can be explained by the average speed of the machine which was 5.05 km h$^{-1}$ that could have been possible because of the wide headlands. In fact, the machine could quickly turn on the next pass without wasting time to undertake manoeuvres at the end of the plots.

The EFC found in other oil crops were also similar, although the combine harvesters were equipped with different headers. For instance, in sunflower harvesting Chaplygin et al. (2019) [68] reported the EFC ranging from 1.50 to 3.70 ha h$^{-1}$, whilst Pari et al. (2008, 2016) [69,70], in cardoon (*Cynara cardunculus* L.) harvesting, reported the EFC ranging from 1.57 to 2.10 ha h$^{-1}$. In those cases, the lower values resulted from the lower working speed, i.e., 3–4 km h$^{-1}$, which was needed for a proper harvesting of the crops [46].

Harvesting cost for camelina seed harvesting was 65.97 € ha$^{-1}$ which is higher than the cost reported by Stolarski et al. (2019) which was 46.70 € ha$^{-1}$ [52]. However, it is similar to that reported by Semerci et al. in 2010 and 2019 tests conducted in sunflower harvesting, whom found the harvesting costs of 57.23 and 82.11 € ha$^{-1}$ respectively [71,72].

Nonetheless, when it comes to money, the harvesting cost are not the only parameter that is to be taken into account. The productivity and selling price of a given product are the major drivers in the farmers' decision making. Thus, in some cases, camelina cropping cannot compete with other oil crops. For example, the average global seed yield for sunflower, i.e., 1.97 Mg ha$^{-1}$ FM [62] is higher than the usual seed yield reported for camelina in Spain [59], with harvesting costs per biomass unit (69.42 € Mg$^{-1}$) higher as well. A similar conclusion can be drawn if camelina seeds harvesting cost is also compared with wheat harvesting costs per biomass unit. Here, the higher yield of grains per unit of surface lowers the cost remarkably [5,73]. Additionally, wheat straw market can further contribute to generate an income for the farmers, which is still being missing for camelina straw.

### *4.3. Seed Loss and Presence of MOG*

The TSL of 80.1 kg ha$^{-1}$ FM (7.82% of the potential seed yield) is mainly related to the combine harvester threshing and cleaning system (CSL), i.e., about 60 kg ha$^{-1}$ FM, whilst only 20.8 kg ha$^{-1}$ FM were due to the impact of the combine harvester header (ISL) on siliques. Sintim et al. (2016) reported that 11.70% of the seeds were lost during the harvesting when using a plot harvester [51], which is supposed to be more accurate than common combine harvesters and then generating as low seed loss as possible. Thus, future studies should focus specifically on the possible available strategies for reducing such source of seed loss. Interestingly, the mean 1000 seed-weight measured for harvested seeds and lost seeds were not statistically different. Indeed, this highlights that there was not enough physical difference among seeds to trigger loss. In fact, the idea behind to such investigation was that those seeds lost by the combine harvester could differ from the others because some physical properties, such as weight, shape or volume that, in turn, could have been linked to different content of oil, proteins or carbohydrates [74]. This was not the case; therefore, the seed loss is to be related only to either the machine setting or the working speed. Camelina seeds are very light in weight, then they are very keen to be blown by the fan installed in the cleaning shoe of the combine harvester. On the other hand, the fan speed cannot be lowered too much otherwise MOG would increase significantly. Unless the cleaning shoe of the combine harvester is profoundly improved by customizing the sieves and fans for the specific harvesting of camelina seeds, lowering the working speed is the most simple and effective expedient for decreasing the loss of seeds.

During the harvesting, the loss of seeds should be as low as possible. For instance, the average seed loss in sunflower harvesting is approximately 2% *w/w* [69], which can be further lowered to 1% if some adjustments and modifications are applied to the header [75,76]. In canola seeds harvesting, if the combine harvester is equipped with a specific rapeseed header, seed loss ranges between 0.97 and 2.76% *w/w* [77–79]. Similar values of seed loss (3%) are also reported in the literature for safflower [46], crambe (*Crambe abyssinica* R.E.Fr.) [80], and cardoon seeds [70].

However, the quantity of seeds lost (therefore the quantity of seeds harvested) is not the only parameter that should be carefully evaluated, but there is another noteworthy aspect to consider that is the high percentage of MOG (weed seeds and fine camelina residues) found in the harvested seeds. MOG is related to the capability of the combine harvester to discriminate efficiently seeds form impurities because they can affect negatively the quality of the seeds in different ways: by lowering the market value and, in the worst-case scenario, jeopardizing the proper conservation of the seeds. Our findings clearly show that the residuals from camelina plants blended with the harvested seeds increased their moisture content up to 15.71% which is above the threshold value of 8% for avoiding spoiling processes [59,81]. The high amount of poppy seeds implied the need to further clean the camelina seeds (test not performed) before being delivered either to the industries for oil extraction or to farmers for sowing. Additionally, the lower bulk density of the collected material caused by the presence of MOG, could increase the cost for transportation, which is a key parameter for the economic sustainability of a biomass supply chain [82–84].

## 5. Conclusions

The cultivation of camelina for vegetable oil production can contribute to reduce the dependence on fossil as valid source for both energy production and raw material supply for industries. Meanwhile, the agricultural fields can benefit from the rotation of cereal crops with camelina. In Spain camelina is cultivated as winter crop and harvested in summer with a combine harvester equipped with cereal header. Seed yield was 0.95 Mg ha$^{-1}$ which represented the 18.60% of the total aboveground biomass. Straw and siliques were not collected but chopped and returned to the ground. Currently a proper supply chain for their exploitation is still missing; proposals to use them as fuel for bioenergy production are found in literature, but still not confirmed at the industrial scale. The combine harvester performed better on camelina seeds harvesting in comparison with wheat, or other herbaceous oil crops as sunflower or cardoon in terms of TFC, EFC and FE, although the latter two species require a dedicated header. Harvesting cost was assessed in 65.97 € $ha^{-1}$ (or 69.42 € $Mg^{-1}$ if considered per Mg of seeds harvested) which is close the cost for wheat harvesting. However, the revenue may change according to the productivity and the market price of the two products. Interestingly, the seed loss was lower than reported by a similar study (even though a plot combine was used) but still not as low as found in other oil crops. Our findings suggest that 5.80% of seed loss out of the TSL of 7.2% derives from the ineffectiveness of the cleaning shoe of the combine harvester, then supporting the hypothesis that further investigations as well as improvements should be done in order to lower that value. Moreover, the harvested seed showed a high presence of MOG which can jeopardize the proper maintenance of the seeds (high moisture content) if impurities are not promptly removed. The lower bulk density could affect negatively the cost of transportation. In conclusion our findings address the main controversial passages of the camelina oil value chain, which are mainly linked to the harvesting stage. Reducing such aspects would in turn contribute to lower costs and increase the overall profitability of the value chain, thus further studies are encouraged to lower MOG content and seed loss.

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# A Comparative Analysis of Two Cable Yarder Technologies Performing Thinning Operations on a 33 Year Old Pine Plantation: A Potential Source of Wood for Energy

**Rodolfo Picchio [1,*], Rachele Venanzi [1], Nicolò Di Marzio [1], Damiano Tocci [1] and Farzam Tavankar [2]**

1 Department of Agricultural and Forest Sciences, University of Tuscia, 01100 Viterbo, Italy; venanzi@unitus.it (R.V.); n.dimarzio@libero.it (N.D.M.); toccidamiano91@gmail.com (D.T.)
2 Department of Forestry, Khalkhal Branch, Islamic Azad University, Khalkhal 56817-31367, Iran; tavankar@aukh.ac.ir
* Correspondence: r.picchio@unitus.it

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**Abstract:** In central Italy, there are extensive European black pine (*Pinus nigra* Arn.) plantations which range from 30 to 60 years of age and where no thinning operations have been made. The main purpose of this study was to provide a comparative analysis of two cable yarder technologies (Maxwald, mobile pulley carriage and Savall, semi-automatic carriage), in terms of fuelwood production and cost, from the first thinning of a 33 year old plantation in slope areas of these plantations. The results showed that fuelwood production was cost-effective in both systems (Savall by 15.1 and Maxwald by 14.8 € $m^{-3}$), although the productivity of the Savall system was higher than the Maxwald system (6.1 vs. 5.7 $m^3$ $h^{-1}$). The respect amounts of productivity have the potential to increase by 27% for the Savall yarder and 25% for the Maxwald yarder upon condition that the delay times are reduced to minimum level by proper training of workers, by a better organization, and planning of operations. The total effective $CO_2$ emission by the Savall yarder was lower than the Maxwald yarder (1735 vs. 1772 g $m^{-3}$). A sustainable production of fuelwood that is economically advantageous and environmentally sound in these plantations can be realized through an appropriate mechanization level and constant interaction with the silvicultural planning. This must be completed with adequate and efficient worker training.

**Keywords:** fuelwood; cable yarder; $CO_2$ emission; pine plantations; time study; energy efficiency

## 1. Introduction

Between the various silvicultural treatments, thinning is one of the most important, generally consisting of the removal of some trees in order to decrease the competition [1,2] and increase the tree dimensions. In fire-prone stands, thinning represents a valid system to prevent surface fires from turning into crown fires [3]. Generally, thinning should be done early to be efficacious [4,5], but early thinning provides low quantities and often low commercial value timber, making it difficult to generate revenue [6,7]. This leads to serious problems, especially in coniferous natural or artificial stands, with real risk of forest degradation and instability [7–9]. Recently, thinning has been reconsidered in forest management thanks to modern forest mechanization, making this treatment less expensive. Futhermore, logging residues for energy purposes bring net income gains. High levels of mechanization require important investments and accurate forest planning [10], so that it is often convenient to carry out late thinning and final harvesting [6,11]. The Full Tree System (FTS) system results in being even more valid to produce structural timber as the chipping operations of residuals can be performed directly at the landing site. Where the risk of fire is high, branch wood removal is an effective method of prevention. Forest logging companies need to make high mechanization investments to adopt FTS. For this reason, FTS is widely used in final cuts. In terms of safety within operational conditions, setting a proper cut-off threshold to the load mass may not be effective. The correct set up of the skyline and good maintenance play an important role in safety risk prevention, for example lubrication and control of corrosion [12].

With slope gradient greater than 30%, usual small-scale technologies offer winches, animal power, and gravity sliding [13]. In some cases, animals can still be competitive but only in particular conditions [14] and their use is hardly compatible with the lifestyle of industrialized countries [15]. The winch can produce good results for short distances [16], and gravity sliding requires a high labor input [17]. Terrestrial extraction systems could be 2–3 times cheaper than aerial systems [18]; nevertheless there might be at least two reasons to promote the cableways systems. Firstly, an additional timber production area can be made which is associated with inaccessible surfaces to terrestrial machinery. Secondly, due to the fact of the growing need to safeguard the environment [19,20]. For these reasons, it is important to optimize the efficiency of logging systems and minimize costs. To support wood and forestry entrepreneurship will be necessary to improve the productivity in the forestry-wood chain [21].

The most widespread extraction system in central Italy is the Short Wood System (SWS) which has been used in coppice, high forest conversion harvesting [22] and also in thinning although rarely. FTS extraction is rarely adopted, but it is rapidly spreading. Tractors equipped by forestry winches or tractors with forwarding bins and pack mules are used in the SWS. New methodologies for bunching and extraction can be competitive with traditional methods, but mainly if associated with different work systems, especially in the FTS. When the slope gradient exceeds 30%, cable yarding could offer much better solutions. Small cable yarding lines, for small-scale forestry, are now available on the market. Such yarders have been made only for small trees (or loads), and low costs allow them to be depreciated in thinning operations and firewood harvesting (small-scale forestry) [13]. To afford the use of a cable system, the harvesting volume should be more than 46 $m^3$ $day^{-1}$ [18]. Forest operations in thinning treatment can be carried out through various logging systems. In central Italy, the most frequent are short wood and whole tree systems [23]. In this specific study, the latter was applied, and two different cable yarder models were tested for extraction operations. After extraction, whole trees were chipped and the wood chips obtained were for energy production.

In recent decades the wood chips market for energy purposes reached an interesting level of profit [24]. Moreover, biomass is a substantial source for energy production and one of the most renewable and sustainable. The recent energy market, the fossil fuel prices, and the lower ecological and environmental footprint of the biomass in comparison to non-renewable fuels (RED II—EU Renewable Energy Directive 2018/2001/EU) are the factors that caused an important biomass consumption increase. [25]. Energy production from woody biomass is a multistage process, where only a careful phases assessment can lead to a complete sustainability following its three main pillars (economy, environment, and society). In this regard, one particular and sensitive issue in forest management is related to assessing the consequences of different forest operations, focusing on the economic, environmental, and social performance of each alternative before a treatment is eventually carried out. The different pillars of sustainability can be a valid guide for decision makers in their actions and to ensure a clear reduction of the impacts related to their decisions [26].

Residual trees/regeneration are less damaged by cable yarders in compression with ground-based logging systems; however, production costs by cable yarders are higher than ground-based logging systems. Also, level of soil disturbance following logging/thinning operation by cable yarders are less than ground-based systems. Soil disturbance can lead to soil erosion, and reduction of site productivity. However, this study has focused on the aspects most closely linked to the operation performance and the production management for energy purposes, leaving further surveys on the environmental impact for future papers. Due to high costs of cable yarder applying in logging/thinning operation, comparative analysis, in term of system productivity, are essential in choosing a suitable machine.

Focusing on the first thinning treatment in the slope area for chips fuelwood production, the main aims of the present study were: (i) to provide a comparative analysis of two cable yarder technologies; (ii) to determine the influence of a detailed assessment of logging methodologies to improve sustainable forest operations.

## 2. Materials and Methods

### 2.1. Study Area

This study was carried out in Central Italy, in an even-aged reforestation plot of European black pine (*Pinus nigra* A.), near the Orvieto municipality, Umbria region, 42°46′51.47′′ N, 12°12′45.01′′ E (Datum: WGS 84, Coordinate format D.M.S.). The study was carried out in a pine plantation that was thinned according to systematic and single tree selection cutting methods in 2010, from March to July. The working site was located within a regional nature park, where reduced impact logging (RIL) techniques are carefully applied. The climate is Mediterranean, characterized by hot, dry summers, mild, rainy autumns, and early springs, so this area could be classified as "humid" (on the basis of De Martonne index of 36). The mean annual precipitation is about 900 mm and the mean annual temperature is 14.8 °C. The highest monthly daily temperatures are in July or August (31 °C) and the lowest ones are in January (2 °C). The study area has a surface of about 40 ha, and it is composed of a 33 year old *Pinus nigra* plantation (Table 1). The planting pattern of European black pine trees was regular, with 3 × 2.5 square meters. The area is located at 500 m a.s.l., on a slope with an average gradient of 40–45% and over. The bumpy surface such as outcrops or emerging boulders covers about 20% of the total surface and represents an obstacle for ground-based extraction systems. The soil is composed of a mix of limestone and marls of Cretaceous-Paleocene-Eocene, and contains numerous nodules of chert, with an average texture, following the USDA classification, of clay-loam. The main hardwood species present as natural regeneration or old trees were Turkey oak (*Quercus cerris* L.), common maple (*Acer campestre* L.) and manna-ash (*Fraxinus ornus* L.).

**Table 1.** Dendrometric characterization of the stand studied, average results obtained from 16 sampling plots (average ± standard deviation). Different letters indicate significant differences between averages by *t* test with *p*-value < 0.05.

| Dendrometric Characteristic | Unit | Before Thinning | After Thinning |
|---|---|---|---|
| Density | trees $ha^{-1}$ | 1326 ± 48a | 472 ± 13b |
| Basal Area | $m^2$ $ha^{-1}$ | 45.3 ± 2.6a | 16.0 ± 1.5b |
| DBH | cm | 20.3 ± 1.8a | 20.5 ± 1.1a |
| Tree height | m | 16.2 ± 1.9a | 16.4 ± 1.1a |
| Tree volume | $m^3$ | 0.353 ± 0.058a | 0.350 ± 0.035a |
| Branch mass | % total | 18.2 ± 2.6a | 18.3 ± 2.0a |
| Stand stocking | $m^3$ $ha^{-1}$ | 468 ± 28a | 165.2 ± 10b |
| Annual yield | $m^3$ $ha^{-1}$ $year^{-1}$ | 14.2 | - |

### 2.2. Thinning Operations and Machines

Thinning was performed for the first time in the study area and consisted of every ten tree rows in the systematic felling of one row, and among the nine standing rows a selective thinning was carried out, with an intensity of 64.4% in number of trees, 64.7% in basal area and 65.3% in stand stocking (Table 1). It is noteworthy that the heavy selection cut follows the silvicultural policy; in fact, it is increasingly popular in Italy, and in many other countries, to steer artificial plantations toward natural prototypes [27]. The area has an uphill landing site, with a single forest road crossing it. The density of forest roads and skid trails was 37.4 and 30.2 m $ha^{-1}$, respectively. The stand presented its original density, because none treatment has ever been done.

Felling operations were carried out by a chainsaw operator (Husqvarna 346 XP, Table 2) and two helpers very useful in the stump for cleaning and tree landing. Logging operations were done by three operators, according to the so-called "full tree system" (FTS). The felled area considered for the study of these operations was divided according to each yarder line typology, and only one team worked in the examined site. The working team had a specific training and experience for the working system applied. Extraction was performed uphill by two mini-yarders with different carriages and a modified forestry winch. Trees were just extracted out of the stand to the forest road, where they were chipped (including the main trunk), and the chips loaded on a truck. Mini-yarder system was mainly composed by one winch, one carriage and two steel wire ropes. The forest mechanic winch, with a maximum pull of 45 kN, was applied to a farm tractor with engine power of 55 kW. The winch was equipped with a main drum for the pulling rope containing 250 m of steel rope with a diameter of 9 mm, and with a secondary drum for the mainline rope containing 200 m of steel rope with a diameter of 14 mm. The two different carriages used were: a semi-automatic carriage with a nominal maximum payload of 1.5 kN (SAVALL 1500), and a mobile pulley carriage with a nominal maximum payload of 1.0 kN (MAXWALD) (Table 2).

The units were designed for installation in gravity skyline configuration only. The mainline wire rope was tightened by a hand-hoist between two end-spars (vigorous trees). The pulling rope connected the winch to the carriage, and it was used to move the carriage back and forth along the mainline wire rope, and also to skid the felled trees and lift up the loads in the planned loading points. The skyline was equipped with two mobile line blocks to stop the carriage, respectively at the loading and unloading points. In particular, in the system with semi-automatic carriage the line blocks were provided with hydraulic clamps, and the system with mobile pulley carriage was equipped with mechanic clamps. Main winch controls were mechanic with manual action, consisting of a clutch and a brake. These two systems represent two different technological devices applicable to small-scale forestry, while remaining in professional application contexts. Understanding their operational differences and limits is an excellent aid to technicians and forestry owners, but also represents the starting point for technological improvements to these machines and equipment.

### *2.3. Data Collection and Analysis*

Pre and post-harvest stand data were obtained through systematic plot sampling. Grid dimension was 150 m × 150 m, the area of each circular plot was 314 $m^2$ (10 m radius), and in total 18 plots in each sampling were established. Diameter at breast height (dbh) and height of tree species were measured by caliper and clinometer, respectively, in each plot. The growing stock and average biomass yield were estimated with a two-way table (dbh and height of tree) developed for *P. nigra* growing in Tuscany [28]. The branch mass was obtained sampling 50 trees.

A time-motion study was carried out to evaluate working productivity and to identify those most likely variables capable of affecting it. Each working cycle was stop watched individually, separating productive time from delay time [29,30]. Delay factor calculated, represents the quotient of delay time over net cycle time. Productivity was calculated both on delay-free time and on actual total time, inclusive of all delays. Inclusion of delays was not capped on the basis of a maximum event duration. Scheduled Machine Hours (SMH) include all time the machine is scheduled to work, Productive Machine Hours (PMH) represent the time during which the machine actually performs work and this exclude time lost to both mechanical and non-mechanical delays.

