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Biomass Characteristics and Energy Yields of Tobacco (*Nicotiana tabacum* L.) Cultivated in Eastern Poland

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Abstract: The present pilot study examined the potential of tobacco (*Nicotiana tabacum* L.) as an energy source. The fresh matter of whole tobacco plants, the yield of dry matter of stems and leaves, as well as the higher heating value and methane production potential from tobacco biomass were determined. The yield of tobacco leaves was on average 4.69 Mg ha^{-1} (dry matter) and 76.90 GJ ha^{-1} yr^{-1} (biomass energy yield). Tobacco stems yielded on average 8.55 Mg ha^{-1} and 150.69 GJ ha^{-1} yr^{-1}, while yields of whole tobacco crops were (on average) 13.24 Mg ha^{-1} and 227.59 GJ ha^{-1} yr^{-1}. Methane potential of tobacco plants was (on average) 248 Nm^3 Mg^{-1} VS (volatile solids). The tobacco plants tested in the study could be used as energy crops as their dry matter and energy yields are similar to those of the most popular energy crops being currently used in biomass production in Poland and the European Union. Nevertheless, further studies to choose the *Nicotiana* species and varieties most suitable for energy production and to assess the cost-effectiveness of tobacco biomass production are needed.

Keywords: tobacco biomass; energy yield; higher heating value; biogas potential; *Nicotiana tabacum*

1. Introduction

Most agricultural land is used for food production purposes as food production is the most important role of agriculture. A portion of agricultural land has always been devoted to non-food products that are used as industrial biomaterials and bioenergy sources [1]. One of the plants that can be used for various non-food purposes is tobacco (*Nicotiana tabacum* L.). Leaves, the main yield of tobacco, contain about 1–4% fatty acids per dry weight, but that can be raised to almost 7% by metabolic engineering (expression of other plant species genes), which makes tobacco a good production platform for biofuel [2]. Tobacco leaves have non-structural sugar content comparable to switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* L.) while their lignin content is low [3]. Moreover, tobacco seeds contain about 40% oil, which can be used as a diesel fuel in turbocharged, indirect injection engines [4]. The yield of tobacco seeds is, however, insignificant (about 400–600 kg/ha according to the authors' knowledge). Tobacco also has a high polysaccharide content. Stems are built of 60% polysaccharides, which could possibly make tobacco a significant source of bioethanol [5]. Other energy carriers, such as biomass and biogas, could also be obtained from tobacco plants.

Currently, tobacco is cultivated in approximately 130 countries, in fields covering almost 3.4 mln hectares, with more than 6 million tons of tobacco harvested each year [6]. More than 40% of the world's tobacco is produced by China. All the largest producers are located outside the European Union (Table 1). Poland is currently the second largest tobacco producer in the European Union, surpassed only by Italy. Domestic plantations produce about 33,000 metric tons (Mg) of tobacco leaves [7], which is only half of the Polish tobacco industry's needs [8]. Tobacco is currently cultivated in Poland by approximately 11,500 farmers on between 13 to 17 thousand hectares [7,9]. The exact area of cultivation and yields are probably strongly underestimated. This is because the statistics of production of tobacco were limited in previous years [10]. According to the Central Statistical Office [7], the average yield of tobacco leaves is about 2.5 Mg per hectare, but according to the authors' knowledge, farmers often get yields as much as two times that amount.

Table 1. The world's largest producers of tobacco (leaves).

Area	Production (Thousands of Mg)	Area Harvested (Thousands of ha)	Average Yield (Mg ha^{-1})
China	2242.2	1003.7	2.2
Brazil	762.3	356.5	2.1
India	749.9	417.7	1.8
USA	241.9	117.9	2.0
Indonesia	181.1	203.0	0.9
Pakistan	106.7	46.3	2.3
Malawi	95.4	86.1	1.1
Argentina	104.1	54.7	1.9
Zambia	115.9	65.7	1.8
Italy	59.3	17.2	3.4
Poland	33.2	16.4	2.0
UE-27 *	178.3	77.9	2.3
World (total)	6094.9	3368.9	1.8

Source: Food and Agriculture Organisation Data (FAOSTAT)(2018); * according to FAOSTAT (2018) tobacco was cultivated in 15 European Union (EU) countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, France, Greece, Germany, Hungary, Italy, Poland, Portugal, Romania, Slovakia and Spain.

