

Article

Analysis of the Energy Efficiency of Production of Winter Rapeseed Fertilized with Biogas Digestate

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Abstract

The research hypothesis of this study assumes that nitrogen (N) from digestate has an equivalent productive effect as mineral fertilizer. Therefore, the use of digestate as a N carrier by farmers significantly reduces the energy costs of oilseed rape production. This hypothesis was verified in field experiments with rapeseed conducted in the 2015/2016, 2016/2017, and 2017/2018 growing seasons. The experiment consisted of three N fertilization systems (FSs)—mineral ammonium nitrate (AN) (AN-FS), digestate-based (D-FS), and $\frac{2}{3}$ digestate + $\frac{1}{3}$ AN (DAN-FS)—and five N_t doses: 0, 80, 120, 160, and 240 kg N ha⁻¹. Maximum seed yields were 3.26, 3.32 and 3.66 t ha⁻¹ and were obtained for optimal N doses of 170, 186 and 189 kgNn ha⁻¹, respectively. Similar trends were observed for the following yields: straw, crude oil, and cake. The values of the Nitrogen Fertilization Replacement Value for the above yield categories slightly exceeded 100%, and for the mixed variant, they were in the range of 108–112% in relation to the mixture with ammonium nitrate. The contribution of straw, oil, and oilcake in the total energy harvested accounted for 64%, 22%, and 14%, respectively. The most favorable energy efficiency ratio, $E_e = 8.15$ (seeds + straw), was achieved under the mixed N fertilization variant (DAN-FS; 8.3 and 15.6 m³ ha⁻¹, respectively) and N fertilizer doses of 40 and 80 kg ha⁻¹. For the highest nitrogen doses, the digestate significantly stabilized the yields and energy output of winter rapeseed production. Overall, based on the results of the field experiment and calculations conducted, it is recommended that winter rapeseed biomass should be used entirely for liquid fuel (oil) and solid fuel (oilcake and/or straw) production.

Keywords: digestate nitrogen; fertilizer nitrogen; mixed fertilization system; energy yield; seeds; straw; oil; oilcake

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1. Introduction

The need to derive energy from alternative sources—such as wind, water, or biomass—stems, among other reasons, from the increasing depletion of fossil fuel reserves. First-generation biofuels (biodiesel, bioethanol) and gaseous fuels (methane) continue to represent the primary renewable energy sources. They are produced from food raw materials via transesterification or fermentation [1,2]. Biodiesel is an alternative fuel to conventional diesel oil. It can be produced from edible vegetable oils (soybean, rapeseed,

sunflower, false flax, palm, cottonseed) or non-edible oils (castor, neem, jatropha), as well as tall oil or waste engine oils and waste frying oils, when appropriately pre-treated [3,4].

By adopting the Renewable Energy Directive [2009/28/EC] and establishing a target of 10% renewable energy in the transport sector by 2020, the European Union laid the foundation for the expansion of the liquid biofuels market across its Member States [5,6]. According to OECD projections, the contribution of biofuels in the global transport sector is estimated to reach 15–23% by 2050 [2]. Various analyses and estimates have predicted that after the introduction of the EU-RED Directive, the EU Member States would become net importers of biodiesel and bioethanol [7]. In 2021, Poland implemented a strategic document “Energy Policy of Poland until 2040” (PEP40), defining the avenues for the development of the fuel and energy sectors. The strategy emphasizes the need to expand renewable energy sources (RES) and nuclear energy and to improve energy efficiency and air quality. PEP40 anticipates maximizing the use of conventional biocomponents produced from food and feed raw materials and implementing E10 and B10 fuels, i.e., gasoline and diesel containing 10% bio-additives [M.P. 2021 item 264] [8]. According to Chmielewski [9], the current use of biofuels in Poland and national energy policy assumptions indicate that biodiesel and bioethanol may further increase their market share in the upcoming years.

Despite the EU-27 being the largest global producer of this biocomponent, the majority of its Member States are net importers of biodiesel. Poland, along with Germany, the Netherlands, and Spain, reports a positive trade balance, which reflects an efficient utilization of domestic production potential [6,10].

Rapeseed (*Brassica napus* L. ssp. *oleifera* Metzg.) belongs to the Brassicaceae family. In the EU-27, its cultivation area was 6.19 million ha, its seed harvest was 195.85 thousand tons, and the average seed yield was 3.16 ton ha. In the same year in Poland, rapeseed was cultivated on 1.1 million ha, with 37.75 thousand tons of seeds harvested and an average seed yield of 3.24 ton ha [11]. A significant increase in the global demand for rapeseed is observed due to its importance as a food crop (oil), feed crop (fat-free seed residue), energy crop (oil, fat-free seed residue, straw), and environmentally beneficial crop (post-harvest residues, phyto-biomass in the form of catch crops) [12,13].