**Table 2.** Models and technical characteristics of the applied machines in the felling and extraction of marked trees from thinning operation.

| Machine | Chainsaw | Tractor | Chipper | Machine | Winch | Machine | Cable Yarder System | |
|---|---|---|---|---|---|---|---|---|
| Model | Husqvarna 346 XP | New Holland TK4.80N | Pezzolato PTH 700/660 | Model | SAVALL 80 kN | Model | SAVALL 1500 | MAXWALD |
| Displacement ($cm^3$) | 50 | 3400 | 6500 | Winch max pull (kN) | 80 | Nominal maximum payload (kN) | 1.5 | 1.0 |
| Engine power (kW) | 2.7 | 55 | 126 | Winch pull for cable yarder (kN) | 45 | Mainline rope diameter of 14 mm (m) | 200 | 200 |
| Mass (kg) | 6 | 3700 | 8200 | Mass (kg) | 720 | Carriage mass (kg) | 80 | 40 |
| Engine type | Gasoline mix | Diesel | Diesel | Pulling rope diameter of 9 mm (m) | 250 | Mainline rope mass (kg) | 250 | 250 |

The felling operation is divided in three phases: "approach to the marked tree" (when the chainsaw operator moves from the last felled tree to the other to be felled), "preparation of felling site" (when the team cleans the tree stump before the felling), and "felling" (when the chainsaw operator turns on the chainsaw and performs the cut and ends with the fall of the tree).

Bunching-extraction distance was determined with a measuring tape. Load volume was calculated multiplying the number of trees per load for the average tree size. The average tree volume was obtained sampling 240 trees (15 trees in each thinning row) (Table 3).

**Table 3.** Dendrometric parameter of the tree harvested, average results obtained from 15 trees per line. ANOVA analysis applied only on DBH and tree volume (d.f. 15, 224), $p > 0.05$ (average ± standard deviation).

| Parameter | Unit | Value |
|---|---|---|
| Tree intensity | trees ha$^{-1}$ | 854 ± 18 |
| DBH | cm | 20.9 ± 1.7 |
| Height | m | 16.3 ± 2.2 |
| Volume | m$^3$ tree$^{-1}$ | 0.355 ± 0.058 |
| Fresh mass per tree | t tree$^{-1}$ | 0.320 ± 0.062 |
| Dry mass per tree | t tree$^{-1}$ | 0.190 ± 0.089 |
| Total felled volume | m$^3$ ha$^{-1}$ | 302.8 ± 24.1 |
| Total felled fresh mass | t ha$^{-1}$ | 272.9 ± 15.2 |
| Total felled dry mass | t ha$^{-1}$ | 162.1 ± 12.1 |

The system boundaries for the study area were set to those of the forest operations, i.e., only by the felling to the chipping site, or by the felling to the chips loading site were taken into consideration. The Functional Unit (FU) used in the analyses was the dry ton ($t_{d.m.}$). During this study, 16 skylines, 8 for each carriage used, were analyzed (Table 4) and every line was 50 m wide.

**Table 4.** Technical description (average ± standard deviation) of the wood extraction lines in two logging systems.

| Parameter | Semi-Automatic Carriage (Savall) | Mobile Pulley Carriage (Maxwald) |
|---|---|---|
| Line length (m) | 165 ± 25 | 160 ± 27 |
| Effective operative line length (m) | 146 ± 16 | 145 ± 11 |
| Line slope (%) | 47 ± 11 | 45 ± 10 |
| Span for line | 2 | 2 |

Operational costs were estimated with the Miyata [31] method as described in Spinelli et al. [13]. Different machines have been estimated considering different periods of use. For the skyline with carriage, winch, and accessories, an annual use of 800 scheduled machine hours (SMH) was estimated and a depreciation period of 10 years [32]. The farm tractor for the skyline winch was depreciated on 1000 SMH per year, assuming that it could be used in other works besides yarding [11,13]. The chainsaw for the felling was depreciated on 800 SMH per year and a depreciation period of 2 years [11]. Labor cost was set to 15 € SMH$^{-1}$ inclusive of indirect salary costs [11,33]. The costs of insurance, repair and service were obtained by other studies [11,13], while the fuel and lubricant average prices by a market survey (second semester 2019) conducted upon three company products. The calculated operational cost, as suggested also in Spinelli et al. [13], increased by 10% to account for overhead costs [34].

As reported in Picchio et al. [2] for the machines and accessories, a complete energy consumption analysis was assessed, following the Gross Energy Requirements (GER) method. The indirect input (MJ $t_{d.m.}$) of machines and tools was determined on the basis of the average energetic values (MJ kg$^{-1}$) of raw materials related to: their quantitative presence (%) estimated and calculated, the total mass of the machine (kg), the total service life of the machine (h $t_{d.m}{}^{-1}$), and the use of the machine during forest operations. The energetic consumption related to human work was assessed following as reported in Christie et al. [35,36] and in Balimusi et al. [37], by applying a value of 0.030 MJ $min^{-1}worker^{-1}$.

To complete the energy balance, the energetic value of wood as the energy released during its combustion was determined as Higher Heating Value (HHV) (CEN/TS 14918) on 20 random samples, one sample per loading, by means of an adiabatic calorimeter (Parr, model 6200) [38].

To assess pollutant emissions during forest operations, emissions due to fuel were calculated as the sum of emissions produced during combustion (Efc) and emissions produced during production process and logistic (Efp). In the Efc assessment were considered the fuel energy content, the specific engine emission factors, and the thermal efficiency of the fuel combustion process. The results were obtained using the formula suggested by Klvac et al. [39], with wheeled tractors emission factors (Table 5), only CO2 emissions were assessed by applying the emission factor adopted by Athanassiadis [40]. In the Efp assessment were considered the fuel energy content and emission factors suggested in Klvac et al. [39], only HC emission factor of 0.0862 was adopted from Athanassiadis [40]. Besides the fuel consumption also the lubricant consumption was assessed, considering as proposed by Athanassiadis [40] and Klvac et al. [39], two main aspects: emissions produced by production processes (Eop) and by reprocessing of used oils for final combustion (Eor). The lubricants were selected on the basis of specific oil types and mix. As reported in Picchio et al. [22], the fuel and oil consumptions were calculated considering engine power, load factor and specific fuel consumption related to the time of use per output unit.

**Table 5.** Emission factors of compression–ignition engines (C) and spark–ignition engines (S) in wheeled tractors as related to engine output power (kg $kWh^{-1}$) [39–41]. Conversion from kWh to MJ: 1 kWh = 3.6 MJ; PM10—particular matters up to 10 microns and less; VOCs—volatile organic compounds.

| Pollutant ($g\ MJ^{-1}$) | Wheeled Tractor | |
|---|---|---|
| | C | S |
| $CO_2$ | 263 | 263 |
| CO | $9.84 \times 10^{-3}$ | $1.90 \times 10^{-1}$ |
| Formaldehyde | $3.78 \times 10^{-4}$ | $3.41 \times 10^{-4}$ |
| $NO_X$ | $1.60 \times 10^{-2}$ | $8.54 \times 10^{-3}$ |
| $PM_{10}$ | $1.70 \times 10^{-3}$ | $4.84 \times 10^{-4}$ |
| $SO_2$ | $1.14 \times 10^{-3}$ | $3.04 \times 10^{-4}$ |
| $VOC_s$ | $2.36 \times 10^{-3}$ | $7.16 \times 10^{-3}$ |

Statistical analysis was done using Statistica Statsoft. Kolmogorov-Smirnov test was used in order to verify data distribution and normality. Dendrometric characteristics of stand studies before and after thinning were compared by independent samples *t* test. Differences between plots were checked with the ANOVA and MANOVA tests, or with its nonparametric equivalent (Kruskal-Wallis) if the data did not reach the normality. Regression analysis of time study data was used to check a model capable of predicting productivity as a function of statistically significant independent variables such as distance and load size. If the data were not normally distributed, a non-parametric Spearman's rank coefficient was applied to analyze the correlation between the variables.

## 3. Results

The data shown in Table 1, referring to a productive stand, harvested for about two thirds of its total stock (nearly 64% of the basal area). The independent samples *t* test showed that dendrometric characteristics (dbh, height, volume, branch mass of residual trees) are uniform before and after thinning operations. Harvesting did not consider only smaller dominated trees but included many dominant trees with stability and structure issues (Table 3). For this reason, the post-harvest dendrometric data returned almost the same average tree size (DBH, height and volume).

The statistical analysis (ANOVA) of the average working times did not show significant differences among the 16 yarder lines. By the ANOVA results between DBH (diameter classes in centimeters: 10, 15, 20) of the felled trees, it can be said there are no significant statistical differences in average felling time. About the analysis of felling phases, "felling" takes about 42% of the total felling operation time. Globally felling operations have a productive time (PMH) of 159.10 h and delays are 39.86 h (20% of the scheduled time—SMH), with a Delay Factor (DF) of 25.1%. On the basis of our calculation, felling productivities (Table 6) resulted 19.78 $m^3SMH^{-1}$ and 24.74 $m^3PMH^{-1}$.

**Table 6.** Time and productivity of felling operation (average ± standard deviation).

| | Unit | Value |
|---|---|---|
| Worker | n° | 3 |
| Machinery | | 1 |
| Trees | | 11,102 |
| Approach to the tree time | min | 0.25 ± 0.19 |
| Preparation of the felling site time | | 0.16 ± 0.10 |
| Felling time | | 0.45 ± 0.26 |
| Delays | hours | 39.86 |
| PMH | | 159.10 |
| SMH | | 199.96 |
| Delay Factor | % | 25.1 |
| Productivity with PMH | $m^3PMH^{-1}$ | 24.74 |
| | t $PMH^{-1}$ (fresh matter) | 22.29 |
| | t $PMH^{-1}$ (dry matter) | 13.24 |
| Productivity with SMH | $m^3SMH^{-1}$ | 19.78 |
| | t $SMH^{-1}$ (fresh matter) | 17.83 |
| | t $SMH^{-1}$(dry matter) | 10.59 |

Notes: PMH = Productive Machine Hours, excluding delays (net cycle time); SMH = Scheduled Machine Hours, including delays (total cycle time); DF = Delay Factor, i.e., delay time/net time [42].

Among the yarder lines, the statistical analysis (MANOVA) of the average working time (Table 7) did not show significant differences in cycle, trees per cycle, bunching and extraction distance. Between the two yarder lines with different carriage, the statistical analysis (MANOVA) of the average working time (Table 7) showed significant differences about cycle, average time for unloaded carriage travel and for choking time. The working time analysis shows a SMH time of 421.10 and 425.60 h for yarder line with the Savall and the Maxwald carriage respectively. The percentages of logistic and preparation time, 12.1% for Savall and 11.8% for Maxwald, are similar and considerably smart for simple yarder lines, as those used. Phase analysis shows that the time necessary for the loaded carriage to travel takes about 26% for the Savall and 25% for the Maxwald of total operation time. Globally, extraction operation for the Savall lines have a productive time (PMH) of 328.90 h and delays are 92.10 h (22% of the scheduled time—SMH), with a Delay Factor (DF) of 28.0% and for the Maxwald lines have a productive time (PMH) of 338.20 h and delays are 87.40 h (21% of the scheduled time—SMH), with a Delay Factor (DF) of 25.8%.

**Table 7.** Time and productivity of bunching—extraction operation (average ± standard deviation) in two logging systems, and results of MANOVA test.

| | Unit | SAVALL | MAXWALD | *p*-Value |
|---|---|---|---|---|
| Worker | n° | 3 | 3 | - |
| Trees | | 5636 | 5466 | >0.05 |
| Working cycles | | 3458 | 3416 | <0.05 |
| Time for line of survey and logistic | min | 98.38 ± 16.12 | 98.38 ± 16.12 | - |
| Time for line of assembly and disassembly | | 285.15 ± 21.28 | 277.50 ± 18.12 | - |
| Time carriage travel unloaded | | 0.69 ± 0.22 | 0.75 ± 0.24 | <0.05 |
| Choking time | | 1.28 ± 0.48 | 1.42 ± 0.34 | <0.05 |
| Time carriage travel loaded | | 1.86 ± 0.58 | 1.84 ± 0.32 | >0.05 |
| Unchoking time | | 0.99 ± 0.29 | 1.05 ± 0.17 | >0.05 |
| Bunching distance | m | 9.40 ± 5.16 | 10.10 ± 3.11 | >0.05 |
| Extraction distance | | 44.42 ± 30.01 | 43.55 ± 20.15 | >0.05 |
| Trees per cycle | n° | 1.63 ± 0.67 | 1.60 ± 0.38 | >0.05 |
| Delays | hours | 92.10 | 87.40 | - |
| Productive Machine Hours (PMH) | | 328.90 | 338.20 | - |
| Scheduled Machine Hours (SMH) | | 421.10 | 425.60 | - |
| Delay Factor | % | 28.0 | 25.8 | - |
| Productivity with PMH system | $m^3PMH^{-1}$ | 6.08 | 5.73 | - |
| | t $PMH^{-1}$ (fresh matter) | 5.48 | 5.16 | - |
| | t $PMH^{-1}$ (dry matter) | 3.25 | 3.07 | - |
| Productivity with SMH system | $m^3SMH^{-1}$ | 4.75 | 4.55 | - |
| | t $SMH^{-1}$ (fresh matter) | 4.28 | 4.10 | - |
| | t $SMH^{-1}$ (dry matter) | 2.54 | 2.44 | - |

Notes: PMH = Productive Machine Hours, excluding delays (net cycle time); SMH = Scheduled Machine Hours, including delays (total cycle time); DF = Delay Factor, i.e., delay time/net time [42].

For both skyline systems, the delays were mainly due to errors committed by the chocking workers, for example through erroneous chocking of chains on the log. The bunching-extraction productivities, on the basis of collected time data and total worked volume, were 4.75 $m^3SMH^{-1}$ and 6.08 m3PMH−1 for the yarder line with the Savall carriage and 4.55 $m^3SMH^{-1}$ and 5.73 cubic meter $PMH^{-1}$ for the yarder line with the Maxwald carriage (Table 7).

The regression analysis (Figure 1) highlighted a good statistical correlation between extraction time, extracted volume and extraction distance, with $R^2$ near to 0.9 for both carriages. In the Maxwald carriage the correlation was considerably higher than in the Savall carriage (93.4% vs. 85.9%).

Among the 16 yarder lines, the statistical analysis (ANOVA) of the average chipping time does not show significant differences (Table 8). Globally chipping operation has a productive time (PMH) of 71.85 h and delays consists of 11.17 h (14% of Scheduled time—SMH). Chipping productivity (Table 8) results, on the basis of our calculation, on 47.48 $m^3SMH^{-1}$ and 54.86 $m^3PMH^{-1}$.

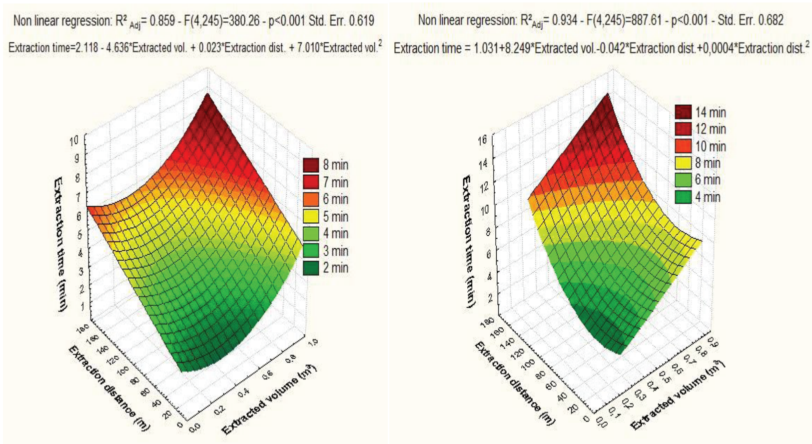


**Figure 1.** Nonlinear regression analysis for the two yarder lines, referred to the extraction time in relation to the extracted volume and extraction distance, with Savall carriage on the left and with Maxwald carriage on the right.

**Table 8.** Time and productivity of chipping (average ± standard deviation).

| | Unit | Value |
|---|---|---|
| Worker<br>Machinery<br>Trees | n° | 1<br>1<br>11,102 |
| Average chipping time for tree<br>Average hydraulic crane time movements for tree | min ± SD | 0.18 ± 0.09<br>0.20 ± 0.11 |
| Delays<br>Productive Machine Hours (PMH)<br>Scheduled Machine Hours (SMH) | hours | 11.17<br>71.85<br>83.02 |
| Delay Factor | % | 15.5 |
| Productivity with PMH system | $m^3 PMH^{-1}$<br>t $PMH^{-1}$ (fresh matter)<br>t $PMH^{-1}$ (dry matter) | 54.86<br>49.45<br>29.36 |
| Productivity with SMH system | $m^3 SMH^{-1}$<br>t $SMH^{-1}$ (fresh matter)<br>t $SMH^{-1}$(dry matter) | 47.48<br>42.80<br>25.41 |

Notes: PMH = Productive Machine Hours, excluding delays (net cycle time); SMH = Scheduled Machine Hours, including delays (total cycle time); DF = Delay Factor, i.e., delay time/net time [42].

If delay times tend to zero, the total productivity of the yard showed in Figure 2 and referred to SMH, could potentially increase to a maximum of 27% for the yarder line with Savall carriage, and 25% for the yarder line with Maxwald carriage.

The hourly machine costs, including fixed cost, variable cost, and labor cost, are shown in Table 9. The yard costs for each case study operation is presented in Table 10. The financial analysis shows the machine operating costs per unit time. These were mainly composed by the variable costs for the chainsaw, tractor and by fixed costs for the skyline (Table 9). As concerns the single operations (Table 10), extraction represented the most relevant expenditure with about 70 € $h^{-1}$, while felling showed the lowest operative costs per hour, with 53.28 € $h^{-1}$. The hourly cost of each operation was divided by its corresponding productivity in order to derive unit cost. The total cost is the sum of the single operation costs. The total yard cost, regarding trees extracted just out of the stand to the forest road, was 18.42 ± 0.12 € $m^{-3}$. The average selling price of the whole tree extracted just out of the stand to the forest road, of about 21.00 ± 1.20 € $m^{-3}$, was found on the basis of wood energy market for contractors with chipper machines and considering the main technological wood chip characteristics (Table 11).

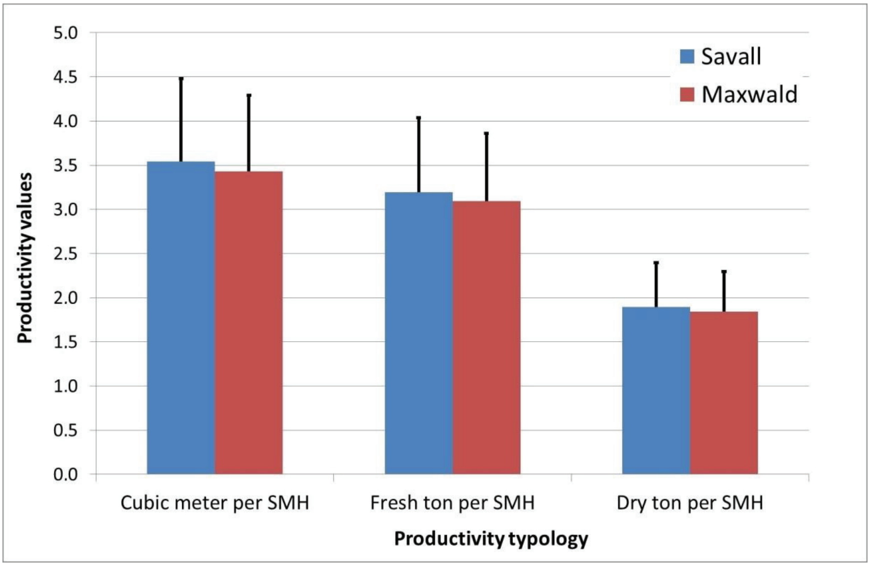


**Figure 2.** Average bunching—extraction productivity (bars) and possible increase of performance (lines) from SMH to PMH.