The most common types of tobacco cultivated in Poland are flue-cured tobacco (Virginia type) varieties (65–75% of plantations) and Burley type varieties (25–35% of plantations) [10]. Tobacco leaves are the main yield of tobacco, while the other parts of the plants are waste and of no-value for the industry. The leaves are often damaged (especially during summertime) by intensive rain and hail. Tobacco can also be damaged by fungal (e.g., *Botrytis cinerea, Sclerotinia sclerotiorum*) and viral diseases (e.g., TMV, tobacco mosaic virus) [11]. Damaged leaves are worthless for the tobacco industry, and diseased crops have to be liquidated immediately to avoid the spread of diseases in the following years. According to the Central Statistical Office [7], about 20% of polish tobacco plantations are insured for weather-caused damage. This means that about 80% of farms that cultivate tobacco have a high risk of loss of their entire income if adverse weather conditions occur. To minimize the negative impact of weather-caused damage to tobacco leaves, alternative ways of management of tobacco yield should be established. One of those alternative ways of management could be the use of damaged plants for energy purposes as a renewable energy source.

Currently, at least 6 million tons of tobacco leaves are produced worldwide [6]. After harvesting, stems of a height of approximately 2.5 m are left on the fields. It is estimated that about 60% of tobacco biomass is unsuitable for industry and is unnecessary waste. Those wastes are most often burned or left on the field's surface. When managed properly, they can contribute to biogas, bioethanol, and biodiesel production [12]. Those stems have to be managed properly, to avoid phyto-sanitary issues (spread of diseases); however, due to the number of plants and their size, management is often too costly for farmers, and thus residues of plants are often crushed and plowed into the soil. The total amount of waste tobacco biomass must be significant, but there are no exact figure in the literature on this topic. However, some authors estimate the total amount of Virginia dried stalks at 6–10 Mg per hectare [13].

The development of the global economy and rapid growth of consumption increases the needs for conventional energy. According to various scenarios, the share of conventional fuels will be reduced as the result of depletion of resources and the related increase in energy prices [14,15]. The adopted European Union (EU) climate-energy package requires the market share of energy consumption from renewables to reach 20% with a 10% share in liquid biofuels by 2020, while the newest ambitions of the EU is to reach 32% renewable energy by 2030. In addition, a 20% reduction of greenhouse gases emissions (40% by 2030) and an increase in energy efficiency are expected [16]. Implementation of these objectives will increase the demand for agricultural substrates intended for use as an energy source [17,18]. Currently, the development of biomass renewable energy is dependent on the availability of appropriate biomass material, which, in most cases, is corn silage. Due to the multifaceted environmental-safety conditions, the growth of the area of this species may be subject to some restrictions. This is why there is a need to search for alternative biomass materials, which should be tested to confirm their suitability as a renewable source of energy [19]. Management of food-crop residues for energy purposes (e.g., cereal straw) and a search for new biomass sources seem to be two of the ways to meet those needs. The production of energy from tobacco waste biomass (stems or damaged tobacco plants) can increase farmers income while preserving the low environmental costs of the biomass production. The production of energy from wastes could also contribute to the goal of sustainable development and fits into the goal of a bioeconomy.

The aim of this study was to evaluate potential biomass yields of tobacco under typical Polish production plantation conditions. Moreover, the calorific value and biogas yield of *Nicotiana tabacum* were estimated.

2. Materials and Methods

The present study was carried out as pilot study in 2016 on three tobacco plantations located near Puławy, Poland. Virginia (flue cured) and Burley types of tobacco were chosen to analyze their biomass yields and potential as energy crops. The tobacco plants were collected both from production plantations (two locations: Virginia A—51°23′11.3″ N 21°53′55.4″ E and Virginia B—51°22′45.2″ N 22°06′19.5″ E). The third plantation was set in the Institute of Soil Science and Plant Cultivation's State Research Institute's (IUNG's) experimental plantation in Osiny (51°27′59.98″ N 21°39′44.28″ E). The third field was planted with Virginia (Virginia C) and Burley (Burley) types of tobacco and established as a split-plot field experiment. The production plantations chosen to be part of the experiment were both of about 0.5 ha, planted with the same Virginia flue-cured type of tobacco, of the same variety (HYV 23). The experimental crop planted at the IUNG experimental station was 200 m^2. The experimental crop was planted with Virginia VRG 10TL (Virginia C) and Burley TN10 (Burley) varieties. The fertilization schemes and other properties of the tobacco plantations are given in Table 2. Plants of tobacco were collected in early October to estimate yields and for further research. The leaves were separated from stems and then dried and weighed. Dried samples of tobacco were burned in a calorimeter (Precyzja-Bit KL-12Mn calorimeter) in order to assess the higher heating value. The biomass energy yield of tobacco was calculated on a basis of dry matter yield and the corresponding heating value.

Table 2. Soil properties and fertilization of tested tobacco plantations.