The Polish and EU biodiesel markets rely primarily on rapeseed oil methyl esters (RMEs), which account for 90% and 65% of biodiesel production, respectively. The direct use of rapeseed oil as engine fuel is limited due to its high viscosity—around ten times greater compared to petroleum-derived diesel fuel. In recent years, technological advancements and widespread access to oil-pressing and biodiesel-processing equipment have contributed to the increased feasibility of rapeseed-based fuel production [14].

The use of rapeseed for energetic purposes in the EU-27 countries is justified not only by high oil yields per ha (1–2 t ha⁻¹) but also by its producing the most favorable ratios between the energy value of harvested biomass and the energy inputs required for its production. The conversion of oilseed biomass to liquid fuels is considered energy-effective when the energy efficiency ratio of seed production is ≥ 5 (i.e., the energy value of seeds is at least five times greater than the energy inputs for production). Under European conditions, such efficiency is attainable only in winter rapeseed cultivation, using appropriately planned and implemented production technology [15]. It is also noteworthy that defatted biomass (oilcake and straw) can be used for energetic purposes and converted into solid fuels [13,16]. When both seeds and straw are considered for energy production, the energy efficiency of winter rapeseed cultivation can reach 11–12 [3,4].

Effective rapeseed production, specifically winter rapeseed production, in the Northern Hemisphere requires not only fertile soil and appropriate pH but also ration-

ally determined nitrogen rates [17,18]. Plant growth during the spring part of the growing season is very dynamic. During the formation of crop structure components, from the rosette stage to flowering, the plant doubles the nitrogen mass in its biomass [19–21]. The nutrients must also be available post-flowering, when the seed yield is being formed [22]. The selection of a nitrogen carrier for winter rapeseed, as well as the timing, requires knowledge not only of the fertilizer chemical composition but also of the processes that determine the availability of the nutrient in an amount that can stimulate plant growth. For this reason, nitrogen fertilization must be applied early enough, using fertilizers containing readily available forms, such as mineral nitrogen fertilizers [19,23].

Biogas production generates a by-product called digestate, i.e., a suspension (pulp) of partially decomposed organic matter [24,25]. A typical 1 MW biogas plant generates approximately 20,000 m³ of digestate annually [24,25]. As reported by the National Support Centre for Agriculture (KOWR), 160 agricultural biogas plants were registered in Poland in 2025 [26].

Originally, maize silage and organic fertilizers (primarily livestock manure) were the main substrates for biogas production; however, due to their high costs and limited availability, producers have increased the use of agricultural by-products and agri-food industry waste (fruit and vegetable waste, distillery stillage, whey, etc.) [24]. As a result, the composition and physicochemical properties of the digestate vary depending on the type and origin of the substrates used for biogas production as well as the fermentation technologies applied [27]. Digestate typically accounts for 85–95% of substrate mass [28] and contains primarily unfermented organic matter residue, mineral components (with contents comparable to those found in substrates), and methanogenic bacteria biomass. It resembles slurry in composition [24,28,29], being an aqueous suspension containing 2–5% of dry matter and having a pH of ~7. Its liquid phase contains both mineral and organic compounds. In addition, digestate bulk contains 2–3% of the total nitrogen in fresh mass, with up to 85% of organic nitrogen present as ammonium nitrogen due to intensive ammonification during anaerobic fermentation. These values may, however, substantially decrease because increased pH and temperature likely trigger ammonia release from the solution [30,31]. Digestate is also rich in micronutrients such as iron, copper, manganese, and zinc, whose concentrations are only negligibly lower compared to those of substrates intended for fermentation [32]. Its characteristics additionally make it a viable source of organic matter indispensable for the proper functioning of the soil environment, whereas its mineralized elements, macroelements, and microelements, which are readily available to plants, make it a perfect substitute for fertilizers [33–38]. Digestate can be distributed directly on the field or treated to separate solid bodies from the liquid [14].

In terms of its speed of action (nutrient uptake by plants), it is similar to mineral fertilizers, as the N, P, and K nutrients are readily available to plants. Digestate also contains an organic matter fraction which positively affects the physicochemical properties of fertilized soils [33,34,36]. The application of unprocessed digestate does not involve any additional costs [39]. The use of digestate as an alternative or supplement to inorganic fertilizers remains controversial, as some studies suggest that its use may have potential negative effects, including increased nitrate leaching, impacts on substrate permeability, and a negative impact on seed germination. Furthermore, digestate produced from sewage sludge may contain traces of human hormones and heavy metals, which can accumulate in plants. The environmental risk potential following the application of anaerobic digestates depends on factors such as fertilization strategies, soil texture, topography, precipitation, and cropping systems. Other important factors include the properties of the digestate and the application rates [40].

The effects of digestate fertilizing on the composition and quality of wheat (*Triticum aestivum* L.) grain; soy (*Glycine max* (L.) Merr) yields; bean (*Phaseolus vulgaris* L.) composition yields of various grasses, i.e., perennial ryegrass (*Lolium perenne* L.), creeping red fescue (*Festuca rubra* subsp. *rubra*), corn (*Zea mays* L.) yield and plant height, sorghum (*Sorghum* Moench) plant height, and switchgrass (*Panicum virgatum* L.) yield; mineral composition and soil properties; and other annual species cultivated to obtain biomass for energy production have also been studied [40,41].