**Table 9.** Machine costs (analytical), fixed, variable, and total operating costs (the Italian cost is referred to in the year 2019).

| Description | MU | Chainsaw | Tractor | Savall Yarder Line | Maxwald Yarder Line | Chipper |
|---|---|---|---|---|---|---|
| Investment cost | € | 1000 | 42,000 | 35,000 | 21,000 | 58,000 |
| Service life | Years | 2 | 10 | 10 | 10 | 10 |
| Annual use | H | 800 | 1000 | 800 | 800 | 800 |
| Recovery value | € | 200 | 8400 | 7000 | 4200 | 11,600 |
| Interest on capital | % | 3 | 3 | 3 | 3 | 3 |
| Fuel consumption | l $h^{-1}$ | 0.98 | 2.00 | 0 | 0 | 2.50 |
| Fuel price | € $l^{-1}$ | 2.0 | 0.8 | 0 | 0 | 0.8 |
| Lubricant cost | % of fuel cost | 20 | 25 | 0 | 0 | 30 |
| Labor cost | € $h^{-1}$ | 15 | 15 | 15 | 15 | 15 |
| Crew | n° | 3 | 1 | 2 | 2 | 1 |
| Fixed costs | | | | | | |
| Depreciation | € $year^{-1}$ | 400 | 3360 | 2800 | 1680 | 4640 |
| Interest | € $year^{-1}$ | 24 | 806 | 672 | 403 | 1114 |
| Insurance and tax | € $year^{-1}$ | 40 | 1344 | 1120 | 672 | 1856 |
| Yearly fixed costs | € $year^{-1}$ | 464 | 5510 | 4592 | 2755 | 7610 |
| Hourly fixed costs | € $h^{-1}$ | 0.58 | 5.51 | 5.74 | 3.44 | 9.51 |

**Table 9.** *Cont.*

| Description | MU | Chainsaw | Tractor | Savall Yarder Line | Maxwald Yarder Line | Chipper |
|---|---|---|---|---|---|---|
| | | | Variable costs | | | |
| Fuel | € $h^{-1}$ | 1.96 | 1.60 | 0 | 0 | 2.00 |
| Lubricant | € $h^{-1}$ | 0.39 | 0.40 | 0 | 0 | 0.60 |
| Repair and maintenance | € $h^{-1}$ | 0.50 | 3.36 | 3.50 | 2.10 | 5.80 |
| Workers | € $h^{-1}$ | 45.00 | 15.00 | 30.00 | 30.00 | 15.00 |
| Hourly variable cost | € $h^{-1}$ | 47.85 | 20.36 | 33.50 | 32.10 | 23.40 |
| Operating cost | € $h^{-1}$ | 48.43 | 25.87 | 39.24 | 35.54 | 32.91 |
| Profit and overhead | % | 10 | 10 | 10 | 10 | 10 |
| Profit and overhead | € $h^{-1}$ | 4.84 | 2.59 | 3.92 | 3.55 | 3.29 |
| Total operating cost | € $h^{-1}$ | 53.28 | 28.46 | 43.16 | 39.10 | 36.20 |

**Table 10.** Operation productivity and costs for single operation and total costs referred to one cubic meter or to one dry ton of wood from whole tree roadside.

| Description | MU | Felling | Extraction Savall | Extraction Maxwald | Chipping | Total Savall | Total Maxwald |
|---|---|---|---|---|---|---|---|
| Real unit cost (SMH) | € $m^{-3}$ | 2.69 | 15.08 | 14.85 | 0.76 | 18.53 | 18.30 |
| Hypothetical unit cost (PMH) | € $m^{-3}$ | 2.15 | 11.78 | 11.79 | 0.66 | 14.59 | 14.60 |
| Real unit cost (SMH) | € $t_{d.m.}$ | 5.03 | 28.20 | 27.69 | 1.42 | 34.65 | 34.14 |
| Hypothetical unit cost (PMH) | € $t_{d.m.}$ | 4.02 | 22.04 | 22.01 | 1.23 | 27.29 | 27.26 |

**Table 11.** Wood chips characterizations from Picchio et al. [43], average values ± standard deviation.

| Types | Code | Samples | Fiber % | Bark % | Twigs % | Other % | |
|---|---|---|---|---|---|---|---|
| FTS | *P. nigra* | 20 | 77.4 ± 7.0 | 15.1 ± 5.1 | 2.9 ± 1.0 | 4.6 ± 0.9 | |
| | | | Oversize % | Acceptable % | Fines % | | |
| | | | 0.5 ± 0.1 | 91.7 ± 2.0 | 7.8 ± 1.3 | | |
| | | | HHV MJ/$kg_{d.m.}$ | Ash $\%_{d.m.}$ | C $\%_{daf}$ | N $\%_{daf}$ | H $\%_{daf}$ |
| | | | 20.4 ± 0.6 | 0.6 ± 0.2 | 50.0 ± 1.2 | 0.2 ± 0.1 | 6.3 ± 0.4 |

The lowest energy efficiency was recorded for the yard extracted by the Maxwald yarder line, with a total input of 129.5 MJ $m^{-3}$ (Table 12). In the yard extracted by the Savall yarder, the energy expenditure reported a total input of 125.8 MJ $m^{-3}$, just slightly lower than the other yard (−2.9%) (Table 12). In particular, the difference was in the direct inputs, which was calculated 3.0% higher in the yard extracted by the Maxwald than in the other one (+3.4 MJ $m^{-3}$). The input concerning human activity and indirect inputs resulted similar between the two yards (Table 12 and Figure 3).

**Table 12.** Total energy inputs and balance in forestry logging yards.

| Description | M.U. | Energetic Output | Direct Input | Indirect Input | Human Labor Input | Total Inputs | Output/Inputs Ratio | System Efficiency |
|---|---|---|---|---|---|---|---|---|
| Savall yard | MJ/$m^3$<br>MJ/$t_{d.m.}$ | 12,444<br>20,400 | 112.77<br>184.87 | 11.52<br>18.88 | 1.56<br>2.55 | 125.84<br>206.30 | 98.9 | 99.0% |
| Maxwald yard | MJ/$m^3$<br>MJ/$t_{d.m.}$ | 12,444<br>20,400 | 116.21<br>190.50 | 11.63<br>19.07 | 1.61<br>2.64 | 129.45<br>212.21 | 96.1 | 99.0% |

A considerable amount of the energetic input concerned the bunching and extraction activities (Figure 3). The results reported that 71.1 ± 0.4% (90.73 MJ $m^{-3}$) of the energetic input for both yards can be associated with the bunching-extraction operation.

The total outputs for both yard typologies were assessed on the basis of felled volume (Table 3) and HHV of the specific biomass (Table 11). The overall results indicated a ratio of the outputs to the inputs of 2.9% higher in the yard extracted by Savall yarder (98.9) compared to the other one (96.1) (Table 12). High values of the percentage energetic efficiency (Energetic efficiency = ((output − input)/output) × 100)) were calculated in both the two sites (on average, 99% ± 0.02) (Table 12).

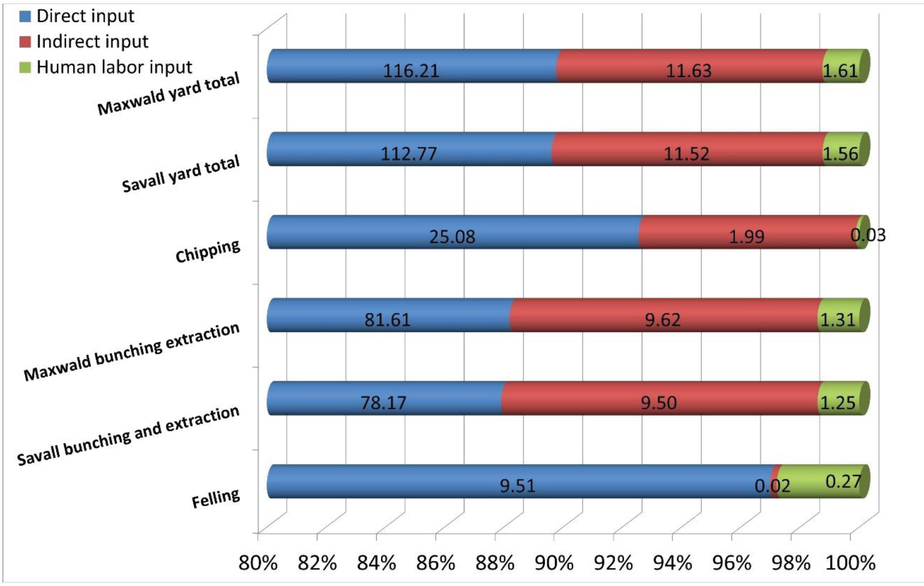


**Figure 3.** Energy inputs categories in forestry logging operations, data reported in percentage referred to the total inputs and detailed data are reported in MJ/m$^3$ for every category and showed in the figure.

The lowest pollutant emission values were assessed for the yard extracted by Savall yarder line, with a total effective $CO_2$ emission of 1735 g m$^{-3}$ (Table 13) and a total of 15.1 kg $CO_{2eq.}$ $t_{d.m.}{}^{-1}$ (Table 14). In the yard extracted by the Maxwald yarder line, the pollutant emission values reported a total effective $CO_2$ emission of 1772 g m$^{-3}$ (Table 13) and a total of 15.6 kg$CO_{2eq.}$ $t_{d.m.}{}^{-1}$ (Table 14), only slightly higher than the other yard (+3.3%) (Table 14). These results, globally at yard level, were equally composed by direct and indirect inputs (Table 14 and Figure 4). Data referred to pollutant emissions and fuel and lubricant consumptions are showed in Table 13. The emissions due to Efp, Eop, and Eor were not significant in comparison with those due to Efc, except for HC. The combustion process was responsible on average for 93.8% of CO2, 99.4% of CO, 36.1% of HC, 97.7% of NOx, and 98.6% of PM10 emissions. A considerable amount of pollutant emission values concerned the chipping activities (Table 14 and Figure 4). The result showed that the 48.9 ± 0.8% (7.5 kg$CO_{2eq.}$ $t_{d.m.}{}^{-1}$, Table 14 and Figure 4) of the pollutant emission for both yards can be associated with the chipping operations.

**Table 13.** Total emission in forestry logging yards, shared in fuel and oil origins.

| | Savall | | | | | Maxwald | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | CO | HC | Nox | $PM_{10}$ | $CO_2$ | CO | HC | Nox | $PM_{10}$ |
| | | | g $t_{d.m.}{}^{-1}$ | | | | | g $t_{d.m.}{}^{-1}$ | | |
| Efc fuel | 3040.3 | 61.3 | 0.3 | 63.4 | 11.5 | 3106.2 | 62.7 | 0.4 | 65.6 | 11.6 |
| Efp fuel | 198.8 | 0.3 | 0.6 | 1.4 | 0.1 | 201.4 | 0.4 | 0.6 | 1.5 | 0.2 |
| Total fuel | 3239.1 | 61.6 | 0.9 | 64.8 | 11.6 | 3307.6 | 63.1 | 0.9 | 67.1 | 11.9 |
| Eop lubricant | 3.294 | 0.003 | 0.006 | 0.039 | 0.007 | 3.262 | 0.003 | 0.006 | 0.038 | 0.007 |
| Eor lubricant | 0.763 | 0.002 | 0.000 | 0.004 | 0.001 | 0.746 | 0.002 | 0.000 | 0.004 | 0.001 |
| Total lubricant | 4.057 | 0.005 | 0.007 | 0.043 | 0.008 | 4.008 | 0.005 | 0.006 | 0.042 | 0.007 |
| Total | 3243.2 | 61.6 | 0.9 | 64.9 | 11.6 | 3311.6 | 63.1 | 1.0 | 67.2 | 11.9 |
| | | | (g $^{m-3}$) | | | | | (g $^{m-3}$) | | |
| Total | 1735.1 | 33.0 | 0.5 | 34.7 | 6.2 | 1771.7 | 33.8 | 0.5 | 35.9 | 6.4 |

**Table 14.** Total emission in forestry logging yards, for single operation and yard, reported in $CO_2$ equivalent, shared in direct and indirect process.

| | Felling | Savall—Bunching/Extraction | Maxwald—Bunching/Extraction | Chipping | Savall Yard | Maxwald Yard |
|---|---|---|---|---|---|---|
| | | | $kgCO_{2eq.}$ $t_{d.m.}{}^{-1}$ | | | |
| Direct inputs | 1.0 | 2.4 | 2.6 | 4.1 | 7.5 | 7.7 |
| Indirect inputs | 0.3 | 3.9 | 4.2 | 3.4 | 7.6 | 7.9 |
| Total | 1.3 | 6.3 | 6.8 | 7.5 | 15.1 | 15.6 |

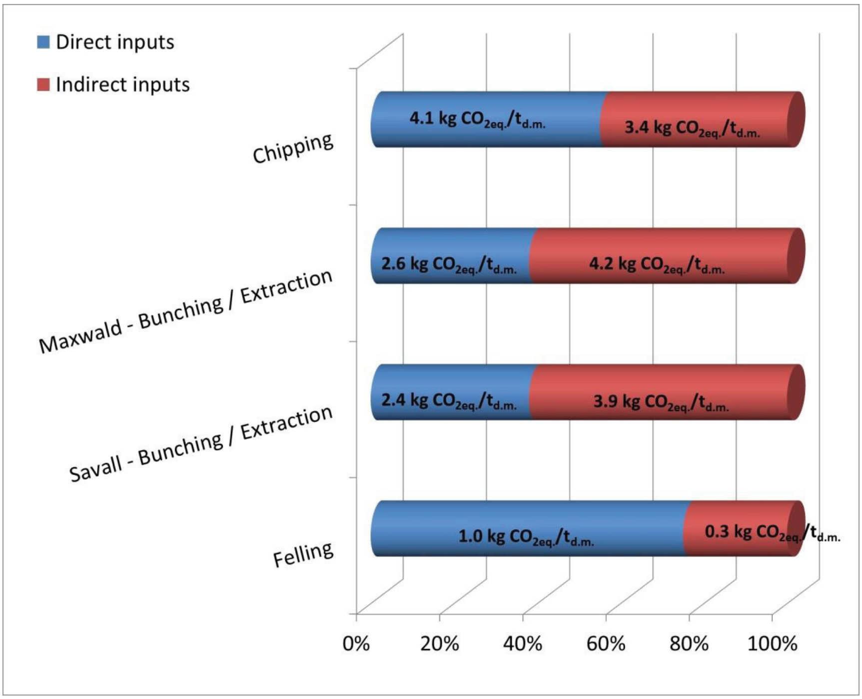


**Figure 4.** Percentage distribution of total emission in forestry logging yards for single operation, reported in $CO_2$ equivalent, shared in direct and indirect process.

## 4. Discussion

Findings referred to a case study made in a 33 year old black pine stand in central Italy. Even if the ideal silvicultural model for these stands, we expected two to four thinnings, with a final clear-cutting and replanting or re-naturalization. Considering the stand evolution and the late thinning, in this case the forest management goal was to ensure a minimal but substantial, canopy cover associated with the progressive replacement of pine trees with late successional tree species, typical of more mature natural evolution stages [23].

Felling productivity was high due to the efficient work planning and the optimal composition of the working team (one chainsaw and two helpers). The delays (about 20%) were mainly due to errors, as to the block of the chainsaw guide bar below the marked tree by dense understory plants, which is very common especially in first thinning. Our results showed higher productivity values (6.08 $m^3$ $PMH^{-1}$ for the yarder line with the Savall carriage and 5.73 $m^3$ $PMH^{-1}$ for the yarder line with the Maxwald carriage) compared with other authors [44–47]. These data could be explained with the high intensity of the harvesting (854 trees $ha^{-1}$) in the study area. The felling intensity of the forest according to workers' experience, is the most influencing factor for the productivity of the site Schweier et al. [23].

Bunching-extraction productivity by cable yarder was comparable with that reported in other similar studies [13] in particular for the Savall 1500 the same of our study. The average duration of the cable yarder cycle recorded on similar distances by Spinelli et al. [13] was slightly longer than 5 min, and very close to the ca. 5.7–5.9 min resulting from our study.

For a very similar cable yarder system, Spinelli et al. [13] reported a net productivity of 2.4 $m^3$ $PMH^{-1}$, considerably less than the average of this study (5.9 $m^3$ $PMH^{-1}$); such difference could be explained by considering the harvest density per linear meter, which sensibly varies between the two studies (near to 0.2 $m^3$ $m^{-1}$ in Spinelli et al. [13], and 1.2 $m^3$ $m^{-1}$ in this study). This significant difference between the two studies in terms of harvest density (1 to 6) did not affect proportionally the productivity (about 1 to 2.5). This can be explained by the significant difference in delay factors found, Spinelli et al. [13] found a delay factor of 0.1, resulting over 0.2 (0.28 for Savall and 0.26 for Maxwald) in this study.

The performance comparison of mini-yarders tested in this study against light tower yarders reported in the bibliography [48] could be very interesting but may lead to erroneous conclusions. Mini-yarders could compete with light tower yarders over short extraction distances: when the distance increases, the heavier load capacity of the light tower yarder allows a better performance [23]. Light tower yarders are generally used for longer yarder lines (over 200 m) than those observed in our tests, and often beyond the capacity of the mini-yarder.

Mini-yarders tested in this study, have also been compared against a forestry-fitted farm tractor with winch reported in Picchio et al. [2], with a lower resulting productivity, which can be motivated by the extreme specialization of tractor winches against the yarder on these kinds of work.

If the comparison is carried out between the yarder and a farm tractor for direct extraction (skidding), [32,49] the difference in terms of productivity is not consistent. In fact, in some cases the cable yarder is more productive.

The regression analysis highlighted a good statistical correlation between the bunching-extraction distance and working time, as reported also by Spinelli et al. [13], while a lower correlation exists between the volume extracted and the working time. This highlights the need for these systems to work in proximity to their maximum load capability. The assessed statistical models, based on a non-linear regression analysis with three variables (Figure 1), showed good prediction capacity for both cable yarder models ($R^2$ of about 0.9).

Chipping productivity was high due to the average three dimensions and the good work planning. The delays (about 13%) were mainly due to incorrect trees positioning at the cable yarder unloading site. The productivity showed higher (double) values compared with findings reported by Schweier et al. [23].

Overall, the two yards show an average productivity that could be considered excellent for a first thinning, this mainly thanks to the integrated planning of the silvicultural intervention and forestry operations. However, as shown in Figure 2, further improvements could be obtained. Productivities could potentially increase 27% and 25% for the Savall and Maxwald carriages, respectively, if the delay times reduced to minimum level. The delays for machines maintenance and fueling allow the equipment to work within optimum parameters and, as a result these delays are difficult or impossible to reduce. Delays included in the non-work time (personal delay, operational delay, and technical delay) could be reduced focusing on a better operation organization and planning. In conclusion, a reduction in delay times may be achieved by proper training of workers and by a better organization and planning of operations.

In Italy for a similar ground slope, distance and silvicultural situation, short wood system was normally applied, associated with the extraction by animals (mules), resulting in negative factors for the work conditions and workers' safety. Wang [14] noted that most of the accidents are caused by improper operations on steep terrain, where animals are used for logging. Cut to length system (CTL) or FTS are often associated with the extraction by tractor with winch, which is a better but limited technology for similar situations with extraction distances less than 80–90 m [2,7]. FTS or also CTL systems associated with the extraction by skyline is a good opportunity for an improvement of the work conditions and workers' safety, but in this case a proper and accurate training is primary. Indeed, the main intervention to improve health and safety is represented by workers training as well as lower pressure of work [50]. An appropriate training course should focus firstly on accident reduction and then on ergonomics for prevention of chronic illnesses [51].