Tobacco Plantation	Virginia A	Virginia B	Virginia C	Burley
Variety of tobacco	HYV 23	HYV 23	VRG 10TL	TN10
Soil classification	Podzoluvisol S—Sand	Loess soil	Pseudo Podzoluvisol LS- loamy sand (on sandy loam)	
Complex of agricultural suitability of soils: from 1 (best) to 9 (worst)	6	2	5	
Soil pH	5.0	6.0	5.9	
Soil P_2O_5 content (mg $100g^{-1}$)	16.2	18.1	16.8	
Soil K_2O content (mg $100g^{-1}$)	15.8	19.1	17.0	
Soil Mg content (mg $100g^{-1}$)	5.9	7.6	7.2	
Mineral fertilization N-P_2O_5-K_2O (kg ha^{-1})	130-50-130	50-45-100	100-43-103	
Organic fertilization N-P_2O_5-K_2O (kg ha^{-1})	0	100-33-38	0	
Density of plants (per hectare)	22,000	20,000	23,000	
Irrigation	Yes	No	No	

Methane potential of tobacco silage was estimated on the basis of three out of the four plantations of tobacco: Virginia A, Virginia B, and Burley. Moreover, estimation of methane potential of maize (*Zea mays* L.) was performed (maize was cultivated in the same research station as tobacco, but was a part of an independent experiment). This was to compare tobacco methane potential to maize methane potential, as maize is currently most widely used substrate in agricultural biogas plants. Both tobacco and maize silage was made from whole plants harvested in October. Plants were chopped and ensilaged for 2 months. Total solids (TS), volatile solids (VS), and ash were determined in accordance to the Polish norms PN-EN 12,880 and PN-EN 12,779 using the gravimetric method after drying at 105 °C and 550 °C, respectively. The potential methane (CH_4) yield from tobacco and maize silage was evaluated by using The Automatic Methane Potential Test System II (AMPTS II) manufactured by Bioprocess Control. Bacterial inoculum was collected from an active, agricultural biogas plant, which used mostly corn silage to produce biogas. The initial ratio of VS content in inoculum to VS content in substrate was 2:1. A single reactor had a volume of 500 mL and it was filled with 400 mL of inoculum-substrate mixture. Twelve reactors were used in the experiment. The substrate in the reactors was mixed continuously for 30 s with 30 s interval, at a speed of 70 RPM. The fermentation temperature was set to 37 °C. The process was performed in three independent replications for about 35 days until no significant methane volume increases were found. The values of the biogas volume obtained were converted into standard conditions (1013 mbar, 273 K). Statistical analysis of data for different plantations was completed on the basis of one-way ANOVA (Analysis of variance) with a post-hoc Tukey HSD (Honestly Significant Difference) test. Significance of difference of other biomass parameters (e.g., average higher heating value (HHV) of stems vs. average HHV of leaves) was assessed with the Mann–Whitney test or *t*-test (depending on data distribution parameters). The aim of the pilot study was to assess the potential range of biomass yields, biomass energy, and methane potential of tobacco. The plants from all plantations were picked up randomly, but production plantations (Virginia A and Virginia B) themselves were not designed as experiments and no further measures were implemented to prevent an error variation (e.g., resulting from variability of soil). In contrast, Virginia C and Burley plantations were established as field experiments with a split-plot design (tobacco types as independent variable) with four replications to minimize the impact of soil variability.

3. Results and Discussion

3.1. Biomass Energy Potential

After harvesting tobacco leaves, plant residues are left on the field. The biomass of those residues (mostly stems) is large, but there is hardly any data about it in the literature. The present study on tobacco biomass yield was carried out in different conditions (different types and varieties of tobacco, different soil conditions and agro-techniques in the fields) in order to gather general knowledge of the tobacco biomass yield potential and the residue biomass potential in varied conditions. The fresh matter of tobacco (whole crop) varied significantly between plantations from 34.8 (Virginia C) to 62.3 Mg ha^{-1} (Virginia A) with an average of 53.2 Mg ha^{-1}. Total average dry biomass yield of tobacco varied significantly between locations from 9.4 Mg ha^{-1} (Virginia C) to 15.8 Mg ha^{-1} (Virginia B), with an average of 13.2 Mg ha^{-1}. The tobacco leaves dry matter differed between locations from 3.4 Mg of dry matter per hectare (flue cured tobacco planted in the IUNG's experimental station) to 5.6 Mg ha^{-1} in one of the production fields (Virginia A). An average yield of leaves for all plantations was 4.7 Mg ha^{-1}. Yield of stems varied between locations of tobacco. The lowest yield of stems was observed again for flue cured tobacco planted at the IUNG's experimental station (6.0 Mg of dry matter per hectare) while flue cured tobacco planted in the second plantation field (Virginia B) yielded the most (10.8 Mg ha^{-1}), while the average yield of stems for all plantation was 8.6 Mg ha^{-1} (Table 3).

Table 3. Yields and properties of the tested tobacco biomass.