While crop production is a source of greenhouse gas (GHG) emissions, applying digestate as a fertilizer may decrease these emissions [42,43] by modifying cultivation practices or reducing reliance on mineral nitrogen fertilizers [1]. Although lower nitrogen inputs may result in reduced seed yields, they remain suitable for grain destined for non-food uses, including oil production [4].

An important aspect of biofuel assessment, besides costs, is energy efficiency analysis, which quantifies the energy inputs required to produce a unit of biofuel. Its advantage is independence from fluctuating prices, which enables comparison of production results [1,3,4]. Kratzeisen et al. [44] and Đurđević et al. [45] studied the combustion properties of dried digestate for energy generation and found that digestate has heating values between 13 and 16 MJ/kg, which is comparable to wood. Taking that the latent heat of the vaporization of water is 2.4 MJ/kg, the heating value of digestate would be between 9.5 and 11.4 MJ/kg for moisture contents of 60% and 40%, respectively [45].

The literature indicates that digestate is generally highly suitable for soil fertilization and poses no toxicological risks, and its impact on fertilization and yield depends on the applied dose and digestate properties, which vary significantly between individual biogas plants. However, the studies mentioned are primarily short-term projects, largely pot experiments conducted under controlled conditions. Few studies address the issue of fertilizing winter rapeseed with digestate. We found no studies examining the effect of digestate on the energy intensity of winter rapeseed production.

The research hypothesis assumes that winter rapeseed production under low and medium N fertilization levels (60, 120, 180 kg ha⁻¹) and medium-to-high digestate rates (15.6 and 24.9 m³ ha⁻¹) may result in a higher energy efficiency of oil and oilcake production compared to technology entailing high rates of both nitrogen (240 kg/ha) and digestate (33.2 m³ ha⁻¹), due to reduced energy inputs for seed production and a higher seed oil content achieved. Therefore, this study aimed to compare the effects of differentiated nitrogen rates with and without digestate application on the energy efficiency of the production of winter rapeseed seeds, oil, straw, and oilcake.

2. Materials and Methods

The energy intensity of winter rapeseed (*Brassica napus* L.) production was calculated based on data from a field experiment conducted during three growing seasons—2015/2016, 2016/2017, and 2017/2018—on a farm in Baniewice (53°05' N; 14°36' E), Banie Commune, West Pomeranian Voivodeship, Poland. The field experiment was established on loamy sand in the topsoil over loamy sand in the subsoil, classified as Albic Luvisol. The soil pH was slightly acidic in the first growing season and neutral in the subsequent two seasons (Table S1). The contents of available phosphorus and potassium in the 0–30 cm soil layer were high, while magnesium content was moderate [32].

Soil samples were collected from three soil depths, 0–0.3, 0.3–0.6, and 0.6–0.9 m, before winter rape sowing. The soil contents of NH₄-N and NO₃-N were determined in field-fresh (not air-dried) soil samples within 24 h of sampling. The total content of inorganic nitrogen (N_{in}) was expressed in kg ha⁻¹. The N_{min} content in a given soil layer was calculated using indices constructed based on the soil textural class and soil bulk density. Soil pH was measured in a 1 M KCl solution (soil/solution ratio of 1:2.5; m/v). The con-

tents of plant-available nutrients, including P, K, Mg, and Ca, were determined using the Mehlich 3 method. The P concentration in the extract was determined colorimetrically using the molybdenum blue method. The concentration of K in the collected extracts was determined using flame photometry, and those of Mg and Ca were determined using flame AAS [32].

The local climate in the study area is transitional between Atlantic and continental. During all analyzed seasons, mean air temperatures during winter rapeseed vegetation were higher than long-term averages. In the 2015/2016 and 2016/2017 growing seasons, autumn air temperatures were highly favorable. In the 2017/2018 season, weather conditions deteriorated in February during crop regrowth. Precipitation recorded from January to July was 332 mm in 2016, 622 mm in 2017 (including 237 mm in July), and only 281 mm in 2017/2018. In the growing seasons of 2016, 2017, and 2018, precipitation totals in May and June were 91.3 mm, 162.7 mm, and 46.7 mm, respectively [32].