The findings of this study showed that the most expensive operation is the extraction, representing for both technologies over 81% of the total logging costs. The possibilities for improvement are not high. According to data collected, the percentage of 81% can at most drop to 80%. However, the costs related to cable yarder extraction, when compared with similar extraction yards [13], are in some cases lower by even half. Results can be attributed only in part to the technologies, and mainly to the interaction between logging and silvicultural planning.

The felling operation in terms of costs and productivity was very similar to that found in other comparable studies [23]. The chipping instead showed lower costs than similar yards [23]. The reasons are related to the possibility to work on little heaps of whole trees and with trees of ideal size for the machine used.

Our results indicated that use costs can be decreased up to 21.5% by reducing delay times through training of workers and by a better organization and planning of operations. This could lead to a total yard cost of about 14 € $m^{-3}$. Compared to other work methods, if supported by adequate logistics and density of harvesting biomass, the mini-yarders can be very competitive unless the skyline yard includes the preparation and implementation costs of the line as well. For a silvicultural treatment, which is often considered with negative income, and subject to environmental constraints, it could be considered a good result.

In this kind of harvesting sites, the plots have been selected to use the skyline, and they were not extracted with tractor and winch if not after the opening of new forest trails (technical and operational parameters were not allowed in this context, due to several legislative restrictions). As shown also in another study [13] mini-yarders could represent a good solution to wood extraction on steep terrain, competitive with animal and winch. However, this is only possible with an adequate work planning and workers training, as already stated that in small-scale forestry it is often difficult to implement, even if extremely necessary.

The human energy consumption was estimated on the basis of a human heart-rate response during field work. The calculated energy expenditure during working ranged from 0.024 to 0.033 MJ $min^{-1}$ per worker. The lower value was for chipping operations and it is significantly lower than what is reported in other studies [22,35,52], but it is clearly explained by the high mechanization used in this operation, as found by Picchio et al. [53]. The higher value was for the extraction by the Maxwald cable yarder, and it is similar to what was reported in other studies [22,35,37,52].

Concerning energy inputs, a comparison was conducted between the results of this study and those of similar studies, where a high mechanization level was applied, and the values found were four times higher [52,53]. The comparison conducted between studies where an intermediate mechanization level was applied [32] showed different results, in this case about eight times higher. That obviously affects also the energy balance (output/input ratio), which is from 3 to 7 times higher, compared to high [52,53] and intermediate [32] mechanization levels.

The percentage of energy efficiency (i.e., 100 × (output − input)/output) was high and on average 99% ± 0.02. This value was near to those reported by Picchio et al. [22] (97%) and slightly higher than those reported by Baldini et al. [32] (91%).

The comparison with previous studies, regarding GHG (Green House Gases) emissions, in particular assessed via $CO_2$ equivalent, highlighted the efficiency of the cable yarder (in this study about 9 kg $CO_{2eq.}$ $m^{-3}$), as it was also demonstrated by previous studies (values ranging from 4 to 11 kg $CO_{2eq.}$ $m^{-3}$) [23,39,54,55]. The findings of this study are clearly lower than those assessed in forest operations carried out with other technologies in thinning treatments, with values ranging from 12 to 33 kg $CO_{2eq.}$ $m^{-3}$ [23,56–59].

## 5. Conclusions

Finally, from the findings, by a comparison between the two scenarios (Maxwald vs. Savall), it is possible to affirm:

(i) The yard with the Savall cable yarder showed the best performance, even if the differences found were minimal and almost zero in terms of costs;
(ii) The findings showed how a detailed assessment of logging methodologies allows improving sustainable forest operations also in first thinning of pine plantations in slope areas, this independently from the two typologies of the light cable yarder.

All that has been affirmed, even if looking at results from the analyses on a yard in a single forest, is an exportable case study along with the good number of replicas conducted and the refutation with similar realities reported in other studies. An adequate choice of the mechanization level and a constant interaction with the silvicultural planning, together with an adequate worker training allow sustainably producing chips for fuelwood, also from forest realities not very appreciated by the market.

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Article

# A GIS Approach Land Suitability and Availability Analysis of *Jatropha Curcas* L. Growth in Mexico as a Potential Source for Biodiesel Production

**Jocelyn Alejandra Cortez-Núñez [1], María Eugenia Gutiérrez-Castillo [2,*], Violeta Y. Mena-Cervantes [1], Ángel Refugio Terán-Cuevas [3], Luis Raúl Tovar-Gálvez [2] and Juan Velasco [4]**

[1] Laboratorio Nacional de Desarrollo y Aseguramiento de la Calidad de Biocombustibles, Centro Mexicano para la Producción más Limpia, Instituto Politécnico Nacional, Avenida Acueducto s/n, Colonia La Laguna Ticomán, 07340 Ciudad de México, Mexico; jacn0421@gmail.com (J.A.C.-N.); vmenac@ipn.mx (V.Y.M.-C.)

[2] Departamento de Biociencias e Ingeniería, Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo, Instituto Politécnico Nacional, 30 de junio de 1520 s/n, 07340 Ciudad de México, Mexico; ltovarg@ipn.mx

[3] Departamento de Territorio y Ambiente, Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo, Instituto Politécnico Nacional, 30 de junio de 1520 s/n, 07340 Ciudad de México, Mexico; ateranc@ipn.mx

[4] Satellite Analysis Branch, NOAA Center for Weather and Climate Prediction, 5830 University Research Ct, College Park, MD 20740, USA; juan.velasco@noaa.gov

* Correspondence: mgutierrezc@ipn.mx; Tel.: +52-(55)57-296-000 (ext. 52746)

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**Abstract:** *Jatropha curcas* L. (JCL) commercial plantations in Mexico, one of the most important JCL origin centers, have failed due to a variety of biological, political and technical factors affecting their productivity. This study explores feasible sites of JCL cultivation as a potential source for biodiesel production in Mexico, given agroclimatic and agroecological considerations. We propose a GIS-based approach for estimating suitable and available lands to grow JCL by integrating an Analytical Hierarchy Process (AHP) in the ArcGIS software. Spatial analysis combined multiple data, different evaluation criteria, three land availability classes (high, medium and low potential) and took into account ecological, ethical, and political restrictions, and considering two scenarios with different restriction levels. Suitability and availability maps were generated using agroclimatic information (climatic, land use/soil, and climate change and extreme weather events risk) together with other socioeconomic factors. Approximately 15.3% of Mexican territory is available for JCL production yielding a biodiesel production of 9.683 $Mm^3$/year. Amelioration of the available land is necessary to improve land selection. GIS-based analysis represents a first approach to establish a successful biodiesel project that avoids, competition with food or feed production, maintains biodiversity conservation, and promotes biofuel supply chain development. This procedure would also be applicable to other energy crops such as oil palm and *Ricinus communis*.

**Keywords:** agroenvironmental mapping; energy crop; *Jatropha curcas* L.; land suitability

## 1. Introduction

The increased interest in the exploitation of inedible oilseed crops as biomass to produce second-generation biofuel has been essentially motivated by diversification of the energy matrix to energy security in order to decrease greenhouse gas emissions and to promote urban and rural sustainable development [1,2]. The renewable energy feedstock selection for conversion to biofuels depends on key factors for achieving success and sustainability, emphasizing economic, social and environmental aspects such as land availability, ecosystem conservation, future food security, and agriculture productivity [3,4]. Currently, the world supply of biodiesel is based on edible crops with relatively low productivity of biofuel per unit area such as soybean (566 kg $ha^{-1}$ year) and rapeseed (862 kg $ha^{-1}$ year) [5]. Thus, the main limitation of this industry to produce biofuel from oily crops is the upstream oil productivity (L $ha^{-1}$), because the refined oils transesterification process is a mature technology. In addition, low productivity at the agricultural stage is directly associated to the operating cost to produce biodiesel since the price of vegetable oil can represent up to 77% of its total manufacturing cost [6].

*Jatropha curcas* L. (JCL) has emerged as a promising alternative feedstock for biodiesel production due to multiple attributes, notable agronomic characteristics and economic viability with environmental benefits such as its remarkable oil yield (1892 L $ha^{-1}$) higher than other energy crops like soybean and canola (446 L $ha^{-1}$ and 1190 L $ha^{-1}$, respectively) [7]. Likewise, its oil content (40–60%) that is greater than that of soybean (12–24%), and its fatty acid profile that is suitable for obtaining biodiesel with good vehicle performance in blends with diesel fuel [8–11], In addition, it is susceptibility to only a few pests and diseases and is resilient to environmental stresses such as droughts and soil hardness [12,13]. However, several efforts and production projects in countries such as Mexico, India, China, Ethiopia, Mozambique, and Ghana have failed or were truncated due to factors affecting levels of productivity like soil requirements, agroclimatic conditions, agronomic practices and supply chain network challenges, among others [14,15]. Despite setbacks and inherent risks, there is persistent focus to take advantage of JCL multi-dimensional capacity to primarily produce biodiesel, in addition to other products [16–18].

Nowadays, the identification and selection of suitable and available land to grow inedible oilseed crop, like JCL, demands observance of three dimensions—societal, economic and environmental—to reduce negative environmental impacts and avoid displacing other crops used for food and/or animal feed [19,20]. From this perspective, several research groups have focused their efforts to integrate territorial characteristics (e.g., land use), climatic information and some socioeconomic aspects to improve land allocation for biomass crop cultivation [21,22].

Countries like China, Uganda and India have shown awareness in agroecological zoning of JCL using an integrated Geographical Information System (GIS) and Remote Sensing (RS) approach that combined meteorological conditions, ecosystem services, roads, settlements, transmission, distribution lines, population density, transportation costs, cost of cultivation, land use policy and regulation and local economic structures. Their studies have shown that abandoned, degraded, and/or marginal lands could represent a good opportunity for biomass energy production [23–25]. A GIS approach in land use suitability mapping and analysis has been used as a decision support tool for spatial planning and management for agriculture. The integration of GIS technology into the multicriteria decision-making approach (MCDA) has become an updated trend in agricultural land suitability classification [26]. The Analytical Hierarchy Process (AHP), based on human judgment ability to structure a multicriteria problem can combine qualitative and quantitative aspects of opinions given by the experts and is formed by main goal, criteria, sub-criteria or variables, and alternatives [27]. This procedure enables integration of different environmental, social and economic data, and depends on the basic units of aggregated observations (according to the selected criteria). Likewise, it allows for questions to be answered that are either related to possible sites that meet natural resource potential, or on the other hand, restricted areas; nevertheless, it can certainly help make a decision on sustainable production of biodiesel [28,29].

Biomass energy use and its production in Mexico has been anticipated since 2007 [30], but the bioenergy potential of the country remains largely unexploited [31]. Unfortunately, the Mexican strategies to assess the potential land availability for energy crops production has been carried out without integrating joint ecological, ethical, political, and technical restrictions, and were mostly based on decisions starting from studies that basically evaluated land agroecological attributes to grow this energy crop [32–37], while disregarding many other key factors that affect its sustainable cultivation.

Mexico, one of the most important JCL centers of origin, has high diversity and genetic richness as well as the potential for the creation of various JCL varieties with favorable agronomic characteristics and high-quality oil (12 to 60%) for biodiesel. These features are worth bearing in mind, in such a way that rational planning could derive a crop with higher and long-term profitability [38–42]. Furthermore, Mexico is part of the North American continent, where the main biodiesel producer—the United States—is located, [5]. Recognizing these viewpoints, the goal of this study was to explore feasible sites of JCL cultivation for biodiesel production in Mexico. To meet this goal, we performed a GIS approach land suitability and availability analysis for growing JCL. The identification and quantification of propitious land integrated several factors, like areas with suitable growth conditions for JCL and others. For equally important sustainability and ecological considerations, we collected ecological, ethical, political, and technical restrictions with the purpose of reducing both probable competition with food crops and controversies from environmental and socioeconomic perspectives. This study is the first in Mexico to consider this kind of information to guarantee food security, ecosystem conservation and promoting the biomass supply chains compared with other studies [33,37]. Also, the article contributes by highlighting the productive capacity of Mexico for JCL cultivation and provides a detailed analysis on where it could be exploited it, considering other limiting factors. For this reason, a MCDA was applied, specifically AHP method, and integrated with GIS application environments to assess of suitable and available land for the growth of JCL to produce biodiesel [43–46] and supports decision-making in the development of bioenergy projects. The AHP is especially helpful when it is difficult to recognize the precise interactions between several evaluation criteria [46]. Finally, based on Google Earth's high-resolution data, and vegetation layers of corn, bean, sorghum and wheat crops from imagery SPOT [47], we carried out a visual inspection to confirm or ratify estimated areas.

## 2. Materials and Methods

### 2.1. Study Area

JCL grows and is distributed worldwide in tropical and subtropical regions (Asia, Africa, North America and South America), primarily in the Neotropics. For this reason, the study area is the entire Mexican territory, which has a continental area of 1,959,248 km$^2$, located at 19°23′26.31″ N 99°6′8.73″ W (Figure 1), has a mean annual temperature of 22.3 °C, a mean annual precipitation of 1777 mm with a single rainy season as the main rainfall supplier, and has a Neotropical region that includes the humid and sub-humid tropical areas of southern Mexico (Mexican Pacific Coast, Mexican Gulf, Chiapas and Yucatan Peninsula), which is a region where the genus *Jatropha* has a wide natural distribution. The region also includes seasonally dry tropical forest [48,49].

### 2.2. Data Sources and Analysis

First of all, the datasets were converted to raster format and homogenized to a spatial resolution of 1 km$^2$. Also, they were projected to geographic coordinate system, datum WGS84. The parameters selected in this study, based on literature reviews studies about land suitability analysis [43–45], were grouped in the following four criteria groups: (a) climatic criteria; (b) land and soil criteria; (c) climate change and extreme weather events criteria and (d) socioeconomic criteria, which are all identified as significant criteria that affect biodiesel projects. Figure 1 presents the spatial distribution of the thematic maps used in this study while Table 1 presents a description of datasets and data sources.

(1) Climate criteria. Annual mean temperature (since 1910 to 2009, in range value −1 to >28 °C) and averages of annual rainfall (from 1950 to 2016, values ranging 62 to 3698 mm).
(2) Land and soil criteria. Elevation (values ranged from 0 to 5610 m.a.s.l); soil type including 21 dominant classes (acrisol, andosol, arenosol, cambisol, castañozem, chernozem, feozem, fluvisol, greysol, litosol, luvisol, nitosol, planesol, ranker, regosol, rendzina, solonchak, solonetz, vertisol, xerosol, yermosol); land cover/land use types that were gruped into 13 categories (temporary and irrigation agriculture, aquaculture, arid lands, bare land, forest, cultivated and natural grassland,

jungle, mangrove, savanna, scrub, urban areas, water); food crops (corn, bean, sorghum and wheat); protected natural areas and RAMSAR sites that included beaches, mangroves, estuary, swamps, parks, biosphere reserves, among others in accordance with the creation decrees published in the Official Gazette of the Mexican Federation. Additionally, erosion grouped as water, wind, and anthropic erosion was analyzed.

(3) Climate change and extreme weather events criteria. In addition to erosion information (grouped as water, wind, and anthropic erosion), the following data was used: vulnerability to climate change; degree of drought risk; freeze hazard rate; frost duration in days; flooding vulnerability that makes areas unsuitable for JCL cultivation.

(4) Socioeconomic criteria. Aspects like distances to road networks, transportation infrastructure, to gas stations, and to power generation plants that can help promote a social value or value chain for distribution of the raw material and distribution of the final product, in this case, the biodiesel produced from the oil obtained from the JCL seed.

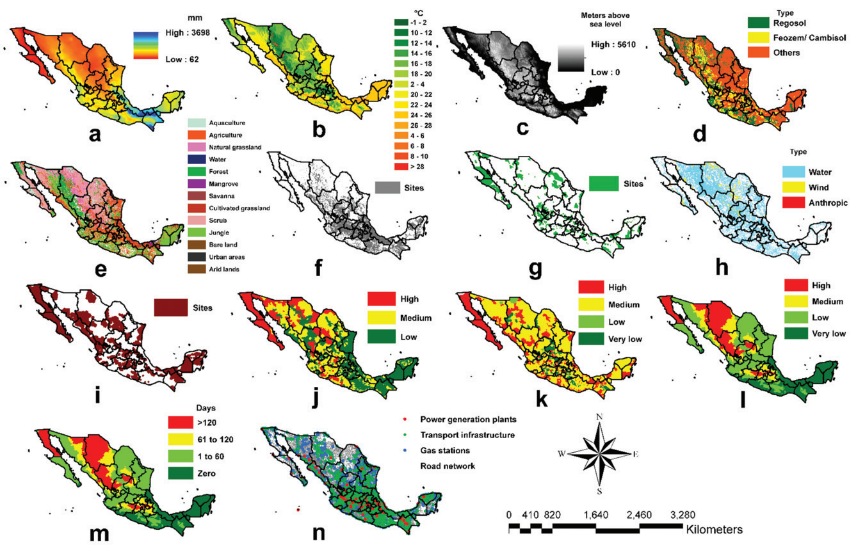


**Figure 1.** Input data: (**a**) rainfall; (**b**)temperature; (**c**) elevation; (**d**) soil type; (**e**) land use/land cover; (**f**) food crops; (**g**) protected natural areas and RAMSAR sites; (**h**) erosion; (**i**) vulnerability to climate change; (**j**) degree of drought risk; (**k**) flooding vulnerability index; (**l**) freeze hazard rate; (**m**) frost duration in days; (**n**) socioeconomic factor.

**Table 1.** Data sets and georeferenced data layers used in the GIS-based suitability and availability analysis.

| Criteria | Description of Parameters | | | | | Source |
|---|---|---|---|---|---|---|
| | **Designation** | **Scale or Spatial Resolution** | **Format/Reference Method** | **Conversion** | **Reference Year** | |
| Climatic | Rainfall | Each 11 km | Vector layer/Grid point data from field and cabinet work | Raster data Interpolation “Ordinary Kriging method, circular semi variogram” tool “Spatial Analyst” ArcGIS | 2016 | [50] |
| | Temperature | 1:1,000,000 | | Raster data | 2015 | [51] |

**Table 1.** *Cont.*

| Criteria | Description of Parameters | | | | | Source |
|---|---|---|---|---|---|---|
| | Designation | Scale or Spatial Resolution | Format/Reference Method | Conversion | Reference Year | |
| Land and Soil | Elevation | 1:7500 | Raster data/Terrain-digital elevation models (DEM map) | Reclassified with tool 'Resample' ArcGIS/Raster data | 2017 | [52] |
| | Soil type | 1:250,000 | Vector layer/Photointerpretation techniques using Landsat TM-8 imagery selected in 2014 | Raster data | 2016 | [53] |
| | Land cover /Land use | 1:250,000 | | Raster data | 2016 | [53] |
| | Food crops (corn, bean, sorghum and wheat) | 1 m | Vector layer/SPOT imagery from Spring-Summer 2018 and field work | | 2019 | [47] |
| | Protected natural areas | 1:50,000 | Vector layer/high spatial resolution imagery data and field work | Raster data | 2017 | [54] |
| | RAMSAR sites | 1:50,000 | | Raster data | 2015 | [54] |
| | Erosion | 1: 250,000 | | | 2014 | [53] |
| Climate Change and Extreme Weather Events | Vulnerability to climate change | 1:50,000 | | Raster data | 2018 | [55] |
| | Degree of drought risk | 1:50,000 | | | | |
| | Flooding vulnerability index | 1:50,000 | | | | |
| | Freeze hazard rate | 1:50,000 | | | | |
| | Frost duration in days | 1: 50,000 | | | | |
| Socioeconomic | Road network | 1:50,000 | | | 2019 | [53] |
| | Transportation infrastructure | 1:50,000 | | | 2017 | |
| | Gas stations | 1:50,000 | | | | |
| | Power generation plants | 1:50,000 | | | | |

## 2.3. Methodology

The GIS-based approach to estimate suitable and available lands to grow JCL inedible oilseed crop in Mexico, was developed by integrating AHP in ArcGIS software, where the Weighted Overlay (WO) tool which was used to overlay the map layers for determining suitability [45,46,56–59]. Figure 2 presents an example of a hierarchal structure of the breakdown of a problem [58].