Plantation and Type of Tobacco	Virginia A	Virginia B	Virginia C	Burley	Average
Yield of fresh matter (FM), (leaves + stems) (Mg ha^{-1})	62.3 ^{a} *	55.7 ^{a}	34.8 ^{b}	59.8 ^{a}	53.2
Total dry matter (DM) in FM (%)	23.0 ^{a}	28.4 ^{b}	27.1 ^{b}	22.4 ^{a}	25.2
Volatile Solids (VS) content in FM (%)	20.5 ^{a}	21.1 ^{a}	16.2 ^{b}	15.9 ^{b}	18.4
Yield of leaves (Mg ha^{-1}) DM	5.6 ^{a}	5.0 ^{a}	3.5 ^{b}	4.7 ^{a}	4.7
Yield of stems (Mg ha^{-1}) DM	8.7^{a}	10.8 ^{b}	6.0 ^{c}	8.7 ^{a}	8.6
Leaf/stem ratio	0.6	0.5	0.6	0.5	0.6
Yield (leaves + stems) (t·ha^{-1}) DM	14.3 ^{ab}	15.8 ^{a}	9.4 ^{c}	13.4 ^{b}	13.2
Higher heating value of leaves (MJ kg^{-1})	17.2 ^{a}	16.4 ^{a}	16.2 ^{a}	15.6 ^{a}	16.3
Higher heating value of stems (MJ kg^{-1})	18.4 ^{a}	17.6 ^{ab}	17.4 ^{ab}	17.0 ^{b}	17.6
Higher heating value (leaves + stems) (MJ kg^{-1})	18.0 ^{a}	17.0 ^{ab}	16.8 ^{ab}	16.3 ^{b}	17.0
Biomass energy yield (GJ ha^{-1} yr^{-1}) of leaves	96.3 ^{a}	81.8 ^{ab}	56.5 ^{c}	73.0 ^{bc}	76.9
Biomass energy yield (GJ ha^{-1} yr^{-1}) of stems	160.3 ^{a}	191.0 ^{b}	103.8 ^{c}	147.7 ^{a}	150.7
Biomass energy yield (GJ ha^{-1} yr^{-1}) of leaves + stems	256.6 ^{ab}	272.8 ^{a}	160.3 ^{c}	220.7 ^{b}	227.6
Methane potential (Nm^{3} Mg^{-1} VS)	298 ^{b}	220 ^{a}	nd	226 ^{a}	248
Yield of methane (Nm^{3} ha^{-1} yr^{-1})	3802 ^{b}	2590 ^{a}	nd	2149 ^{a}	2847

Source: own study; * different lowercase letters indicate significant differences according to one-way ANOVA with a post-hoc Tukey HSD test at $p < 0.05$.

Bilalis et al. (2009) [20] reported that the dry matter of tobacco leaves ranged from 1.9 Mg ha^{-1} to 5.0 Mg ha^{-1} and was strongly influenced by irrigation and fertilization. In the present study, tobacco yields varied among locations. According to the authors' knowledge, there are only a few studies about dry matter yields of stems or whole tobacco plants. Radojičić et al. (2014) [13] estimated the yields of Virginia tobacco stems at about 6–10 Mg per hectare. Dry matter yields are expected to be highly variable and dependent on soil and weather conditions, fertilization, and agrotechnical treatments, in particular loosening the soil. Szewczuk (2009) [21] found that Virginia type tobacco industrial yields (leaves) can vary (in Poland) from 2.5 Mg ha^{-1} to 3.7 Mg ha^{-1}, and they are dependent on fertilization scheme. According to Pawełek (2000) [22], industrial yields of Virginia tobacco can be even greater and could reach from 2.7 Mg to 5.0 Mg per hectare. Annual yields of other widely used biomass plants are strongly differentiated depending on genotype and site conditions. According to McKendry (2002) [23], poplar (*Populus* L.) and willow (*Salix* L.) yields could reach 10 to 15 Mg of dry matter per hectare per year (which is very similar to the tobacco biomass yields presented in this study), while switchgrass yields are estimated at 8 Mg ha^{-1}, and yields of miscanthus biomass could reach up to 12–30 Mg ha^{-1} (Table 4). Yields of industrial hemp (*Cannabis sativa* L.), according to Prade et al. (2011) [24], reach 9.9–14.4 Mg ha^{-1}, depending on harvest period (Table 4). Concerning maize dry matter (DM) (whole aboveground biomass), Jurekova et al. [25] found variation of yields at 8 and 32 Mg ha^{-1} while Stolarski et al. (2020) [26] found that yields of willow in Poland can range from 2 to 18 Mg ha^{-1} yr^{-1} (11 Mg ha^{-1} yr^{-1} on average) (Table 4). Niemczyk et al. [27] showed that in the conditions found in Poland DM yields of poplar range from 2 to 8 Mg ha^{-1} yr^{-1} and are lower than those in countries located in southern parts of Europe. Yields of DM of tobacco and other energy sources are given in Table 4. Sheen (1983) [28] cultivated tobacco for biomass yield under high plant density conditions (about 766,000 per hectare). Sheen found that tobacco fresh biomass, harvested once a year in June, can reach from 44 to 70 Mg ha^{-1} depending on tobacco cultivar. Moreover, Wildman (1979) [29] found that tobacco fresh biomass yields from a stand of 370,000 plants and multiple harvests could reach up to 150 Mg ha^{-1} yr^{-1}. In the present study, the density of plants was not that high (up to 23,000 plants per hectare) and reached on average 53.2 Mg ha^{-1} (Table 3). Thus, tobacco could be an important source of biomass, especially when cultivated for energy purposes, with the introduction of new management techniques (higher density of plants, different fertilization schemes, and multiple harvests during vegetation).