The field experiment was arranged in a two-factor design and was set up in a randomized block design with four replications. Experimental variants were randomly assigned separately within each block. The first factor was the fertilization system (FS), i.e., (I) ammonium nitrate 34-0-0 (AN-FS), (II) digestate-based fertilization (D-FS), and (III) mixed system—2/3 digestate + 1/3 AN (DAN-FS). The second factor was nitrogen rate (N): 0 (absolute control), 60, 120, 180, and 240 kg ha⁻¹. Raw digestate was sourced directly from a biogas plant. Each year, the digestate was applied in late November and ammonium nitrate (AN) in the first week of March of the following year. The digestate tested in the study came from Goodvalley Agro S.A., located in Bara (Nawodna) in the West Pomeranian Voivodeship, Poland. The digestate consisted of a mixture of: corn silage 25%, crop waste (wheat, triticale, rye, rapeseed and soybean) 15%, and pig slurry 60%. The digestate met the standard requirements for organic fertilizer. The digestate in the years of the study had a pH in the range of 7.2–7.5. Digestate composition was as follows (kg m⁻³): dry matter (DM)—72; total N—7.2; NH₄-N—3.7; P₂O₅—2.85; K₂O—5.45; Ca—0.32; Mg—1.13; and S—1.99. The results of the chemical composition of the digestate are presented in Table S2 (Supplementary Materials). The chemical composition of the digestate was determined in the Laboratory of the Department of Agricultural Chemistry and Environmental Biogeochemistry of the Poznań University of Life Sciences according to the methods adopted by the National Chemical-Agricultural Station. These methods are described in the description of methods for determining chemical properties of soil [32].

Table 1 presents doses of NPK and digestate used in particular study treatments.

Table 1. Nitrogen and basic nutrient doses.

N Dose kg N ha ⁻¹	Digestate Dose m ³ ha ⁻¹	AN-FS		D-FS		DAN-FS					
						² / ₃ D			¹ / ₃ AN		
		P ₂ O ₅	K ₂ O	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
60	8.3	31	45.2	31	45.2	40	20.7	30	20	10.3	15.2
120	15.6	62	90.4	62	90.4	80	41.4	60	40	20.6	30.4
180	24.9	93	135.7	93	135.7	120	62.0	90	60	31	45.7
240	33.2	124	180.8	124	180.8	160	82.8	119	80	41.2	61.8

Phosphorus was applied as single superphosphate (19% P₂O₅) and potassium as 60% potassium salt. Winter barley was the forecrop for winter rapeseed. The hybrid winter rapeseed *Impression Cl* cultivar, characterized by a high yield potential on moderately fertile soils, was used as the test crop. The crop was sown at a sowing rate of 4.0 kg ha⁻¹ (40–45 plants per m²) at the end of August and harvested at the end of July from a plot

area of 12 m². The seeds were harvested when their moisture content reached 8% dry weight.

Table 2 lists agrotechnical measures, plant protection treatments, and digestate/ammonium nitrate application dates. The same procedures were carried out every year; only specific dates varied.

Table 2. Agrotechnical measures on experimental plots (2015/2016 season).

No.	Agrotechnical Measure	Date
1	Fertilization before pre-sowing ploughing: digestate—8 m ³ ha ⁻¹	6 August 2015
2	Pre-sow ploughing	7 August 2015
3	Sowing	25 August 2015
4	Spraying: Cleravis 492.5 SC herbicide—2.0 L ha ⁻¹ + Dash HC adjuvant—1.0 L ha ⁻¹	16 September 2015
5	Spraying: Toprex 375 SC fungicide—0.3 L ha ⁻¹ ; Dursban 480 EC insecticide—0.6 L ha ⁻¹ ; Foliar fertilizers: magnesium sulfate—2.5 kg ha ⁻¹ ; manganese sulfate—5 kg ha ⁻¹ ; Adob Bor—2 L ha ⁻¹ ; RSM 32—30 L ha ⁻¹ ; CCC 720 SL retardant—0.2 L ha ⁻¹	2 October 2015
6	Spraying: foliar fertilizers: Adob Bor—2 L ha ⁻¹ ; Basfoliar—2.2 L ha ⁻¹ ; RSM 32—5.5 L ha ⁻¹ ; magnesium sulfate—2.3 kg ha ⁻¹ ; CCC 720 SL retardant—0.3 L ha ⁻¹	26 October 2015
7	Fertilization: digestate according to study design	20 November 2015
8	Fertilization: ammonium nitrate according to study design	3 March 2016
9	Spraying: Toprex 375 SC retardant—0.3 L ha ⁻¹ ; Dursban 480 EC insecticide—0.6 L ha ⁻¹ ; foliar fertilizer: Adob Bor—2 L ha ⁻¹	2 April 2016
10	Spraying: Pictor 400 SC fungicide—0.5 L ha ⁻¹ ; Proteus 110 OD insecticide—0.5 L ha ⁻¹	4 May 2016
11	Spraying: Biscaya 240 OD insecticide—0.3 L ha ⁻¹	25 May 2016
12	Harvest and transport of seeds and straw	10 August 2016

Seed samples were collected from each plot at harvest maturity (BBCH 89). Seed oil content was determined by near-infrared spectroscopy (NIRS).

2.1. Computation Parameters

Seed and straw yields of winter rapeseed were converted to dry matter yields. The calorific value of 1 kg of seed dry matter was assumed to be 24 MJ kg⁻¹, and that of 1 kg of straw was assumed to be 14 MJ kg⁻¹ [4]. Rapeseed oil calorific value was assumed to be 28.5 MJ kg⁻¹ and that of oilcake as 15 MJ kg⁻¹ [3].