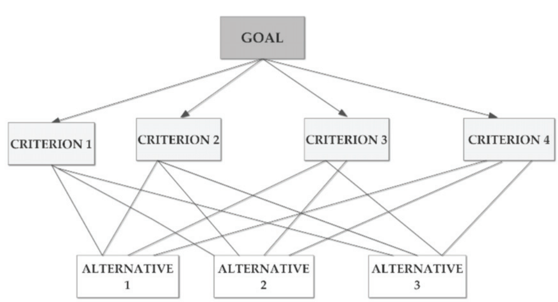


**Figure 2.** Example of a hierarchy of criteria in AHP analysis.

First, the criteria are pairwise compared for their importance of each criterion in relation to others in order to determine the main eigenvector. The importance values of each criterion were determined through the methodology developed by Saaty [58] (See Table 2).

**Table 2.** Scale for pairwise comparison.

| Intensity of Importance | Definition |
|---|---|
| 1 | Equal importance |
| 2 | Equal to moderate importance |
| 3 | Moderate importance |
| 4 | Moderate to strong importance |
| 5 | Strong importance |
| 6 | Strong to very strong importance |
| 7 | Very strong importance |
| 8 | Very to extremely strong importance |
| 9 | Extreme importance |

Ref. [58].

A pairwise comparison matrix can be mathematically expressed in the following Equation (1) [59]. The number of rows and columns is defined by the number of criteria in order to be weighed by the criteria used [58,59]. This process was conducted by using the experience of the authors and based on literature review of previous experimental studies of JCL cultivation in Mexico [60–67].

$$A = [a_{ij}], i, j = 1, 2, 3, \ldots, n \tag{1}$$

The spatial analysis functions of GIS through steps included the flowing: identification and collection of spatial data, weighting with the AHP, data integration and GIS analysis; output evaluation. The flowchart in Figure 3 shows the procedures carried out to achieve the objective in this study [44,45,57,58]. The suitability classes used in this study were "high potential", "medium potential" and "low potential" where "high potential" represents that the area with favorable climatic conditions for profitable production of JCL. A "medium potential" area indicates a second priority for JCL growing. Lastly, "low potential" areas represent the zones that are not appropriate for JCL cultivation. For standardization of each criterion selected, they were reclassified based on their suitability for JCL production. These levels were established based on National Institute of Forestry, Agriculture and Livestock Research (INIFAP, by its acronym in Spanish) technical reports on the cultivation of JCL in Mexico [40,68,69].

The first step was to obtain a spatial assessment of suitable areas for JCL plantation in Mexico, rethinking agroclimatic zones. Table 3 presents the classes, potentiality and suitability score of the four criteria, to achieve Agroclimatic Zoning (AZ). The suitability criteria were defined with four main physiological requirements for growth and yield of JCL: rainfall, temperature, elevation, and soil type. Based on existing literature, we selected physiological requirements that have been analyzed and evaluated in the field for the states of Michoacan, Jalisco and Chiapas [40] (p. 28) [68,69]. The elevation and rainfall information were reclassified to obtain the ranges where JCL is growing with a high, medium and low potential (Table 3). The annual rainfall between 900–1500 mm is considered optimal ranges for field-based growing conditions. Rainfall higher than 1500 mm could cause problems with fungal attack, root rot, and other diseases [43]. The suitability scores were defined for each criterion, where score 3 represents a "high potential", score 2 represents a "medium potential" and score 1 means "low potential" for JCL cultivation.

A second crucial point was to identify the type of land that can be dedicated or replaced to grow JCL in Mexico and can be used in the sustainable development of biodiesel. At this point, it is possible to evaluate several alternatives. We introduced social, environmental and economic constraints mainly based on current national government regulation, environmental policy to limit land use, climatic risk factors that can damage JCL plantation, and energy policies, such as the Law on the Promotion and Sustainable Development of Biofuel from energy crops.

In the first scenario, land use/land cover classes with environmental value and ecological relevance were included, such as forest, agriculture, mangrove and cultivated grassland, but they were classified as low potential. Meanwhile, in the second scenario, we restricted these types of areas in order to promote sustainable feedstock production within the context of food security, ecosystem conservation and reducing land use change. We worked to avoid converting given portion of the following types of land: land currently dedicated to food and livestock production; protected natural areas, and RAMSAR sites; land with climate change vulnerabilities such as, flooding, drought and frost. The output product was a land availability map that displays "high potential", "medium potential" and "low potential" areas of JCL production in Mexico, with a scale of 1:50,000. Table 4 summarizes the list of the nine criteria used to develop Agroecological Zoning (AEZ) and the score assigned to each criterion for two scenarios representing different level of restriction.

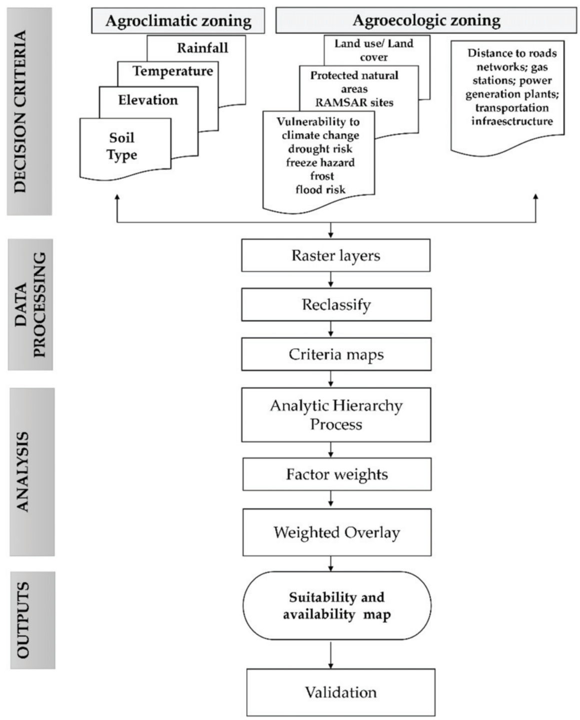


**Figure 3.** Methodological workflow developed to estimate suitability and availability of land (high potential, medium potential and low potential) for JCL cultivation in Mexico.

**Table 3.** Land Suitability Criteria for JCL cultivation to perform the AZ.

| Criteria | Units | Classes | Potentiality | Score |
|---|---|---|---|---|
| Elevation | Meters above sea level | 0–900 | High | 3 |
| | | 900–1500 | Medium | 2 |
| | | <1500 | Low | 1 |
| Rainfall | mm | 900–1500 | High | 3 |
| | | 300–900 | Medium | 2 |
| | | <300/>1500 | Low | 1 |
| Temperature | °C | 18–28 | High | 3 |
| | | 12–18 | Medium | 2 |
| | | <10/>28 | Low | 1 |
| Soil type | Type | Regosol | High | 3 |
| | | Cambisol/Feozem | Medium | 2 |
| | | Others | Low | 1 |

**Table 4.** AEZ criteria for JCL cultivation. Variables and scores of the two scenarios.

| Criteria | Classes | Scenario 1 | | Scenario 2 | |
|---|---|---|---|---|---|
| | | Potential | Score | Potential | Score |
| ACLIM | High | High | 3 | High | 3 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | Low | 1 | Low | 1 |
| LU/LC | Aquaculture | Restricted | Restricted | Restricted | Restricted |
| | Urban zone | Restricted | Restricted | Restricted | Restricted |
| | Forest | Low | 1 | Restricted | Restricted |
| | Water | Restricted | Restricted | Restricted | Restricted |
| | Agriculture | Low | 1 | Restricted | Restricted |
| | Jungle | Low | 1 | Restricted | Restricted |
| | Cultivated grassland | Low | 1 | Restricted | Restricted |
| | Mangrove | Low | 1 | Restricted | Restricted |
| | Savanna | Low | 1 | Restricted | Restricted |
| | Scrub | Low | 1 | Restricted | Restricted |
| | Natural grassland | Medium | 2 | Medium | 2 |
| | Bare land | High | 3 | High | 3 |
| | Arid lands | High | 3 | High | 3 |
| PA | Restricted | Restricted | Restricted | Restricted | Restricted |
| NON_PA | High | High | 3 | High | 3 |
| RAM | Restricted | Restricted | Restricted | Restricted | Restricted |
| NON_RAM | High | High | 3 | High | 3 |
| VCC | Restricted | Restricted | Restricted | Restricted | Restricted |
| W_VCC | High | 3 | 3 | 3 | 3 |
| DR | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | High | 3 | High | 3 |
| FLUV | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low | High | 3 | High | 3 |
| FHR | High | Low | 1 | Low | 1 |
| | Medium | Medium | 2 | Medium | 2 |
| | Low/Very low | High | 3 | High | 3 |
| FDD | >120/61–120 | Low | 1 | Low | 1 |
| | 01–60 | Medium | 2 | Medium | 2 |
| | Zero | High | 3 | High | 3 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; NON_PA: non-protected areas; RAM: RAMSAR sites; NON_RAM: non-RAMSAR sites; VCC: vulnerability to climate change; W_VCC: sites without vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

Afterwards, we completed a final analysis in which included consideration of logistical conditions around the estimated areas in scenario 2, such as the spatial distribution of road networks of road networks, gas stations, power generation plants and transportation infrastructure; "high potential" areas are represented by a distance from 0 to 15 km; "medium potential" areas by a distance from 15 to 30 km; and "low potential" area by distances greater than 30 km (Table 5).

The weights are calculated by normalizing the pairwise comparison matrix that was obtained by dividing the column elements of the matrix by the sum of each column (Equation (2)). Then, row elements in the obtained matrix were summed, and the total value was divided by the number of elements in the row as is presented in Equation (3) [59]:

$$A' = [a'_{ij}],\ i, j = 1, 2, 3, \ldots, n \quad (2)$$

where A′ is the normalized matrix and the $a'ij$ is defined as:

$$a'_{ij} = a'_{ij} / \sum_{i=1}^{n} a'ij \quad (3)$$

For all $i$, $j$ = 1, 2, 3, . . . , $n$. Before, criteria weights were estimated as a priority vector or weight vector as is presented in Equations (4) and (5):

$$wi = \sum_{i=1}^{n} a'ij / \sum_{i=1}^{n} \sum_{j=1}^{n} a'ij \quad (4)$$

Weights values are within 0 and 1, and their sum is equal to 1:

$$\sum_{i=1}^{n} w_i = 1 \quad (5)$$

**Table 5.** Proximity influence on available land for JCL cultivation.

| Criteria | Classes | Potentiality | Score |
|---|---|---|---|
| Agroecological zoning | High | High | 3 |
| | Medium | Medium | 2 |
| | Low | Low | 1 |
| Distance to roads (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to gas stations (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to power generation plants (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |
| Distance to transportation infrastructure (km) | 0–15 | High | 3 |
| | 15–30 | Medium | 2 |
| | >30 | Low | 1 |

Finally, the WO tool in ArcGIS software was used to estimate categories of "high potential", "medium potential" and "low potential" lands for JCL cultivation. Each criterion was multiplied with the weights assigned for each criterion to estimate the suitability index and develop the final suitability and availability maps [45,57]. For determining the relative importance of each criterion in the resultant of AHP, pair-wise comparison matrix using a Saaty's method was performed. The relative importance of the criterion of each row is calculated in relation to the criterion of its corresponding column. The entire matrix was completed by entering the upper right triangle, the values of the lower left triangle being the inverse values of those of the corresponding cells [57]. Similarly, the Consistency Ratio (CR), a measure to evaluate whether an AHP is acceptable for decision making, was calculated. Values of CR exceeding 0.10 are indicative of inconsistent judgments during pair-wise comparison because they are too close for randomness [45,57]. CR was estimated using Equations (6) and (7):

$$CR = (\lambda_{max} - n)/(n - 1) \quad (6)$$

$$CR = CI/RI \quad (7)$$

where $n$ is the number of criteria being compared, $\lambda_{max}$ is the largest Eigen value of the matrix comparation, RI is the random index representing consistency of a randomly generated pair-wise comparison matrix, which depends on the number of elements being compared (See Table 6), and CI is the consistency index (values closer to zero are more acceptable).

**Table 6.** The order of the matrix (n) and the equivalent random index (R).

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.3 | 1.4 | 1.45 | 1.49 |

## 3. Results and Discussion

Land suitability analysis for growing JCL in Mexico was determined considering historical spatial and temporal variability of two agroclimatic parameters (rainfall and temperature) for the period spanning 1950 to 2016 and 1910 to 2009, respectively, and was accompanied by terrain attributes (elevation and soil type). Table 7 presents the pair-wise comparison matrix of AZ, while Table 8 shows weights of the four criteria. The results indicate that suitable areas for JCL cultivation were mainly attributed to elevation and rainfall with importance weights of 46% and 32%, respectively. Figure 3 shows the spatial result of this analysis after applying the weight values in order to estimate categories of "high potential", "medium potential" and "low potential" lands for the JCL cultivation. The consistency property of matrices was estimated. Table 9 presents the CR with a value less than 0.1, indicating acceptable.

**Table 7.** Pairwise comparison matrix for factor criteria in the AZ analysis.

| Criteria | ELV | RAI | TEM | SOI |
|---|---|---|---|---|
| ELV | 1 | 2 | 3 | 5 |
| RAI | 1/2 | 1 | 3 | 5 |
| TEM | 1/3 | 1/3 | 1 | 3 |
| SOI | 1/5 | 1/5 | 1/3 | 1 |
| Total | 2.03 | 3.53 | 7.33 | 14.00 |

ELV: elevation; RAI: rainfall; TEM: temperature; SOI: soil type.

**Table 8.** Weights of the four criteria of the AZ analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| ELV | 0.46 | 46 |
| RAI | 0.32 | 32 |
| TEM | 0.15 | 15 |
| SOI | 0.07 | 7 |
| Total | 1.00 | 100 |

ELV: elevation; RAI: rainfall; TEM: temperature; SOI: soil type.

**Table 9.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.05 |
| Random index (RI) | 0.89 |
| Consistency ratio (CR) | 0.052 |

The AZ results allowed the identification of areas with similar combinations of limitations and potential for JCL crop growth, based solely on agronomic potential. Figure 4 presents a suitability map of suitable and unsuitable lands that allows the understanding of attainable grown of JCL in certain regions.

We can see the geographical distribution of estimated areas under high potential category exhibited higher proportions of land extending towards coastal areas, mainly land adjoining the Gulf and Caribbean coasts, and to a lesser proportion, land adjoining the Pacific region. Interestingly, medium potential regions are positioned in greater proportion to the North of Mexico.

Mexico's territorial extension estimated with "high potential", "medium potential" and "low potential" represent 95% of the national territory (Table 10), whereas "high potential" and "medium potential" represents 82.4%.

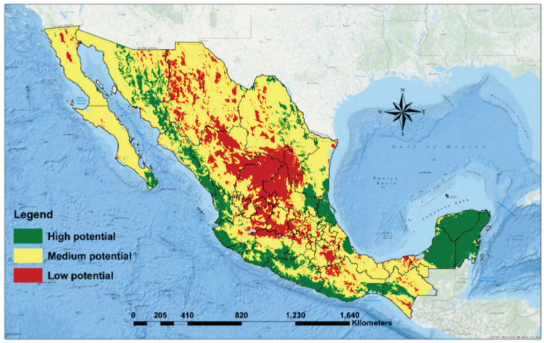


**Figure 4.** Agroclimatic spatial areas estimated for JCL cultivation in Mexico. High potential (green polygon), medium potential (yellow polygon) and low potential (red polygon).

**Table 10.** Suitable areas for JCL cultivation in Mexico.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 39,204,911 | 21.1 |
| Medium | 113,728,651 | 61.3 |
| Low | 32,684,173 | 17.6 |
| Total | 185,617,735 | 100 |

[1] Land requirement (% of national territory).

These findings are not entirely consistent with the incipient bibliographic data available for Mexico, such as the case reported by [32], in which they reported 6,089,023 hectares for two suitability classes (high, and medium). Based on the GIS approach applied, we estimated nearly 92.5 million ha. It is very reasonable to think that the divergence from that study is of methodological nature, although the process of assigning land suitability classes was not explained in the referred study. On the other hand, we detected a significantly higher value for medium suitable land in the northern region of Mexico, where arid lands, bare land and shrubland are present and they could be used to grow JCL, without a great water supply because its cultivation subjected to an irrigation system, tends to present an increase in yield [70]. We also obtained a limited high-potential suitable land towards West, Central, Gulf, and Southern regions with the exception of the Yucatan Peninsula.

Based on the two scenarios analyzed and the assessment criteria applied on GIS-based AEZ land evaluation, the available land for JCL cultivation in Mexico is reduced. For the first scenario, Tables 11 and 12 presents the results of AHP and Table 13 show that the analysis is acceptable because CR has a value less than 0.1.

**Table 11.** Pairwise comparison matrix for factor criteria in the AEZ analysis.

| Criteria | ACLIM | LU/LC | PA | RAM | VCC | DR | FLUV | FHR | FDD |
|---|---|---|---|---|---|---|---|---|---|
| ACLIM | 1 | 1/7 | 1/5 | 1/5 | 1/7 | 1/7 | 1/7 | 1/7 | 1/7 |
| LU/LC | 7 | 1 | 1/3 | 1/3 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 |
| PA | 5 | 3 | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| RAM | 5 | 3 | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| VCC | 7 | 5 | 3 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 |
| DR | 7 | 5 | 3 | 3 | 2 | 1 | 1/2 | 1/2 | 1/2 |
| FLUV | 7 | 5 | 3 | 3 | 2 | 2 | 1 | 1/2 | 1/2 |
| FHR | 7 | 5 | 3 | 3 | 2 | 2 | 2 | 1 | 1 |
| FDD | 7 | 5 | 3 | 3 | 2 | 2 | 2 | 1 | 1 |
| Total | 53.0 | 32.14 | 17.53 | 17.53 | 3.93 | 9.93 | 8.43 | 4.43 | 4.43 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; RAM: RAMSAR sites; VCC: vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

In contrast with previous estimations in our AZ, the AEZ projections clearly demonstrates that, after the consideration of restrictions, the potential areas for growing JCL are reduced by about 40% in scenario 1 (less restrictive conditions), Mexico's territorial extension estimated with "high potential", "medium potential" and "low potential" represent 57.32% of the national territory (Table 14).

**Table 12.** Weights of the nine criteria of the AEZ analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| ACLIM | 0.02 | 2 |
| LU/LC | 0.04 | 4 |
| PA | 0.06 | 6 |
| RAM | 0.06 | 6 |
| VCC | 0.12 | 12 |
| DR | 0.14 | 14 |
| FLUV | 0.16 | 16 |
| FHR | 0.20 | 20 |
| FDD | 0.20 | 20 |
| Total | 1.00 | 100 |

ACLIM: agroclimatic zoning; LU/LC: land use/land cover; PA: protected areas; RAM: RAMSAR sites; VCC: vulnerability to climate change; DR: degree of drought risk; FLUV: flooding vulnerability index; FHR: freeze hazard rate; FDD: frost duration in days.

**Table 13.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.08 |
| Random index (RI) | 1.45 |
| Consistency ratio (CR) | 0.053 |

**Table 14.** Available areas for JCL cultivation in Mexico, scenario 1.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 421,501 | 0.22 |
| Medium | 92,080,663 | 47.00 |
| Low | 19,807,528 | 10.11 |
| Total | 112,309,692 | 57.32 |

[1] Land requirement (% of national territory).

The highest percentage is in "medium potential" with 47%, covering mainly the northern states of Mexico. Figure 5 illustrates the spatial distribution of the land areas available for JCL cultivation under the perspective of this same scenario.