Table 4. Yields, higher heating value (HHV), and energy yield of selected energy crops.

Crop	Crop Yield DM ($Mg\ ha^{-1}\ yr^{-1}$)	HHV ($MJ\ kg^{-1}$)	Biomass Energy Yield ($GJ\ ha^{-1}\ yr^{-1}$)
Tobacco	9–16	16.3–18.0	160–273
Wheat (*Triticum aestivum* L.)	14 [1] 7–13 [3]	12.3 [1]	123 [1] 128–231 [3]
Poplar	10–15 [1] 2–8 [6]	17.3 [1]	173–259 [1] 33–230 [8]
Willow	10–15 [1] 2–18 [5]	18.7 [1]	187–280 [1] 203–210 [7]
Switchgrass	8 [1]	17.4 [1]	139 [1]
Miscanthus	12–30 [1] 11–29 [3]	18.5 [1]	222–555 [1] 186–486 [3]
Industrial hemp	10–14 [2]	17.5–19.1[2]	246–296 [2]
Maize	8–32 [3]	17.5 [4]	142–545 [3]

Sources: own study and: [1]—McKendry (2002) [23], [2]—Prade et al. (2011) [24], [3]—Jurekova et al. (2015) [25], [4]—Jóvér et al. (2018) [30], [5]—Stolarski et al. (2020) [26]. [6]—Niemczyk et al. (2016) [27], [7]—Stolarski et al. (2014) [31], [8]—Stolarski et al. (2020) [30].

The average HHV of tobacco leaves was significantly lower (16.3 MJ kg^{-1}) than the average HHV of its stems (17.6 MJ kg^{-1}) (t-test, p-value < 0.001). The lowest HHV for whole tobacco plants was observed for the Burley type of tobacco (16.3 MJ kg^{-1}), while the highest at 18.0 MJ kg^{-1} was for flue cured tobacco cultivated on sandy soil (Virginia A). The average HHV for whole tobacco plants was 17.0 MJ kg^{-1} (Table 3). There are not many accurate reports about the energy value of tobacco plants in the literature. Some authors [13,32] have estimated (on the basis of chemical analysis of tobacco stems) the average higher heating value of Virginia (flue cured) stems at around 18.2 MJ kg^{-1}, which is similar to the HHV of Virginia stems presented in this study. In addition, Indahsari (2018) [33] found tobacco stems' HHV to be 18.2 MJ kg^{-1}. Moreover, Mijailovic et al. (2014) [32] found Burley stems' HHV to be 18.3 MJ kg^{-1}, which is a higher value than the average HHV of Burley stems measured in the present study (17.0 MJ kg^{-1}). The difference in Burley's HHV value is probably due to rather poor nutrition and growth rate of burley plants at the IUNG's experimental station. Nevertheless, the average HHV for all tested tobacco varieties was at a rather good level, comparable with other energy plants. According to McKendry (2002) [23] the HHVs of poplar and switchgrass are at a comparable level (17.3 MJ kg^{-1} and 17.4MJ kg^{-1}, respectively) to tobacco's HHV presented in this study (17.03 MJ ha^{-1}), while the HHVs of willow and miscanthus are higher (18.7 MJ kg^{-1} and 18.5 MJ kg^{-1}, respectively) (Table 4). Prade et al. (2011) [24] found that industrial hemp's HHV can reach from 17.5 to 19.1 MJ kg^{-1}, depending on the time of harvest (Table 4).