Energy intensity of winter rapeseed production was calculated as the sum of material and energy inputs incurred in the crop yields produced and all energy inputs for subsequent cultivation, care, and protection treatments in individual production technologies. Four energy streams were included in the input calculation—human labor, energy carriers (diesel oil), materials (fertilizers, seed material, plant protection products), and machinery and tools—according to Equation (1) [1,2]:

$$E_I = E_{TR} + E_M + E_T + E_L + E_{ON} + E_N + E_P \quad (1)$$

where E_I (MJ ha⁻¹)—total energy input, E_{TR} —tractors, E_M —machinery, E_T —transport means, E_L —human labor, E_{ON} —fuel, E_N —mineral fertilization, and E_P —pesticides.

The inputs of production means, labor, and traction force incurred for cultivation, sowing, plant protection, and harvesting of winter rapeseed were converted into MJ, where the energy intensity indicators were: man work (human labor)—80 MJ mh⁻¹ (MJ per hour of human labor), nitrogen fertilizers (N)—77 MJ kg⁻¹, phosphorus fertilizers (P₂O₅)—14 MJ kg⁻¹, potassium fertilizers (K₂O)—10 MJ kg⁻¹, winter rapeseed seeds—10 MJ kg⁻¹, plant protection products (in A.S.)—300 MJ kg⁻¹, diesel oil—52 MJ kg⁻¹, wear of tractors and agricultural machinery—112 MJ kg⁻¹, spare parts—80 MJ kg⁻¹, repair materials—30 MJ kg⁻¹, and lubricants—22 MJ kg⁻¹. The energy value of the digestate was

compared to the energy value of the slurry—0.05 MJ dm^{−3} [46–48]. Cumulative unit energy intensity indicators for nitrogen fertilizers are values in [MJ kg^{−1}], which determine the amount of energy (primary, cumulative) required to produce 1 kg of nitrogen fertilizer (e.g., nitrate, urea), taking into account energy from the production process (natural gas, electricity), transport, and raw materials. They are crucial in life cycle analyses (LCAs) in agriculture. These indicators may vary depending on the type of fertilizer, production technology, and country [48].

For all tractors, self-propelled machines, implements, and equipment used in crop production processes, consumption was determined based on the equipment's mass in kilograms and operating time throughout its entire operating period on the farm, which was then converted to megajoules using energy intensity indicators. Spare parts and repair materials were taken into account. The mass of spare parts was assumed to be 30% of the mass consumption of self-propelled machines and agricultural implements, and repair materials constituted 4% of the mass of spare parts [48].

The energy transferred during one hour of use of equipment “*k*” on the farm (*D_k*) was calculated according to the following formula:

$$D_k = \frac{(m_k \times w_c + m_{zk} \times w_z + m_{mmk} \times w_m)}{T_k \times L_k} \text{ (MJ ha}^{-1}\text{)} \quad (2)$$

where

m_k—mass of equipment “*k*” (tractor, self-propelled machine, implement, device) (kg);

w_c—specific energy consumption index of the tractor, self-propelled machine, implement or device (MJ kg^{−1});

m_{zk}—mass of spare parts for equipment “*k*” (kg);

w_z—specific energy consumption index of spare parts (MJ kg^{−1});

m_{mmk}—mass of repair materials for equipment “*k*” (kg);

w_m—specific energy consumption index of repair materials (MJ kg^{−1});

T_k—annual duration of use of equipment “*k*” on the farm (h);

L_k—number of years of use of equipment “*k*” on the farm.

With *D_k*, the energy inputs of investment funds were calculated:

$$E_i = \sum_{k=1}^n \frac{(D_k \times t_k)}{p_k} \text{ (MJ ha}^{-1}\text{)} \quad (3)$$

where

n—total number of tractors, self-propelled machines, tools, and equipment used in crop production;

t_k—time of use of equipment “*k*” in the year in the production of a given crop species (h);

p_k—area under crop cultivation.

Aggregates made using Massey Ferguson 5710 M Dyna-4 tractor (Beauvais, France, 105 HP) with machinery appropriate in terms of mass of working widths were used for energy intensity calculations [49,50] (Table 3). According to MF tractor producer's declaration, fuel consumption was assumed to be 14.9 L cgh^{−1} (liters of fuel per hour of tractor operation) for ploughing and 11.9 L cgh^{−1} for light work.

Energy efficiency was calculated as the ratio of the energy value of seed and straw yields to the energy inputs required for their production, according to Formula (4):

$$Ee = \frac{Psd + Pst}{Nsd + Nst} \quad (4)$$

where P denotes energy value of seed and straw yields per 1 ha (MJ), where the calorific value of 1 kg of seed and straw dry matter is 24 and 14 MJ/kg [4], and N denotes total energy inputs incurred to produce respective yield per 1 ha (MJ).

Table 3. Characteristics of agrotechnical measures and machinery used.