Additionally, the map of Figure 5 shows a comparison between the land areas available pattern obtained for the scenario 1 and preexisting JCL plantations reported in different Mexican studies and located according to authors criteria in high suitable potential lands. We overlaid geographical points where it has been described that JCL grows; 406 points correspond to living fences, common gardens, plant nurseries and wild populations; 68 points correspond to experimental and commercial plantations; 306 points were none of the previous, and were located mainly in Baja California, Durango, Chiapas, Colima, Guerrero, Hidalgo, Jalisco, Michoacan, Morelos, Nuevo Leon, Oaxaca, Puebla, Quintana Roo, Sinaloa, Sonora, Tabasco, Tamaulipas, Veracruz and Yucatan [63,71–78]. Based on our data and method applied it is detected that the JCL plantations could be relocated to medium available land areas.

On the other hand, in scenario 2 (with more restrictive conditions), Mexico's territorial extension estimated with "high potential" and "medium potential" represent only 15.3% of the national territory (Table 15).

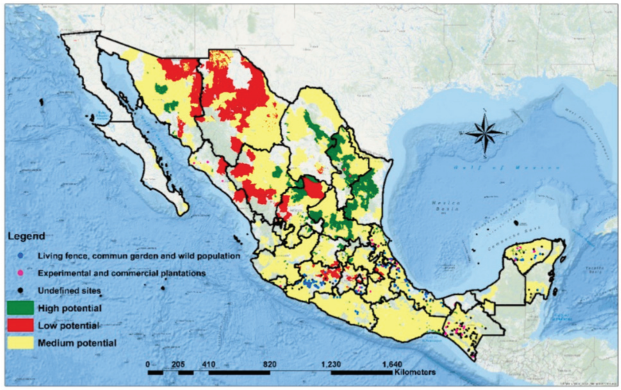


**Figure 5.** Agroecological spatial areas estimated for JCL cultivation in Mexico, scenario 1. High potential (green polygon), medium potential (yellow polygon) and low potential (red polygon).

**Table 15.** Available areas for JCL cultivation in Mexico, scenario 2.

| Potential | Area (ha) | % [1] |
|---|---|---|
| High | 5,331,477 | 2.7 |
| Medium | 24,740,998 | 12.6 |
| Total | 30,072,474 | 15.3 |

[1] Land requirement (% of national territory).

Figure 6 illustrates the spatial distribution of land areas available for JCL cultivation under more restrictive conditions. Interestingly, lands with "low potential" do not appear, because they overlapped with other committed land cover/land use areas like forest, jungle, mangrove, agriculture, cultivated grassland and those restricted in accordance with national government regulation, environmental policy that limits land use, and energy policies such as the Law on the Promotion of Bioenergy Production and Sustainable Development. On the other hand, a notable percentage of land with "high potential" and "medium potential" areas for JCL cultivation were vulnerable to both flooding and drought risk, in addition to freeze hazards and vulnerability to climate change. Also, the length of frost duration is greater for medium potential lands. Finally, the total estimated area in AZ analysis decreased sharply after adjustments based on the AEZ analysis to around of 84%.

Turning to the analysis of extreme weather events that may damage or have a negative effect on seed yield of JCL, and linked to the effect of a more restrictive scenario, we explored the spatial distribution of land availability for JCL in the scenario 2. Notwithstanding the restrictions, we observed that all the federal states of Mexico present sites with "high potential" and "medium potential" (Table 16), with a total estimated area nearly 92.5 million ha and a significantly higher value for medium suitable land (81.99%) in the northern region of Mexico and a limited "high potential" and "low potential" suitable land (18.01%) towards West, Central, Gulf, Southern and Yucatan Peninsula regions. A data comparation with study reported by [32], allowed to examine in more detail the methodological differences and identify areas with greater portion of available sites.

Lastly, it is convenient to analyze the accessibility of roads and energy infrastructure, because this factor can help reduce JCL feedstock transportation costs in these regions. The consideration of socioeconomic dimensions in the selection of candidate sites for the cultivation and exploitation of this inedible oilseed crop became even more relevant. This more detailed analysis of the local potentials enables better planning of agroenergy chain sustainability.

When reviewing the results of AHP to determinate the influences of distance to road networks, gas stations, power generation plants and transportation infrastructure from the socioeconomic parameter on JCL cultivation for scenario 2, we can observe that judgments selected in Tables 17 and 18 are consistent and acceptable because CR has a value less than 0.1 (Table 19).

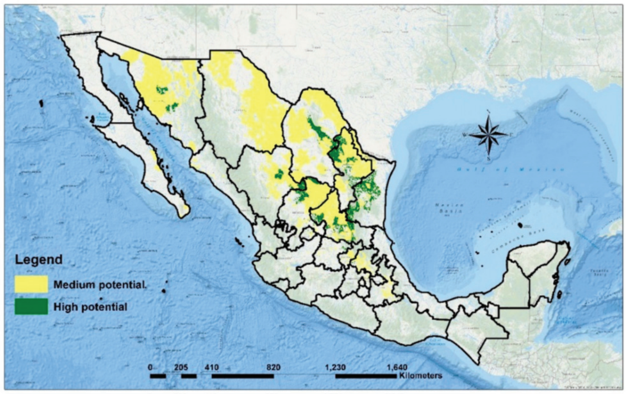


**Figure 6.** Agroecological spatial areas estimated for JCL cultivation in Mexico, scenario 2. High potential (green polygon) and medium potential (yellow polygon).

**Table 16.** Summarized high and medium suitable land areas by federal state per findings in our study in contrast to findings of [32].

| State | This Study Calculation Scenario 2 | | | [32] | |
|---|---|---|---|---|---|
| | Level of Suitability | | | Level of Suitability | |
| | High | Medium | Low | High | Medium |
| | Area (hectares) | | | | |
| Northern region | | | | | |
| Chihuahua | | 7,614,523 | 8,003,358 | - | - |
| Coahuila | | 7,143,153 | 74,091 | - | - |
| Durango | | 5,405,175 | 2,586,587 | - | - |
| Nuevo Leon | | 4,820,849 | 258 | >100,000, <175,000 | - |
| San Luis Potosi | 1458 | 5,523,643 | 256 | - | - |
| Zacatecas | | 1,954,229 | 3,629,927 | - | - |
| Northwest region | | | | | |
| Baja California | | | 2724 | - | - |
| Baja California Sur | | 411,620 | | - | - |
| Sinaloa | | 789,045 | 880,833 | 557,641 | - |
| Sonora | | 8,346,748 | 3,324,948 | - | 348,446 |
| West region | | | | | |
| Colima | | 411,151 | | >100,000, <175,000 | - |
| Jalisco | | 5,719,559 | 8286 | >100,000, <175,000 | - |
| Michoacan | | 3,839,363 | 668,607 | 197,288 | - |
| Nayarit | | 773,796 | 131 | - | - |
| Central region | | | | | |
| Estado de Mexico | | 1,010,179 | 249,505 | - | - |
| Guanajuato | | 1,780,169 | 138,827 | - | - |
| Hidalgo | 102 | 1,551,709 | 4059 | - | - |
| Puebla | 69,100 | 2426 | 144,197 | - | - |
| Queretaro | 356 | 580,708 | 3547 | - | - |
| Gulf region | | | | | |
| Tamaulipas | | 4,853,378 | | 317,690 | 442,935 |
| Tabasco | | 522,530 | | - | - |
| Veracruz | | 5,684,942 | | - | 336,314 |

**Table 16.** *Cont.*

| State | This Study Calculation Scenario 2 | | | [32] | |
|---|---|---|---|---|---|
| | Level of Suitability | | | Level of Suitability | |
| | High | Medium | Low | High | Medium |
| | Area (hectares) | | | | |
| Southern region | | | | | |
| Chiapas | 78,850 | 3,750,786 | | 230,273 | - |
| Guerrero | | 5,186,786 | | 282,158 | 283,191 |
| Oaxaca | 271,529 | 8,351,109 | | >100,000, <175,000 | - |
| Yucatan Peninsula region | | | | | |
| Campeche | | 464,602 | | - | - |
| Yucatan | 376 | 2,995,017 | | >100,000, <175,000 | - |
| Other 10 states | | 2,596,593 | 87,927 | <25,000 | - |
| Total | 421,501 | 92,080,663 | 19,807,528 | 2,614,425 | 3,474,598 |

**Table 17.** Pairwise comparison matrix for factor criteria in Socioeconomic Analysis.

| Criteria | AEZ | DR | DGS | DP | DT |
|---|---|---|---|---|---|
| AEZ | 1 | 5 | 5 | 5 | 5 |
| DR | 1/5 | 1 | 2 | 2 | 2 |
| DGS | 1/5 | 1/2 | 1 | 2 | 2 |
| DP | 1/5 | 1/2 | 1/2 | 1 | 1 |
| DT | 1/5 | 1/2 | 1/2 | 1 | 1 |
| Total | 1.80 | 7.50 | 9.00 | 11.00 | 11.00 |

AEZ: agroecological zoning; DR: distance to roads; DGS: distance to gas stations; DP: distance to power generation plants; DT: distance to transportation infrastructure.

**Table 18.** Weights of the five criteria of the socioeconomic analysis using the AHP.

| Criteria | Relative Weight | Weight (%) |
|---|---|---|
| AEZ | 0.54 | 54 |
| DR | 0.17 | 17 |
| DGS | 0.13 | 13 |
| DP | 0.08 | 8 |
| DT | 0.08 | 8 |
| Total | 1.00 | 100 |

AEZ: agroecological zoning; DR: distance to roads; DGS: distance to gas stations; DP: distance to power generation plants; DT: distance to transportation infrastructure.

**Table 19.** Consistency indices.

| Criteria | Total of Rows |
|---|---|
| Consistency index (CI) | 0.05 |
| Random index (RI) | 1.12 |
| Consistency ratio (CR) | 0.048 |

Figure 7 also shows the spatial distribution of the suitable and available lands that have greater closeness to communication and energy infrastructure. It was recognized that high potential lands have greater proximity than medium potential lands to roads, gas stations, power generation plants and transportation infrastructure with radius of 30 km. So, we calculated Euclidean distance using vector layers [79]. The proximity of a road network is a very important criterion in site suitability analysis, so the need for transportation access should be considered. The incorporation of these socioeconomic criteria enabled us to keep the proposed areas, which were associated with the best regions discussed by [22].

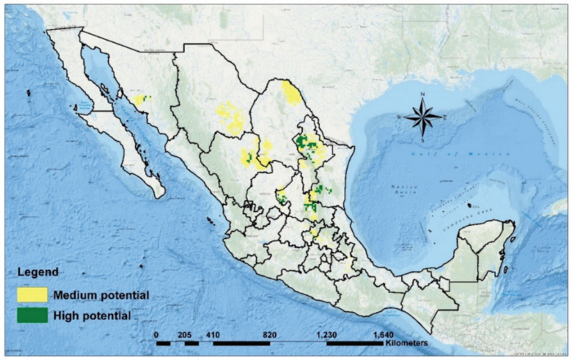


**Figure 7.** Distance to gas stations, power generation plants and transportation infrastructure in high potential and medium potential areas, distance less than 30 km in scenario 2.

Additionally, the results of several reports about JCL studies in Mexico showed that technical and socioeconomic factors have limited the success of biodiesel projects and profits for farmers. This is due to inadequacies for the following: the establishment of a production chain; the structured production of raw material, recollection of fruit, commercialization and distribution of the final product, in this case, biodiesel, along with byproducts [80–85]. For this reason, the introduction of these parameters can help promote a social value or value chain for distribution of the raw material and distribution of biodiesel produced from oil obtained from the JCL seed. Ultimately, the analysis of economic and social information can impact the supply chain (e.g., proximity to transportation or fuel and energy supply) for creating and sustaining competitive advantages that contribute to biodiesel project profitability.

Conforming to several studies, the incorporation of environmental and socioeconomic factors and criteria, as well as detailed data of those factors for choosing land allocation for biomass energy crop cultivation, contribute to the sustainability of biofuel production [21,22]. Our findings from the AZ and AEZ mapping for JCL offer the opportunity to understand both risks and opportunities in sustainable cultivation and exploitation of this energy crop in Mexico, and to promote a successful biodiesel market and local development of communities where it is cultivated through the creation of jobs and well-being. The findings in this study concerning estimates of available areas for JCL cultivation also help avoid those susceptible to risk of extreme weather events.

The integration of GIS-MCDA on the analysis of suitability and availability land for the growth of JCL allows us to get closer to projections related with technical potential of JCL as source for biodiesel production in Mexico. For instance, if we decide selecting candidate locations for JCL inedible oilseed crop cultivation in Mexico under the perspective of scenario 2, we could get a more realistic situation for sustainable production of biodiesel because:

(1) Some 5,331,477 hectares from available land with "high potential" was projected
(2) Valuable information that integrates aspects related with value chain of raw materials, such as proximity of the road and transportation infrastructure was considered.
(3) It is known that 70.48% of total available estimated area is affected by erosion (around of 3.57 million hectares)
(4) Principally, there is no competition with food or animal feed production, while considering biodiversity conservation.
(5) Finally, we consider an oil yield of 1892 L $ha^{-1}$ [86]; a density of 901–922 kg/$m^3$ [87]; a calorific value of the oil 39.5 MJ/kg [88] and a biodiesel production yield of 96% [89]. With this data, the biodiesel production potential could be estimated in 9.683 $Mm^3$ biodiesel/year, which is equivalent to 344.636–352.669 Giga J/year. With this biodiesel production potential, Mexico would

become one of the top five producers in the world of this biofuel and the most positive aspect is that it would be through the use of areas that meet sustainability criteria [5].

Non-edible biofuel crops are expected to use lands that are largely unproductive and those that are located in degraded forests [90], and/or the largest amount of suitable and potentially available land with arid and semiarid conditions [91]. In our study, we found that the northern part of Mexico exhibits arid (desert) and semiarid characteristics; it is the region with predominantly localized availability of land with a medium suitability level for JCL cultivation. In Mexico, there is currently no consensus about better land allocation for JCL cultivation, and a persistent attentiveness to benefit from its multi-dimensional potentials exists. The GIS-based approach was applied to allow project-level analyses or decision-support beyond the 'site-searching' process for investors, policy makers and prospective developers who wish to perform a techno-economic study using site specific inputs, and consider the methodology of this study, with the aim of promoting the bioenergy industry in any country in the world. Alternatively, several studies show that JCL has the ability to be employed for dry land reforestation because it is helpful for restoration of degraded ecosystem, to alleviate soil and degradation [92–94]. In this sense a comprehensive promotion of JCL cultivation can be planned in regions like southeastern Mexican states challenged with a high rate of change in its ecosystems and land use in the last 10 years, with increments in the incidences of deforestation processes, forest conversions to grassland and slash-burning practices [95–97].

Finally, to validate the consistency of the results we carried out a visual inspection of the estimated areas of the scenario 2, we compared (through overlay operations) Google Earth's high-resolution data and food crop SPOT satellite data provided by [50], which, pertain to vector layer/SPOT imagery from Spring-Summer 2018 and field work (1 m spatial resolution). This verification was performed using a random sample of 927 pixels, a 95% confidence level and a 3% margin of error. Additionally, Kappa Coefficient (k) was calculated in accordance with Equation (8). In Table 20 we present the confusion matrix. The value k represents a very good concordance [98]:

$$k = N \sum_{i=1}^{r} x_{ii} - \left(\sum_{i=1}^{r} x_{ij} \times x_{ji}\right) / N^2 - \sum_{i=1}^{r} x_{ij} \times x_{ji} \quad (8)$$

where $r$ is the number of rows in error matrix; N is the total number of pixels observed; $x_{ii}$ is the number of observations in row $i$ and column $i$; $x_{ij}$ is the total number of observations in row I; $x_{ji}$ is the total number of observations in column I; k = 1 indicates perfect agreement.

**Table 20.** Error matrix of the MCDA analysis in scenario 2.

| | Estimated | | |
|---|---|---|---|
| **Observed** | **High Potential** | **Medium Potential** | **Row Total** |
| High potential | 109 | 0 | 109 |
| Medium potential | 17 | 729 | 746 |
| Errors of commission | 38 | 34 | 72 |
| Column total | 164 | 763 | 927 |
| Overall Accuracy = 0.90; k = 0.90 | | | |

After visual inspection, it was found that nearly the whole feasible space analyzed for scenario 2 showed consistency, and, the regions categorized as "medium potential" presented a better level of confirmation, followed by the regions categorized as "high potential".

## 4. Conclusions

The use of AHP was integrated with GIS application environment to assess land suitability and availability for "high potential", "medium potential" and "low potential" to cultivate JCL in Mexico, combining agroclimatic criteria, land cover/land uses, soil type, extreme weather events and socioeconomic information, allowing the identification of suitable and available lands where this inedible oilseed crops can grow in a more sustainable way while avoiding competition with food or animal feed production, and considering biodiversity conservation, promoting the biomass supply chain, and addressing climate-related extreme weather event risks to crop production. So, a GIS approach is beneficial by including other key factors that affect its sustainable plantation, which improves land allocation for biomass JCL cultivation and provides reliable data for preliminary planning of biodiesel production.

The result of the MCDA analysis for AEZ (in both scenarios) indicates that around of 82% of the area estimated in Mexico has a "medium potential". Important extensions of land with medium potential sites for JCL cultivation were found in the northern part of Mexico corresponding to 53.88% of the area estimated, in states such as Chihuahua, Coahuila and Sonora. We consider that the scenario 2 is the most important analysis because it suggests the guarantee of the food security, ecosystem conservation and the reduction land use change. So, in this scenario 15.3% of Mexican territory is available for JCL production. Overall, our findings focused on producing a preliminary study that aggregated information supporting regional and national planning of JCL cultivation in Mexico. Future studies could integrate indicators about other social externalities like harvesting and transportation costs. Finally, the visual images of the sample areas inspected (using high resolution satellite data), allowed us to observe that within the areas estimated for JCL cultivation, there were marginal areas (i.e., abandoned lands) that were previously dedicated to the cultivation of food crops, but that currently do not produce. Related to this, it is also invaluable to acquire the most updated reference data and perform field visits to confirm the availability of land.

Although, further research is recommended, the calculated potential of biodiesel production in Mexico though the proposed methodology resulted in 9000 million liters which implies that it would become one of the leading production countries in the world of this biofuel, with the additional advantage of being located in a strategic geographical position next to the major consumer of this product, the United States of America. Future research should be oriented on data quality and model improvement, including enhancement of data sampling and enhanced selection of predictive variables.

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# Optimizing Resource Utilization in Biomass Supply Chains by Creating Integrated Biomass Logistics Centers

**Xuezhen Guo [1,*], Juliën Voogt [1], Bert Annevelink [1], Joost Snels [1] and Argyris Kanellopoulos [2]**

1 Wageningen Food & Bio-Based Research, Bornse Weilanden 9, 6708 WG Wageningen, The Netherlands; julien.voogt@wur.nl (J.V.); bert.annevelink@wur.nl (B.A.); joost.snels@wur.nl (J.S.)

2 Operations Research and Logistics, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands; argyris.kanellopoulos@wur.nl

* Correspondence: xuezhen.guo@wur.nl

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**Abstract:** Bio-based supply chains are by nature complex to optimize. The new logistic concept of integrated biomass logistical center (IBLC) provides us the opportunity to make full use of the idle capacity for a food/feed plant to produce biobased products so that the entire chain efficiency can be improved. Although research has been conducted to analyze the IBLC concept, is yet to be an optimization model that can optimally arrange the activities in the supply chain where an IBLC stands in the middle. To fill the knowledge gap in the literature, this paper makes the first step to develop a MILP model that enables biobased supply chain optimization with the IBLC concept, which supports logistic and processing decisions in the chain. The model is applied in a case study for a feed and fodder plant in Spain where managerial insights have been derived for transferring the plant to a profitable IBLC.