Energy yield of whole tobacco plants reached values from 160.3 GJ ha^{-1} to 272.8 GJ ha^{-1} per year. On average, tobacco energy yield was estimated at 227.6 GJ ha^{-1} (Table 3). This means that one hectare of tobacco plants had the same energy potential as 9.5 tons of coal (24 MJ kg^{-1}). Plant residue management (mostly stems) is an important issue in tobacco plantations. The amount of that waste biomass is often large. The present study showed that tobacco stems are about 65% of the tobacco dry biomass yield (average leaf/stem ratio of 0.55). In addition, energy yields of stems were about two times higher than energy yields of leaves, which was due to the significantly higher yields of stems (Mann–Whitney test, p-value < 0.001) and also the significantly higher heating value of stems (t-test, p-value < 0.001). According to Sheen (1983) [28], tobacco plants planted in more dense stands (up to 670,000 plants per hectare) produce more fresh biomass of leaves than that of stems (leaf/stem ratio from 1.77 to 3.02). The differences were probably due to density of stands, genotypes of plants, and harvesting time. This study showed that the energy yields of stems were approximately two times higher (150.7 GJ ha^{-1} yr^{-1}) than the energy yields of leaves (76.9 GJ ha^{-1} yr^{-1}) (Table 3). This can be valuable information for farmers who want to use tobacco residues as energy biomass. Yields of energy of other plants are strongly differentiated. For example, McKendry (2002) [23] found energy yields of wheat (123 GJ ha^{-1} yr^{-1}) and switchgrass (139 GJ ha^{-1} yr^{-1}) to be lower than the energy yields of tobacco estimated in the present study. Moreover, the author found that willow (187–280 GJ ha^{-1} yr^{-1}) and poplar (173–259 GJ ha^{-1} yr^{-1}) yields of energy are at a similar level as the tobacco energy yields presented in this study, while miscanthus energy yields can outperform other crops (222–555 GJ ha^{-1} yr^{-1}). Jurekova et al. (2015) [25] found miscanthus and maize energy yields to be at a similar level (186–486 GJ ha^{-1} yr^{-1} and 142–545 GJ ha^{-1} yr^{-1}, respectively). According to Prade et al. (2011) [24], energy yields of industrial hemp can reach up to 246–296 GJ ha^{-1} yr^{-1} (Table 4). Stolarski et al. (2020) [30] found poplar's energy yield (cultivated in Poland) to be able to reach up to 230 GJ ha^{-1} yr^{-1} for the best-performing clones while the average energy yield for all genotypes and rotations of poplar was at a level of 115 GJ ha^{-1} yr^{-1}. This is lower than the energy yields for Virginia A and Virginia B presented in this study.

3.2. Methane Potential of Tobacco Silage

According to Weiland (2010) [34], methane yield of different plant substrates is strongly affected by the chemical composition of the crop. Generally, the methane potential of plants is lower in older plants, which are strongly lignified, which causes slower anaerobic decomposition of a substrate. Biogas production from different agricultural substrates can vary from 231 Nm^{3}CH$_4$ t^{-1} VS (volatile solids) for sunflower to 400 Nm^{3}CH$_4$ t^{-1} DMO (organic dry matter) for sugar and fodder beet (Table 5).

Table 5. Gross crop yield (fresh) and methane potential of different crops.

Crop	Crop yield (t FM ha^{-1})	Nm^3 CH$_4$ t^{-1} VS (MIN)	Nm^3 CH$_4$ t^{-1} VS (MAX)
Tobacco [1]	35–62	220	298
Maize [1]	36	346	437
Corn-cob-mix (CCM) [2]	10–15	350	360
Fodder beet [2]	80–120	398	424
Grass [2]	22–31	286	324
Maize [2]	40–60	291	338
Red clover [2]	17–25	297	347
Rye grain [2]	4–7	297	413
Sorghum [2]	40–80	286	319
Sugar beet [2]	40–70	387	408
Sunflower [2]	31–42	231	297
Triticale [2]	28–33	319	335
Wheat [2]	30–50	351	378
Wheat grain [2]	6–10	371	398

Sources: [1] own study, [2] Weiland (2010) [34].