Measures	Aggregate	Machine Mass	Machine Use Within a Period	Labor Input h ha ⁻¹	
		kg	H	Mh	Cnh
Massey Ferguson 5710 Dyna-4 Tractor	-	4300	12,000	-	-
Shallow ploughing	KOS 3.0 B	1650	1500	1.5	1.5
Pre-winter ploughing	U-160/4	600	2000	2.5	2.5
Harrowing	U-212/2	240	1500	0.7	0.7
PK fertilization	N-011	960	1000	0.5	0.5
N fertilization	N-011	960	1000	0.5	0.5
Digestate distribution over field—septic tanker	PN-100/2	3050	1000	1.2	1.2
Seed sowing	S-052	1070	700	0.7	0.7
N fertilization	N-012	960	1000	0.5	0.5
Chemical protection against agrophages (5 treatments)	P-616	365	1000	1.5	1.5
Seed harvest	Z-056	8000	2000	1.2	1.2
Seed transport	T-041	2080	6000	1.0	1.0
Straw pressing	Z224/1	1510	1300	1.2	1.2
Straw transport	T-041	2080	6000	1.2	1.2

Explanations: h ha⁻¹—hour per ha, Mh—man work (human labor) per ha, Cnh—tractor hour per ha.

Rapeseed oil yield (L/ha) was calculated using Formula (5):

$$BP = Eoil \times PZ \quad (5)$$

where $Eoil$ denotes theoretical oil extraction efficiency (L/t) and PZ denotes seed yield (t/ha).

The research results and calculations made enabled determination of energy efficiency of winter rapeseed biomass production, including oil, oilcake, and straw. The energy efficiency of biofuels is most often defined by the EROEI (energy return on energy investment) index [13], which expresses the ratio of energy contained in a unit of biofuel to the non-renewable energy required to produce it (6):

$$R_E = \frac{E_{OUT}}{E_{IN}} \quad (6)$$

where R_E —efficiency index (dimensionless), E_{OUT} —energy in biofuel (oil + oilcake + straw), and E_{IN} —non-renewable energy required to produce the biofuel.

2.2. Calculation Procedures

1. Regression models for yields evaluation

The general pattern of winter rapeseed yield (GY) in response to increasing N doses (N_{fi}) was described by two regression models:

$$1. \text{ Linear: } GY = aN_{fi} + B \quad (7)$$

$$2. \text{ Quadratic: } GY = aN_{fi}^2 + bN_{fi} + C \quad (8)$$

The main estimated parameters of these function are

$$N_{op} = -\frac{b}{2a} \quad (9)$$

$$GY_{max} = c - \frac{b^2}{4a} \quad (10)$$

where

GY—grain yield, t ha⁻¹;

N_{fi}—“i” dose of fertilizer N, kg ha⁻¹;

N_{op}—optimal N rate, kg ha⁻¹;

GY_{max}—maximum GY for the N_{op}, t ha⁻¹;

A, B, C, a, b, c—constants of the respective regression model.

2. Nitrogen Fertilization Replacement Value—NFRV

For Y_{max} for given yield category of rapeseed, NFRV values were calculated using the equation below:

$$NFRV = \frac{Y_{maxi}}{Y_{maxAN}} \times 100 (\%) \quad (11)$$

where

Y_{maxi}—maximum yield for a given yield trait for digestate and an AN and digestate mix variant;

Y_{maxAN}—maximum yield for the AN fertilization variant.

Statistical analysis was conducted via analysis of variance (ANOVA) with the F-Snedecor test, followed by its distribution calculation. Significance of differences was evaluated using Tukey's test ($\alpha = 0.05$ and $\alpha = 0.01$). Excel 7.0 and Statistica 12 (StatSoft Inc., Tulsa, OK, USA, 2013) were used for calculations and statistical processing.

3. Result

Seed and Straw Yield

In the present study, winter rapeseed seed yield depended significantly on digestate application (D-FS) and increasing N rates (AN-FS), as well as on the interaction thereof (DAN-FS) (Figure 1, Table S2). The highest rapeseed seed yield was obtained in the combined digestate and nitrogen (DAN-FS) system (2.978 t ha⁻¹), which was on average 8.54% higher than that observed in the other combinations. When varying N fertilization rates (AN-FS) were used, the highest winter rapeseed seed yield was obtained with 180 kg N ha⁻¹ (2.308 t ha⁻¹) and was 51.57% higher than the control (without nitrogen). A significant interaction was demonstrated when combining the study factors. In this case, the most favorable rapeseed yield (3.308 t ha⁻¹) was obtained by combining the DAN-FS system with a nitrogen dose of 180 kg ha⁻¹. The least favorable results were obtained in each fertilization system (FS) in combination with the control variant and the lowest N dose—60 kg N ha⁻¹—where the yield was on average 2.21 t ha⁻¹ and was 33.19% less in relation to the most favorable variant. An equally high seed yield was produced in the 2015/16 and 2016/17 growing seasons. In 2017/18, the seed yield was lower (by 39.4% on average), due to low temperatures recorded in February 2018, when rapeseed was regrowing, and low precipitation in May and June, i.e., in the period of flowering and silique formation.