**Keywords:** bio-based supply chains; integrated biomass logistical center; mixed integer programming model

## 1. Introduction

The world population is growing fast. There were approximately 7.5 billion people living on the earth in 2017 with an annual growth rate of 80 million [1]. The fast-growing world population requires more food to be supplied but the total amount of land for agricultural production hardly changes [2]. The large world population also leads to enormous energy consumption and per-capita energy use is also rising [3]. Crude oil, coal, and gas are still the main resources for humans to obtain energy; however, fossil fuel reserves are limited and continuously declining [4]. Moreover, fossil fuels are the major source of GHG emissions which is responsible for climate change [5]. One of the alternatives for fossil energy is bioenergy and biofuels. The wide availability of biomass enables biofuel to become an appealing source of renewable energy to replace fossil energy [6]. Furthermore, the processing of biomass does not contribute to a build-up of CO2 in the atmosphere, because the amount of carbon taken up during plant growth is roughly the same as the emission of carbon during the conversion of biomass [7].

The production of bioenergy and other biobased products from available biomass is a promising solution to reduce the global consumption of fossil fuels and thus greenhouse gas emissions. While significant research efforts have been devoted to exploring the potential of biomass production and conversion technologies, the importance of efficient logistics and supply chain management was only detected recently [8]. Efficient biomass logistics would focus on coordinating the flow of materials and operations within the biomass supply chain to maximize economic output for the same or even lower environmental impacts.

Designing efficient biomass supply chains is a rather complex process. The production of biomass is seasonal and location-specific, influenced directly by the biophysical, climatic, and socio-economic environments. Because of this, availability of biomass can differ between periods, years and locations. Moreover, in many cases, biomass is highly perishable and pre-treatment and storage can be crucial stages for the quality of the final products. Different pre-treatment and conversion technologies can be used to process different types of biomass in order to produce a variety of final biobased products. The quantity and quality of the produced final biobased products depend on the technology but also the scale of conversion. Important sources of biomass are crop residues and wastes from the food industry (what is waste for one is raw material for another). Decisions in other industries (e.g., farming, food processing) can influence availability and quality of biomass which can have direct consequences on idle time of machinery and available resources. To design an efficient biomass supply chain, all these decisions must be optimized simultaneously taking into account all these special features of biomass supply chains.

One way to improve machinery utilization is to combine food and/or feed processing with biomass processing in the same processing facility, i.e., an integrated biomass logistical center (IBLC) [9]. An Integrated Biomass Logistical Center (IBLC) is a new logistics concept that aims to integrate operations of different biomass supply chains (e.g., food, feed, and energy) in order to improve the efficiency of using the available resources like machinery and labor. More specifically, an IBLC is a facility that produces food and/or feed as their primary business but makes use of the idle capacity of the equipment and labor to produce biobased products. In practice, a lot of food and/or feed processing plants—which are equipped with pelletizers, drying systems, silos, conveyors, etc.—just operate in a specific period of the year because of the seasonal availability of the primary feedstocks [10]. Within an IBLC setting, during a few months after the harvesting period, the equipment and labor force of the IBLC will be devoted to processing primary food and/or feed products. For the rest of the year, the same equipment and labor force of the IBLC will be used to process biomass into biobased products to improve capacity utilization. Combining the food and non-food processing in one facility leads to less idle time of (already existing) equipment which brings in a reduction of the total costs [11]. Also, the required storage facilities can be used to store both food and non-food products as well as their feedstocks. In general, the IBLC concept introduces flexibility by aligning decisions related to the supply of different types of biomass (e.g., taking seasonality into account), the (pre)processing of raw materials, and meeting the demand of the various biobased product. As a result, the use of available pre-treatment, conversion, and storage facilities in the value chain can be optimized. Since the concept of IBLC is new, its economic and environmental consequences must be evaluated quantitatively before implementation. Such evaluation requires advanced decision support models. Even though there have been many models developed to optimize decisions of the biomass supply chain (e.g., [12–19]), hardly any looked into the optimal use of the equipment and available resources in an existing similar to an IBLC.

To fill the aforementioned knowledge gap, this paper developed the first mixed-integer programming model that optimizes the machinery utilization using the IBLC concept where the processing of biomass is combined into the business of existing food and/or feed manufacturing plant. The objective of this research is to improve the economic and environmental efficiency of current biomass supply chains by using IBLCs. We developed a mixed integer linear programming (MILP) model that optimizes the resource allocation decisions of an IBLC. To demonstrate the rationale and practicability of the model, a case study for a feed and fodder manufacturer in Spain was carried out. Managerial implications were derived from the case study to support the company's decision making in turning the feed manufacturing plant into an IBLC.

## 2. Improving Efficiency in Biomass Supply Chains

This section reviews studies focusing on improving efficiency in biomass supply chains. Biomass is not only used as a source to produce bioenergy but also used for the production of food, feed, and other biobased products, like bioplastics and chemicals [20]. Because of the global scarcity of agricultural land and the increasing demand for biobased products, the utilization of biomass should be optimized to its full potential. One of the ways to achieve this is to redesign biomass supply chains to improve their economic and environmental performance. Redesigning a biomass supply chain is a complex process. First of all, the biomass supply chain for bio-energy production contains five general system components, namely (I) biomass harvesting and collection, (II) pre-treatment, (III) storage, (IV) transport, and (V) energy conversion. For these interrelated processes, it has to be determined where, when, and how they take place. Therefore, systematic thinking from the supply chain management perspective is required. It plays an important role in the management of biobased production processes. The objectives of biomass supply chain management are to minimize the costs and environmental impacts of the supply chain and to ensure continuous feedstock supply [6]. Secondly, a wide range of biobased products can be produced from various types of biomass with different treatment technologies, which leads to additional complexity of the biomass supply chain. Besides specially grown novel non-food crops, and the residuals of the traditional food-crops, there are also tertiary residues, the so-called post-consumer biomass products, that can be used to produce biobased products [21]. Because of the high variety of biomass inputs, pre-treatments, processing options, and biobased products as outputs, the system becomes very complex. Thirdly, the availability of biomass feedstocks depends on the harvesting period of the crop [11]. The seasonality leads to a non-continuous use of equipment that is needed for processing biomass [22]. If year-round processing of biomass is applied to avoid low capacity utilization, large amounts of biomass need to be stored for a long period and incur significant storage costs. This further increases the complexity of biomass processing planning.

A number of research papers reviewed, deal with the question of how biomass supply chains can be organized in a cost-efficient manner to collect, process, and transfer available biomass to a specific biorefinery plant [23–26]. As stated by Iakovou et al. [27], one of the most crucial bottlenecks in increased biomass utilization is the costs of logistics operations. In their study, they specifically refer to the utilization of biomass for energy production but such a bottleneck issue can also be considered valid for any other biorefinery outlet.

Hong et al. [28] address the topic of sustainable biomass supply chains from the viewpoint of supply chain management. In that study, sustainable biomass supply chains or network of supply chains is considered as the operational management method and optimization approach to reduce environmental impacts and the costs of manufacturing in the full life cycle of the bioproducts: from the raw material to the end product. Hong, How, and Lam [28] mentioned that a sustainable biomass supply chain should not only emphasize efficient transportation but also the conservation of mass and energy used in the processes, as well as the possibility to exploit multiple biomass sources. In the same study, the concept of industrial symbiosis is discussed together with the network synthesis with multi-goals of environmental, technical, economic, safety, and social factors. This is in line with the IBLC concept which looks at the synergy between existing agro-industries, the (regional) availability of biomass (residues), and the opportunity to develop value chains for biobased products.

Lautala et al. [29], come up with the concept of advanced feedstock supply systems, i.e., versatile preprocessing depots that can utilize multiple types of biomass. Typical preprocessing operations in such depots could include particle size reduction, moisture reduction, densification, and some advanced processes such as blending, partial pre-treatment, even fractionation to oil, sugar, or char intermediate products. Biomass leaves these depots as a commodity feedstock which is stable, dense, flowable, and has a defined grade of material specification.

Similarly, Eranki et al. [30] introduce the concept of advanced regional biomass processing depots (ARBPDs). An advanced RBDP produces intermediates and products beyond those for biochemical and thermochemical biofuel production, including higher-value animal feeds, nutraceuticals, and biocomposite materials, and thereby leveraging the capital and expertise of these well-established industries. In addition, Eranki, Bals, and Dale [30] come up with the concept of tailor-made, or enhanced RBPD: facilities that employ specific technologies that depend primarily on regional feedstock availability and biomass characteristics also on synergies among these technologies. Given the features of regional biomass availability and technology synergy, the enhanced RBPD can be considered as similar to an IBLC.

A similar approach is developed by Bals and Dale [31]: the local biomass processing depots (LBPDs). To overcome the difficulty of biomass as a bulky, inhomogeneous, difficult-to-transport, and perishable product, they propose to establish a network of regional or local biomass processing depots. Biomass supplied to LBPDs can then be homogenized, processed, and densified at a rural (local) level prior to shipping it to a biorefinery for conversion into final bioproducts such as fuels, chemicals. Campbell [32] describes LBDPs as a concept for processing regional specific biomass streams into densified, stable, and transportable commodities. Campbell identified the following functions for an LBDP: (i) purchasing biomass from farmers/growers, (ii) short-term storage, (iii) sorting and cleaning, (iv) biomass pretreatment, and (v) densification (e.g., palletization).

In another study, alternative options and configurations of biomass supply systems were investigated for the U.S. cellulosic biofuel industry [33,34]. The authors concluded that decentralized biomass processing facilities, or depots, may be needed to achieve lower feedstock costs but supply the quantity and quality required. Two types of depots exist (see Appendix A). The main function of a standard depot is to improve feedstock stability (for storage), increase bulk density (for transportation), improve flowability (for stable in-feed rates), and decrease material losses. On a contrary, a quality depot actively addresses feedstock quality aspects specific to the market it targets. It produces enhanced feedstock (with a lower contamination level) or even process intermediates and hence reduces the pre-treatment requirements at the client facility. To satisfy demand in its final markets, different kinds of pre-treatment steps are possible within advanced depots (thermal/chemical pre-treatment).

Annevelink [35] bring up the biomass yard as a logistical concept that different types of biomass from different supply sectors are collected in one location for pre-treatments. Within the biomass yard, biomass suppliers and collectors collaborate with biobased processing industries in organizing efficient regional biomass collection. When necessary, biomass is pre-treated into a specific bio-commodity for further biobased industrial processing. The function of the biomass yard is to improve the value chain of biomass (residues). To realize this, the biomass yard has several technical/ operational tasks concerning the sustainable collection of multiple streams, regional buffering, pre-treatments and densification, and transportation to market outlets. Also, the biomass yard manages various biomass supply chains from suppliers of unprocessed biomass to buyers of specified processed biomass components for biobased markets.

In Austria, the regional agricultural chamber Steiermark (Landwirtschaftskammer Steiermark) established the 'Biomassehof' as a regional service center for solid biofuels [36]. The Biomassehof was co-developed in 2011 by a farmer group within the framework of the BiomassTradeCenter project (2009–2011). This farmer group is responsible for operations related to the processing and exploitation of woody biomass into a solid biofuel. The goal of the center is to make locally grown woody biomass available for the bio-energy market and to guarantee the quality standards of both products and services in the market. In 2013, the Steiermark province had seven regional Biomassehöfe.

In addition to the aforementioned European research, there are also US studies worth being mentioned. For example, Perlack et al. [37] conducted an in-depth analysis of the biomass resources in the US context while Langholtz et al. [38] discussed the benefits of avoided CO2 emissions by replacing fossil fuels with biofuels. Moreover, Lautala, Hilliard, Webb, Busch, Hess, Roni, Hilbert, Handler, Bittencourt, and Valente [29] developed a Biofuel Infrastructure, Logistics, and Transportation model to calculate the optimal locations of multiple biorefineries.

Based on the previous research, this paper takes a step further by developing the first MILP model that enables the optimization of resource utilization in the biomass supply chain for an IBLC.

## 3. MILP Model for an IBLC

In this section, we describe the main components of the developed MILP model for IBLC's. The MILP model maximizes the profit of a defined biomass supply chain subjected to a set of periodical constraints: feedstock availability, storage capacity, machinery capacity, and product demand. It also takes into account the logistics and the processing aspects within the IBLC to derive the optimal logistic and processing plans. The MILP model is schematically represented in Figure 1.

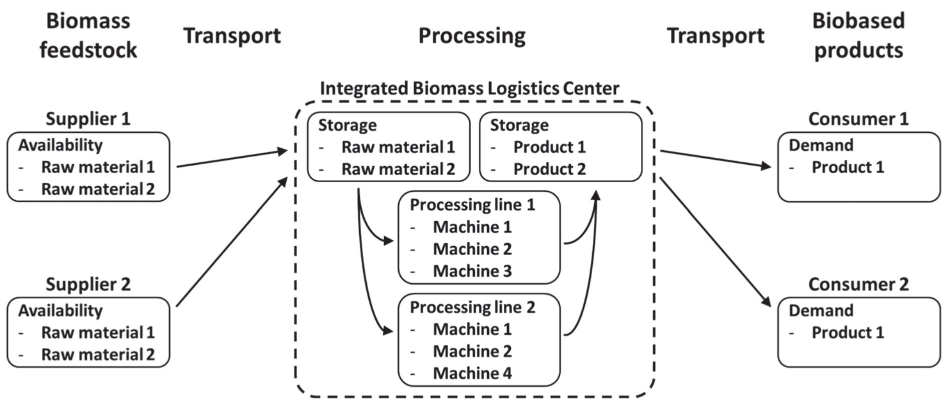


**Figure 1.** Schematic representation of the MILP model for an IBLC.

Multiple suppliers (e.g., farms) can supply several raw materials. Each supplier is at a specified distance from the IBLC. The raw materials are available in different (harvesting) periods. The weight decay of the raw materials stored at the supplier due to degradation can be specified. In each period, for each supplier, the MILP model decides the quantities of raw material that are stored at the supplier or moved to the IBLC. The storage costs at the supplier and the transportation costs are added to the raw material costs.

When raw materials are transported to the IBLC, the MILP model decides either to process them in the same period when they arrive or to move them into the storage of the IBLC. To process raw material, a certain processing line existing of one or more machines is used. Each of the machines has a fixed processing capacity per period. When the capacity of a machine is the limiting factor, the MILP model allows the IBLC to purchase an extra machine. The required investment costs are annualized considering a depreciation period of 10 years. Each raw material has specified processing costs. Cleaning costs and switching costs—i.e., costs related to adopting a process line for processing a different raw material—can be specified. For each processing line, a product yield is applied to account for the loss of material during processing.

Both raw materials and products can be stored at the IBLC at specified storage costs. When the storage capacity is the limiting factor, there is an option to increase the storage capacity at extra costs. Both for the raw materials and the products in the storage of the IBLC a decay factor per time period can be specified. Each product has its selling price and a certain demand at a specified distance. The selling price includes outbound transportation costs.

The results of the MILP model provide insights in terms of:

- distinction in the production costs (e.g., raw material costs, processing costs);
- storage plans for raw materials and products at the supplier and at the IBLC;
- processing schedule of the IBLC including utilization rate of the machinery;

- potential investment for extra machinery and storage capacity in the IBLC.

## 4. MILP Model Applied to a Feed and Fodder Supply Chain

The developed MILP model was applied to analyze the potential of an IBLC for a feed and fodder supply chain in Zaragoza, Spain. For modeling and demonstration purposes, the MIP case study was made more generic by adding data from other sources and by estimating certain values that were not available. In the current situation, lucerne bulk and lucerne bales are processed into respectively feed bales and feed pellets. The lucerne raw material is available 8 months per year. The idle time of most of the machinery can be used to process a mixture of wheat straw and wood chips into energy pellets. A detailed description of the supply chain is given below. The key parameters used in this MILP model are provided in the Appendix B. The main parameter values used in the model are provided in Appendix C. All monetary values used in this research refers to that in the year 2019.

In the MILP model the next processing lines were defined:

- Processing line 1—Lucerne bulk is processed into lucerne feed bales using a dryer, a cooler (#1), and a baler. Lucerne bulk is available within a distance of 30 km to the IBLC from April to November.
- Processing line 2—Lucerne bales are processed into lucerne feed pellets using a grinder, a mill, a pelletizer, and a cooler (#2). The lucerne in bales has usually a lower quality compared to the lucerne in bulk. Lucerne bales are available within 100 km of the IBLC from April to November.
- Processing line 3—Wheat straw (60%) and wood chips (40%) are processed into energy pellets using a wood grinder, a dryer, a hopper, a grinder, a mill, a pelletizer, and a cooler (#2). The composition of wheat straw and wood chips is chosen based on the ash content and related to the quality of the energy pellets. The wood chips are processed in a wood grinder, dryer, and hopper before they are mixed with grinded wheat straw and enter the pelletizing process. The wheat straw is available within 30 km to the IBLC in July and August. The wood chips are assumed to be available the whole year, but the transport distance is further than 100 km. Both raw materials are assumed to be available in abundance. Therefore, the mixture is assumed to be available from July to August at a distance of 100 km to the IBLC.

A simplified overview of the current situation and the baseline scenario is given in Figure 2.

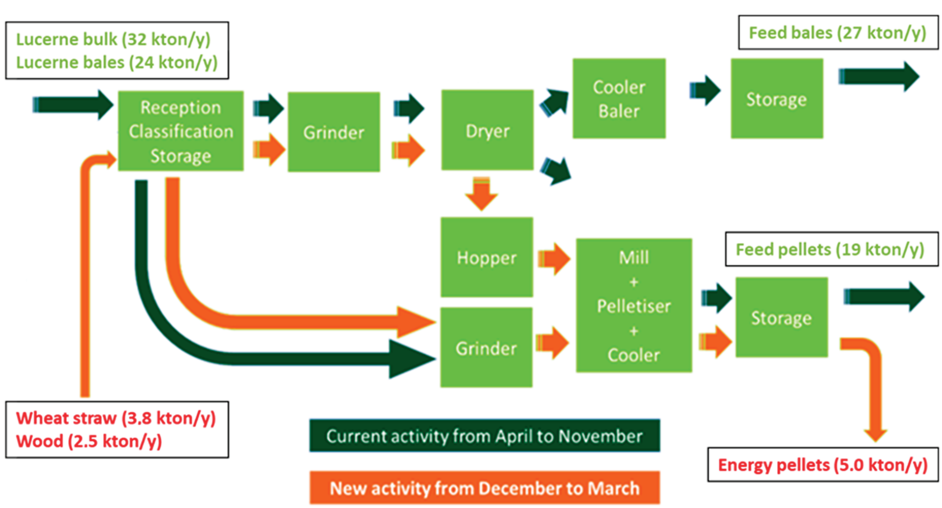


**Figure 2.** Equipment usage and production of the current situation and baseline scenario.

The selling prices of the products (per tonne wet weight, including product transport to the buyer) are assumed to be 225 €/tonne for the lucerne feed bales, 180 €/tonne for the lucerne feed pellets, and 143 €/tonne for the energy pellets. The production costs are allocated to raw material costs (excluding transport), raw material (RM) transport, processing costs, costs for obtaining extra equipment, and product transport to the buyer. An overview of the various costs and the potential profit is given in Figure 3. The costs are expressed in euro per tonne product, which means that the processing yield (loss of raw material) is incorporated in the costs. Note that this overview is based on the input parameters of the MILP model, which means an average raw material transport distance is used and the costs for extra equipment are excluded. These aspects are taken into account in the scenario analysis of the MILP model.

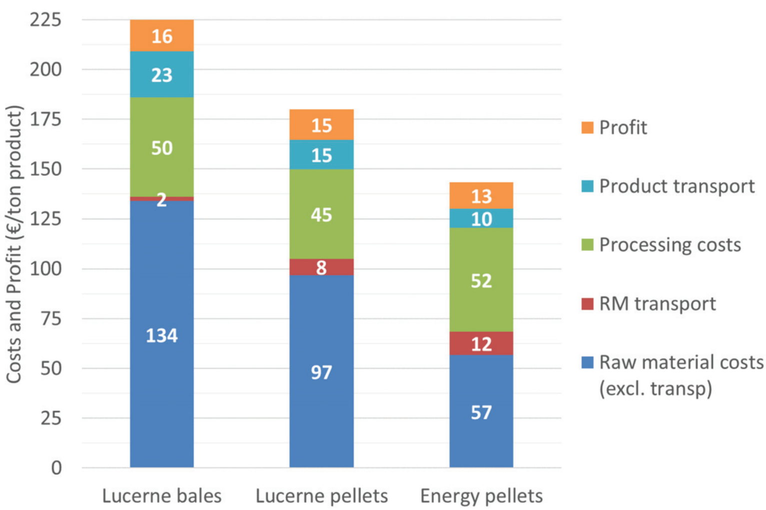


**Figure 3.** Various costs and potential profit for each of the three products (using the average raw material transport distance, excluding costs for extra equipment).