Some authors have cultivated energy crops in similar conditions as those presented in this study. Matyka and Księżak (2013) [19] cultivated canary grass (*Phalaris arundinacea* L.) in the same experimental farm that cultivated the Virginia C and Burley tobacco presented in this study. Authors reported that ensiled canary grass can produce up to 273 Nm^{3}CH$_4$ t^{-1} VS. Kacprzak et al. (2012) [35] reported that, on average, 389 Nm^{3}CH$_4$ t^{-1} VS can be produced from ensiled sorghum, while maize silage can produce 566 Nm^{3}CH$_4$ t^{-1} VS. Kacprzak et al. (2013) [35] also tested canary grass and maize cultivated in the Osiny Experimental Farm for its biogas potential. They found that ensiled canary grass produced, on average, 187 Nm^3 t^{-1} DM (dry matter) of CH$_4$ while maize silage produced 208 Nm^3 t^{-1} DM of CH$_4$. Oleszek et al. (2014) [36] found that biogas yield from canary grass, also cultivated in the Osiny Experimental Farm, can reach up to 406 Nm^3 t^{-1} VS. This shows how varied are the outputs of studies on methane potential of different crops. In contrast, the tobacco silage tested in this study seems to be a rather poor substrate for methane production. Methane potential for tested tobacco varied between 220 to 298 Nm^{3}CH$_4$ t^{-1} VS (248 Nm^{3}CH$_4$ t^{-1} VS on average) (Table 3), and was lower than the methane potential of maize, which was tested during the same analysis as tobacco silage (Figures 1 and 2). Li et al. (2019) [37] tested four varieties of tobacco stalks for their methane potential and found that they can reach up to 132 Nm^3CH_4 t^{-1}, which is less than half of the maximum methane potential of tobacco shown in the present study. The differences are probably due to the substrate; while Li et al. tested only tobacco stems (which are strongly lignified), the present study shows the methane potential of the whole tobacco plant. According to Weiland (2010) [34], the optimal dry matter contents of plant substrates for ensilage should be 25% to 35%. The general quality of silage made of a substrate of TS (total solids) content below 25% can be poor and has high leachate formation, which results in slow fermentation and low methane yields. It is possible that tobacco harvested earlier, when plants are less lignified, would have better methane potential, but this still needs to be tested. The production of methane (Nm^3 CH_4·t^{-1} VS) from tobacco was at a level of 65% of what can be produced from maize (methane potential of maize was tested in the same conditions and at the same time as methane potential of tobacco,) (Table 5, Figure 2). Moreover, the calculated average yield of methane per hectare of tobacco (2847 Nm^3 ha^{-1} yr^{-1} (Tabel 3)) was only half of calculated annual yields of methane of maize (5900 Nm^3 $ha^{-1}yr^{-1}$, not showed in a table). Daily methane production from tobacco was as intensive, or even more rapid, as methane production from maize in the first four days of production. In the following days, methane potential of tobacco declined rapidly, while the decrease in methane production from maize was slower (Figure 1). Low methane production potential of tobacco, comparable to sunflower methane production in Weiland's (2010) [34] study, probably was due to a rather low dry matter content of the tobacco substrate. Moreover, the tobacco plants of the present study at the time of harvesting (October) were in large part lignified, which probably resulted in slow anaerobic decomposition of silage. This might also explain why methane production from tobacco was less efficient (compared to maize) especially at the later stages of methane production (Figure 1). Tobacco can contain more than a dozen (up to 20%) carbohydrates [38,39]. Probably, as a large part of those carbohydrates are easily digestible simple soluble sugars, the methane fermentation process of tobacco was most efficient at the initial stage of fermentation. With the depletion of simple substances, fermentation slowed down significantly (Figure 1).

Tobacco samples in the present study were taken from plantations cultivated as typical production plantations (leaves as main yield), with low plant density (20,000–23,000 plants per hectare). Tobacco, however, probably could be a higher biomass yielder, especially when cultivated for energy purposes in more dense stands (according to Sheen (1983) [28] even up to 670,000 plants per hectare). Moreover, tobacco plants have high biomass growth with increased nitrogen fertilization. This is, however, linked with deterioration of leaves' quality for the industry and thus use of N fertilizers on production plantations of tobacco is usually low. Tobacco plants often create additional stems, which are unwanted by farmers as they result in lower yield and quality of leaves. This natural ability of tobacco to create extra stems could, however, be useful when cultivating tobacco for energy purposes. This process could also be stimulated by cutting in early growth phases (according to authors' observations, tobacco plants can easily regrow when the main stem is cut off; side shoots in such conditions appear in large numbers and easily grow on the plant). Tobacco in the present study was cultivated in soils of different quality (Table 2), but even in the soil of the poorest quality (Virginia A), yields of biomass were acceptable (Table 3). While tobacco is cultivated on production plantations as an annual plant (planted as seedlings each year) it is actually a perennial plant that can regrow (from stem and/or roots) after being cut down. It cannot be excluded that other species of tobacco could be cultivated as perennials, or even mowed (harvested) 2–3 times per year in moderate climate conditions.

The profitability and risks (lack of established knowledge) linked with production of tobacco entirely for energy purposes compared to production of leaves for the industry would probably be an issue for Polish farmers. Economic efficiency of tobacco cultivation is often at a significantly higher level than economic efficiency of energy crops. According to Stolarski et al. (2014) [31], the direct surplus of the plantation of willow in Poland can reach up to 1860 PLN ha^{-1} $year^{-1}$, while the direct surplus of tobacco production is at a level of 10,000–20,000 PLN ha^{-1} $year^{-1}$ (assuming the 100% share of labor in cultivation and harvesting of tobacco). Currently, due to the ending of support for tobacco cultivation (subsidies), the expected economic efficiency will drop significantly. It is therefore highly probable that in the coming years, due to the decline in tobacco production profitability, a transition from cultivation of tobacco for leaves to energy purposes would become more attractive for farmers. Tobacco cultivation requires up to 4000 man-hours per hectare [40]. A multi-stage collection of leaves and their preparation for drying consumes most of this time. In the case of production for energy purposes, a large part of this work could be saved and allocated elsewhere on the farm.