The straw yield in the experiment also depended significantly on rapeseed fertilization with the digestate (D-FS) and progressive nitrogen rates (AN-FS), as well as on the

interaction of both experimental factors (DAN-FS) (Figure 1, Table S2). The highest rapeseed straw yield was obtained in the combined digestate and nitrogen (DAN-FS) system (7.80 t ha^{-1}), which was on average 6.28% higher than that observed in the other combinations. When varying N fertilization rates (AN-FS) were used, the highest winter rapeseed straw yield was obtained after applying 180 kg N ha^{-1} (8545 t ha^{-1}) and was 55.44% higher than that observed in the control (without nitrogen). A significant interaction was demonstrated when combining the study factors. In this case, the most favorable rapeseed straw yield (9206 t ha^{-1}) was obtained by combining the DAN-FS system with a nitrogen dose of 240 kg ha^{-1} . The least favorable results were obtained in each fertilization system (FS) combined with the control, where the yield averaged 4737 t ha^{-1} , which was 51.50% less than that observed in the most favorable variant. Similarly to seed yield, the straw yield produced in 2017/18 was the lowest, by 46.1% on average, which stemmed from unfavorable temperatures in February and low precipitation in May and June.

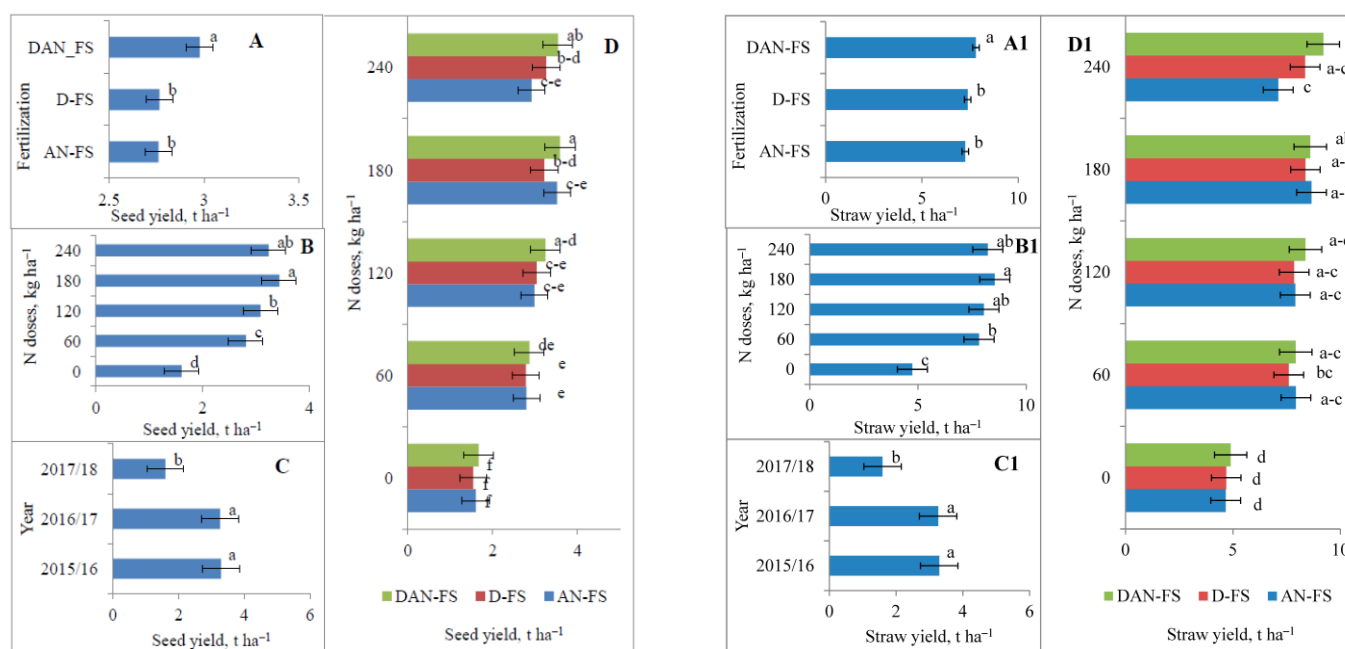


Figure 1. Seed yield (left) and straw yield (right) in response to nitrogen fertilization systems. Bars with the same letters indicate a lack of significant differences between experimental treatments using Tukey's test; the vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS × N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

The oil content of the rapeseed seeds was stable and averaged 44.7% (Table S2). However, the highest winter rapeseed oil yield was obtained in the combined digestate and nitrogen (DAN-FS) system (1322 t ha^{-1}), which was on average 8.81% higher than that observed in the other combinations. When varying N fertilization rates were used (AN-FS), the highest oil yield was obtained with 180 kg N ha^{-1} (1464 t ha^{-1}) and was 51.57% higher than that observed for the control (without nitrogen). A significant interaction was demonstrated when combining the study factors. In this case, the most favorable rapeseed yield (1602 t ha^{-1}) was obtained by combining the DAN-FS system with a nitrogen rate of 180 kg ha^{-1} . The least favorable results were obtained in each fertiliza-

tion system (FS) combined with the control, where the oil yield averaged 0.709 t ha^{-1} , which was 55.76% lower than that observed in the most favorable variant. As in the case of seed yield, the oil yield noted in 2017/18 was also the lowest (by 37.9% on average), due to unfavorable weather conditions in this growing season.