It is shown that for all three products the raw material costs and processing costs dominate the production costs. Because of the small raw material transport distances, raw material transport has only a small contribution to the production costs. The raw material transport costs are highest for energy pellets, because of larger distances. Based on the general assumptions, slightly less profit can be made on the energy pellets (13 €/tonne) compared to the lucerne feed pellets (15 €/tonne) and lucerne feed bales (16 €/tonne).

### *4.1. Scenarios*

For the analysis, different scenarios were defined. For all scenarios, the MILP model calculates the situation in which the profit is optimized. The analyzed scenarios are:

- Current situation: Only lucerne is processed into feed bales or feed pellets.
- Baseline scenario: Compared to the current situation also wheat straw and wood chips can be processed into energy pellets.
- Variations on baseline scenario:
  - Lucerne availability +/− 50%
  - Raw material costs of wheat straw and wood chips +/− 25%
  - Processing costs of all products +/− 25%

- ◦ Energy pellet selling price +/− 25%

For the current situation, the equipment is set to full capacity for the production of the lucerne feed products. In the MILP model, the option is given to double the capacity of the equipment by making extra investments. The investment costs are annualized by distributing the investment costs over 10 years. Costs related to maintenance, labor, and overhead for extra equipment are assumed to be already included in the processing costs.

Storage capacity at the IBLC, for raw materials and products combined, can be extended to a maximum of 17 kilotonnes per month. The decay during the storage of raw material is set to 1% per month. In all scenarios, the costs related to cleaning, product changeover, and storage capacity are negligible, because in this specific case study these costs turned out to be marginal compared to other costs.

### *4.2. Sensitivity Analyses*

The annually produced products with the highest profit for the different scenarios are shown in Figure 4. The annual costs and profit of the different scenarios are shown in Figure 5. The total costs, revenues, profit, and margin are shown in Table 1.

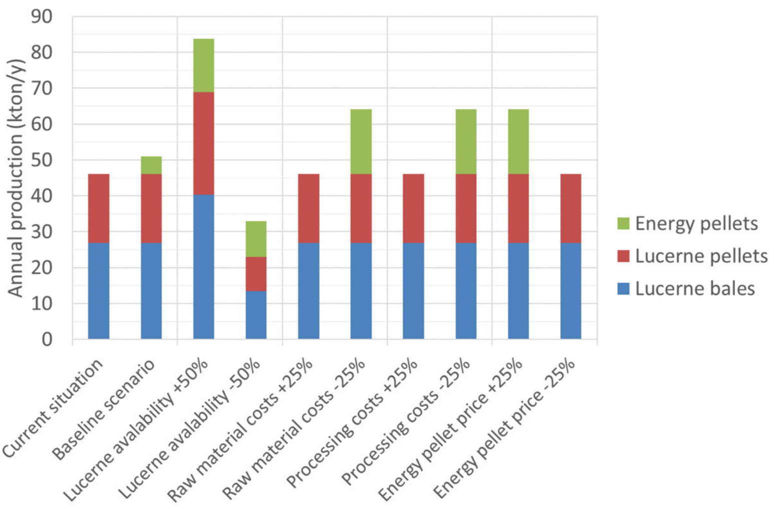


**Figure 4.** Annual production of pellets in different scenarios.

**Table 1.** Costs, revenue, profit, and margin in the different scenarios.

| | Current Situation | Baseline | Lucerne Availability | | Raw Material Costs | | Processing Costs | | Energy Pellet Price | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | +50% | −50% | +25% | −25% | +25% | −25% | +25% | −25% |
| **Extra equip.?** | no | no | yes | no | no | yes | no | yes | yes | no |
| **Costs (M€/y)** | 8.8 | 9.4 | 15.3 | 5.7 | 8.8 | 11.0 | 9.3 | 10.5 | 11.3 | 8.8 |
| **Revenue (M€/y)** | 9.5 | 10.2 | 16.3 | 6.2 | 9.5 | 12.1 | 9.5 | 12.1 | 12.7 | 9.5 |
| **Profit (M€/y)** | 0.7 | 0.8 | 1.1 | 0.5 | 0.7 | 1.0 | 0.2 | 1.6 | 1.4 | 0.7 |
| **Profit margin (%)** | 7.8% | 7.7% | 6.4% | 7.7% | 7.8% | 8.7% | 2.0% | 13% | 11% | 7.8% |

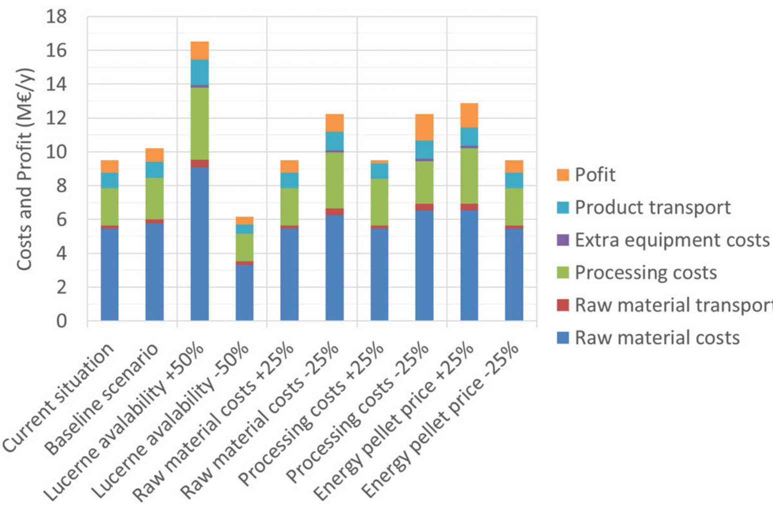


**Figure 5.** Annual optimized costs and profit in different scenarios.

In the current situation, the lucerne bulk and lucerne bales are processed in the months in which they are available. All lucerne that is available is processed. During these months, the equipment is running at full capacity. The calculated profit is 0.7 M€ /year which results in a margin of 7.8%.

In the baseline scenario, the idle time of the processing of the lucerne products is used to produce energy pellets. In this scenario, it is not profitable to invest in extra equipment. The calculated profit increases only 0.1 M€/y and the margin decreases slightly to 7.7%.

When lucerne availability increases by 50%, it is profitable to invest in extra equipment. Not only more lucerne but also more energy pellets can be produced in the (extra) idle time of the lucerne processing equipment. In this scenario, the raw materials are stockpiled and processed in the months that they are not available. In the optimized scenario, the storage reaches its maximum and therefore there is no production in March. The calculated profit increases significantly with 0.4 M€/y to a total of 1.1 M€ /year. The margin decreases to 6.4% because the margin on energy pellets is smaller compared to the lucerne products. When the lucerne availability decreases by 50%, more energy pellets can be produced, also in the months in which lucerne is available. In this scenario, the profit decreases by 0.2 M€/y to a total of 0.5 M€/year, but the margin decreases slightly to only 7.7%.

When the raw material costs of wheat straw and wood chips increase by 25%, it is not profitable to produce energy pellets, even not in the idle time of the production of lucerne products. This change does not affect the production of lucerne products. For the scenario of decreasing energy pellet price by 25%, the same pattern is observed.

When increasing the processing costs for all raw materials by 25%, no energy pellets are produced and the profit decreases to 0.2 M€/y with a margin of just 2.0% because the profitability for producing lucerne products also decreases.

When raw material costs of wheat straw and wood chips decrease or energy pellet prices increase by 25%, or processing costs decrease 25%, it is profitable to produce energy pellets. In these scenarios, it is also profitable to invest in extra equipment. Especially in the scenarios with decreased processing costs and increased selling prices of energy pellets, the profit and margin increase significantly.

## 5. Discussion and Conclusions

In this research, we developed a MILP model to optimize biomass supply chains using IBLCs. The reasoning behind an IBLC is to optimize resource utilization of an existing biomass supply chain. Resources are not only biomass availability, but also storage capacity, machinery capacity, and labor availability. Through leveraging between the primary production of food and/or feed and the production of other biobased products, the IBLC can improve the utilization rates of machinery, process more locally available biomass, and increase the profit margin.

The MILP model takes into account the feedstock availability, feedstock transportation from the suppliers to the IBLC, feedstock processing in the IBLC, product transportation from the IBLC to the market, and the intermediate storage steps at the suppliers and the IBLC. It can calculate the optimal business strategy with respect to the feedstock sourcing plan, the IBLC processing schedule, and potential investment in machinery.

To demonstrate the added value of the MILP model in facilitating decision making on IBLC operations and investment. a case study for the feed and fodder sector was conducted. The case study gave relevant insights into the economic aspects of establishing an IBLC. Although the conclusions are very case-specific, some more general indications emerge for setting up an IBLC:

- Raw material costs and processing costs often dominate the total production costs.
- Raw material transport costs have only a small contribution to the total costs in the case when the transport distance to the IBLC is relatively small. At larger distances, transport costs will of course have a more significant contribution.
- The efficient planning of the use of process lines and storage capacity in the IBLC is required.
- Using the idle time of the existing processing equipment to produce biobased products, such as energy pellets, can increase the profit of the IBLC.
- To determine the economic feasibility of additional process lines, accurate estimates of all cost aspects, including investment costs for extra equipment, are required.
- The demand for biobased products should be adequate, so market size should be checked in practice.

The general indications for setting up an IBLC always need to be verified for the specific IBLC design at hand. For this purpose, the MILP model is an important supporting tool to fill the gap for decision supports on IBLC establishment in biomass supply chains. There are also limitations associated with the current version of the model which needs future development of its functions and applications in more case studies. For example, the assumption for the decay parameter was simplified as a fixed value, which should in fact depend on the moisture content. Future research should focus on further refining the MILP model to make it capture more realistic and detailed supply chain activities, especially within the IBLC. Moreover, the results of the case study are actually based on a specific location in Spain where the IBLC locates. To extrapolate the results to other locations, the location-specific factors—such as feedstock availability, sourcing distances, and demand—must be taken into account. This also requires to apply the MILP model to more case studies that cover diversified sectors and geography for the validation and further development of the MILP model.

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## Appendix A. Definitions of Different Types of Depots

Standard depot: a depot to improve feedstock stability (for storage), increase bulk density (for transport), improve flowability (for stable in-feed rates), and reduce material losses.

Quality depot: on top of the function of a standard depot, a quality depot actively addresses feedstock quality aspects specific to the end-use market it targets.

## Appendix B. Mathematical Formulation of the MILP Model

$$Maximize\{TP = TR - TC\} \tag{A1}$$

*TP* is the total profit.
*TR* is the revenue.
*TC* is the costs.

$$TR = \sum_{i,k,t} W_{i,k,t} * P_{i,k} \tag{A2}$$

$W_{i,k,t}$ is the sold intermediate product (*i*,*k*) in month *t*.
$P_{i,k}$ is the price for the intermediate product (*i*,*k*).

$$TC = TPCraw + TTC + TSC + TPTC + TECC \tag{A3}$$

*TPCraw* is the production costs of the raw materials.
*TTC* is the transportation costs.
*TSC* is the storage costs.
*TPTC* is the total pre-treatment costs.
*TECC* is the costs to purchase extra machinery capacity.

$$TPCraw = \sum_{i,t,f} X_{i,t,f} * PCraw_{i,f} \tag{A4}$$

$X_{i,t,f}$ is the mass of raw material *i* harvested in period t on farm *f*.
$PCraw_{i,f}$ is the production price of raw material *i* on farm *f*.

$$TTC = TTCraw + TTC\text{int} \tag{A5}$$

*TTCraw* is the transportation costs for the raw materials from the farms to the IBLC.

*TTCint* is the transportation costs for the intermediate product (after pre-treatment) sold from the IBLC to the market.

$$TTCraw = \sum_{i,f,t} U_{i,f,t} / density_{raw\ i} * Draw_f * TranspC \tag{A6}$$

$U_{i,f,t}$ is the mass of raw material *i* on farm *f* that is moved to the IBLC in month *t*.
$density_{raw\ i}$ is the density of the raw material *i*.
$Draw_f$ is the distance from farm *f* to the IBLC.
*TranspC* is the per-unit transportation costs based on the volume of the materials.

$$TTCint = \sum_{i,k,t} W_{i,k,t} / density_{int\ i,k} * Dintermediate_{i,k} * TranspC \tag{A7}$$

$density_{int\ i,k}$ is the density for the intermediate product (*i*,*k*).

$Dintermediate_{i,k}$ is the distance from the IBLC to the market which purchases the intermediate product (*i*,*k*).

$$TSC = VSCraw + VSCint + VSF + TFSC + SINV \tag{A8}$$

*VSCraw* is the variable storage costs for the raw materials in the IBLC.
*VSCint* is the variable storage costs for the intermediate products in the IBLC.
*VSF* is the variable storage costs on farm.
*TFSC* is the fixed costs based on the space occupied in the IBLC.
*SINV* is the annualized investment costs for purchasing extra storage capacity.

To save space, the detailed calculations of each type of storage costs are not listed here but they are available when requested by the readers.

$$Srawonfield_{i,t,f} = a_{i,f} * Srawonfield_{i,t-1,f} + X_{i,t,f} - U_{i,t,f} \;\forall\, i \in (1 \ldots I),\; f \in (1 \ldots F) \; and \; t \in (2 \ldots T) \tag{A9}$$

$$Srawonfield_{i,1,f} = a_{i,f} * Srawonfield_{i,T,f} + X_{i,1,f} - U_{i,1,f} \;\forall\, i \in (1 \ldots I) \; and\,,\; f \in (1 \ldots F) \tag{A10}$$

Equations (A9) and (A10) are the conversion constraints for raw materials being transported and stored on field from one month to another.

$Srawonfield_{i,t,f}$ is the mass of raw material *i* stored on farm *f* in month *t*.

$a_{i,f}$ is the decay factor per month for raw material *i* stored on farm *f*.

$$Srawiblc_{i,t} = e_i * Srawiblc_{i,t-1} + \sum_f U_{i,t,f} - \sum_k Y_{i,k,t} \;\forall\, i \in (1 \ldots I) \; and \; t \in (2 \ldots T) \tag{A11}$$

$$Srawiblc_{i,1} = e_i * Srawiblc_{i,T} + \sum_f U_{i,1,f} - \sum_k Y_{i,k,1} \;\forall\, i \in (1 \ldots I) \tag{A12}$$

Equations (A11) and (A12) are the conversion constraints for transferring the raw materials stored in the IBLC from one month to another.

$Y_{i,k,t}$ is the mass of material *i* processed by the pretreatment *k* in month *t* in the IBLC.

$Srawiblc_{i,t}$ is the mass of raw material *i* stored in the IBLC in month *t*.

$e_i$ is the decay factor per month for raw material *i* in the IBLC.

$$\sum_k Y_{i,k,t} \le EoP_{k,q}\left(Cap_{i,q} + ExtrPreChoice_q * ExtrCap_q * NormalF_{i,q}\right) \forall\, i \in (1 \ldots I), \; q \in (1 \ldots Q) \; and \; t \in (1 \ldots T) \tag{A13}$$

$Cap_{i,q}$ is the capacity of machine *q* to process material *i*.

$ExtrCap_q * NormalF_{i,q}$ is the extra capacity of machine *q* for material *i* that can be purchased where $NormalF_{i,q}$ is a normalization factor.

$ExtrPreChoice_q$ is a binary variable to indicate whether or not the extra piece of machine *q* to be purchased.

$EoP_{k,q}$ is a binary variable to indicate whether or not the pretreatment *k* includes machine *q*.

$$TECC = \sum_q ExtrPreChoice_q * ExtrCosts_q \tag{A14}$$

Equation (A14) is used to calculate the costs to purchase extra machinery.

$ExtrCosts_q$ is the annualized investment costs to purchase the extra piece of machine *q*.

$$PTC = \sum_{i,k,t} Y_{i,k,t} * PTCK_k \tag{A15}$$

*PTC* is the total pretreatment costs for processing the raw materials into the intermediate products.

$PTCK_k$ is the unit pretreatment costs for processing the raw materials through pretreatment *k*.

$$Y_{i,k,t} * b_{i,k} = Z_{i,k,t} \;\forall\, i \in (1 \ldots I), k \in (1 \ldots K) \; and \; t \in (1 \ldots T) \tag{A16}$$

$Z_{i,k,t}$ is the produced intermediate products (*i*,*k*) in month *t*.

$b_{i,k}$ is the conversion factor to transfer $Y_{i,k,t}$ to $Z_{i,k,t}$.

$$X_{i,f,t} \leq Avraw_{i,f,t} \;\; \forall\, i \in (1 \ldots I),\; f \in (1 \ldots I) \; and \; t \in (1 \ldots T) \tag{A17}$$

$Avraw_{i,f,t}$ is the mass of raw material $i$ that is available on farm $f$ in month $t$.

$$W_{i,k,t} \leq Demand_{i,k,t} \;\; \forall\, i \in (1 \ldots I), k \in (1 \ldots K) \; and \; t \in (1 \ldots T) \tag{A18}$$

$Demand_{i,k,t}$ is the demand for the intermediate product ($i$,$k$) in month $t$.

## Appendix C. Parameters MILP Model Feed and Fodder Sector

**Table A1.** Raw material availability.

| | From | Until | Zone 1 10 km (kton/Month) | Zone 2 30 km (kton/Month) | Zone 3 100 km (kton/Month) | Total (kton/y) |
|---|---|---|---|---|---|---|
| **Lucerne bulk** | Apr | Nov | 2 | 2 | 0 | 32 |
| **Lucerne bales** | Apr | Nov | 0.5 | 0.5 | 2 | 24 |
| **60% Straw 40% Wood** | Jul | Aug | 0 | 0 | 17 | 34 |

**Table A2.** Parameters of raw materials and processing.

| | Density (ton/m$^3$) | Raw Material Price (No Transp) (€/ton) | Average Transport (km) | Yield (P/RM) | Processing Costs (€/ton P) | Costs (€/ton RM) |
|---|---|---|---|---|---|---|
| **Lucerne bulk** | 0.250 | 112.5 | 20 | 0.840 | 50.0 | 42.0 |
| **Lucerne bales** | 0.250 | 77.5 | 73 | 0.800 | 45.0 | 36.0 |
| **60% Straw 40% Wood** | 0.225 | 46.8 | 100 | 0.826 | 51.8 | 42.8 |

**Table A3.** Product parameters.

| | Density | Transport | Selling Price |
|---|---|---|---|
| | **(ton/m$^3$)** | **(km)** | **(€/ton)** |
| **Feed bales** | 0.380 | 400 | 225 |
| **Feed pellets** | 0.600 | 400 | 180 |
| **Energy pellets** | 0.562 | 250 | 143 |

**Table A4.** Extra equipment capacity and costs. The costs are annualized by distributing the investment costs over 10 years.

| | Extra Capacity (ton/Month) | Extra Equipment Costs (k€/y) |
|---|---|---|
| **Wood grinder** | 600 | 5 |
| **Grinder** | 3000 | 10 |
| **Hopper** | 600 | 10 |
| **Mill** | 3000 | 6.5 |
| **Dryer** | 4000 | 90 |
| **Baler** | 4000 | 25 |
| **Pelletizer** | 3000 | 19 |
| **Mizer** | 3000 | 6.5 |
| **Cooler 1** | 4000 | 3.5 |
| **Cooler 2** | 3000 | 3 |
| **Storage** | 5775 | 25 |

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