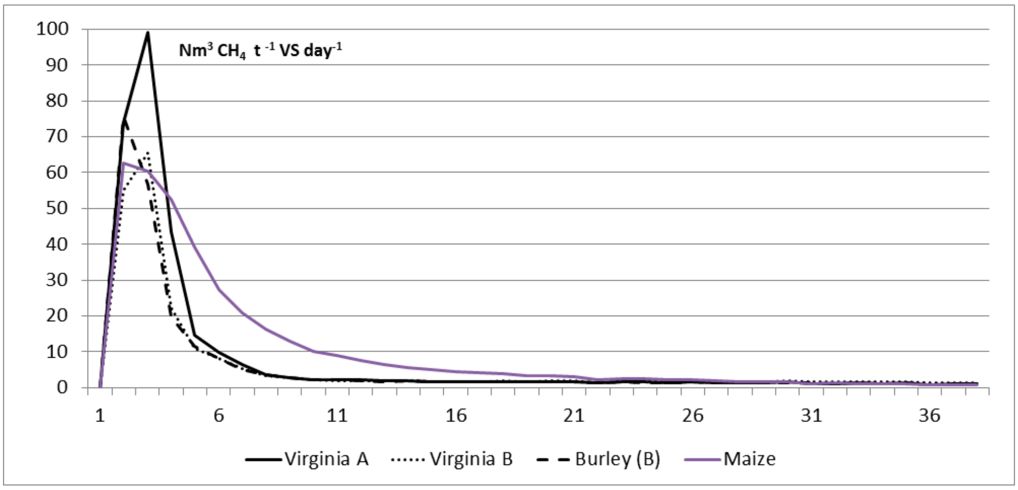

Figure 1. Daily rate of methane production from different substrates.

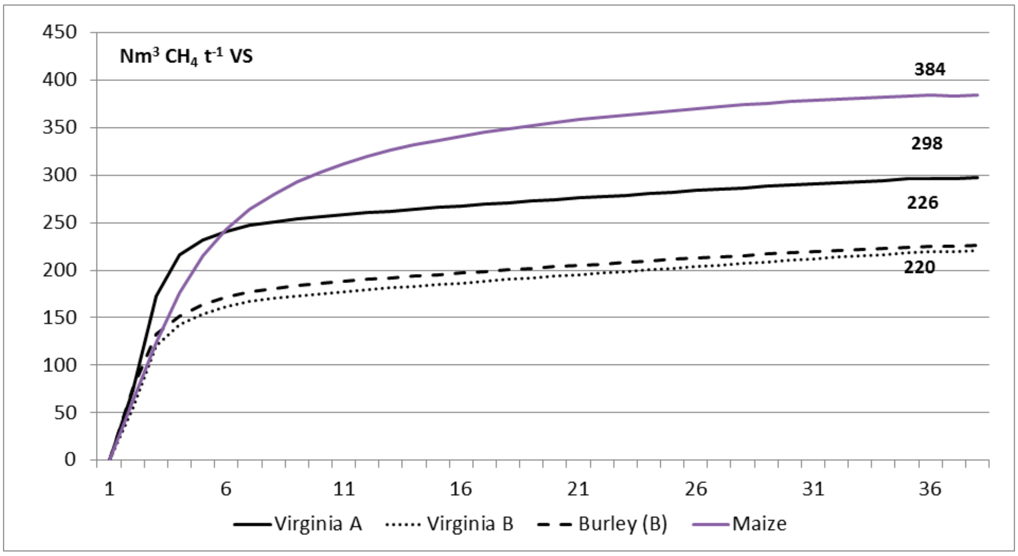

Figure 2. Methane potential from different tobacco plantations and from maize.

The present pilot study covered just one year of vegetation. It is expected that different years with different weather conditions would affect the results to a greater or lesser extent. Nevertheless, this study showed that tobacco biomass can match the energy potential of other commercial energy crops. Residues (or damaged plants) of tobacco can be a valuable source of energy that could be used directly on farms (e.g., as pellet biomass). Moreover, it seems that with the right choice of varieties and species of tobacco and the adjustment of its management (planting density, harvest cycles) it would be possible to cultivate this species for energy purposes. Therefore, further studies to choose *Nicotiana* species and varieties most suitable for energy production as well as to assess the cost-effectiveness of tobacco biomass production are needed.

4. Conclusions

The present study shows that tobacco biomass and energy yields can match other commercial energy crops in Poland. Its energy yields varied between 160 and 273 GJ ha^{-1} yr^{-1}, which is comparable to poplar and willow energy yields. Tobacco, however, could be a valuable biomass energy crop, especially when cultivated deliberately to obtain biomass. This study showed that tobacco can be cultivated on soils of poor quality and high yields can be still maintained. The tested tobacco (harvested in October) seemed to be a rather poor source of substrate for biogas production, which was probably due to harvesting time and the high lignification rate of tobacco tissues. Yield of methane per hectare of tobacco was 2847 Nm^3 ha^{-1} yr^{-1}.

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