The oilcake yield in the experiment depended significantly on digestate fertilization (D-FS) and progressive nitrogen doses (AN-FS), as well as on the interaction of both these experimental factors (DAN-FS) (Figure 2, Table S2). The highest winter rapeseed oilcake yield was obtained in the combined digestate and nitrogen (DAN-FS) system (1656 t ha^{-1}) and was on average 17.20% higher than that observed in the other combinations. When varying N fertilization rates (AN-FS) were used, the highest oilcake yield was obtained after applying 180 kg N ha^{-1} (1845 t ha^{-1}) and was 54.53% higher than that observed for the control (without nitrogen). A significant interaction was demonstrated when combining the study factors. In this case, the most favorable cake yield (on average 1867 t ha^{-1}) was obtained by combining the AN-FS and DAN-FS systems with a nitrogen dose of 180 kg ha^{-1} . The least favorable results were obtained in each fertilization system (FS) in combination with the control variant, where the cake yield was on average 0.893 t ha^{-1} and was 52.15% less than that observed in the most favorable variant. As in the case of seed yield, the oilcake yield in 2017/18 was the lowest (by 38.9% on average) due to unfavorable air temperatures in February and low atmospheric precipitation recorded in May and June.

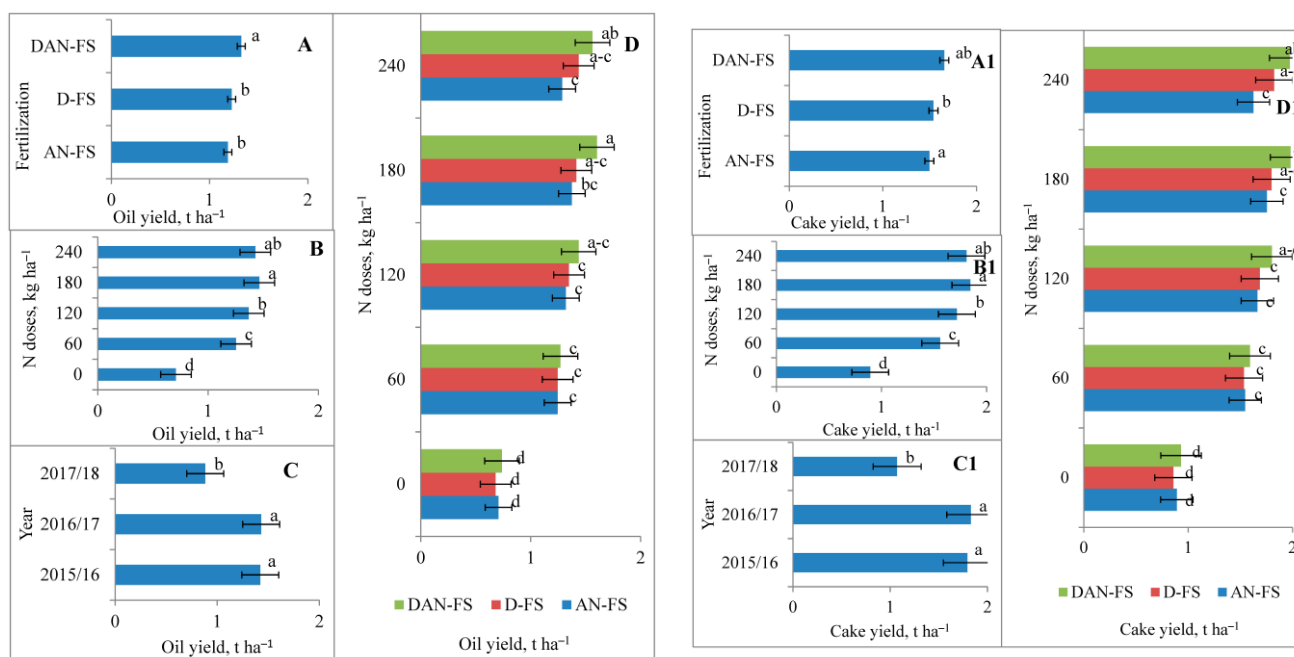


Figure 2. Oil yield (left) and oilcake yield (right) in response to nitrogen fertilization systems. Bars with the same letters indicate a lack of significant differences between experimental treatments using Tukey's test; the vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS × N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

Figures 3 and 4 and Table S3 present the energy values of seeds, straw, oilcake, and oil. The analysis of the study results showed that these values depended on the product of the yields of these biomass components and the corresponding energy coefficient. It was impossible to statistically determine significant differences in the effect of the inter-

action of experimental factors (DAN-FS) on the energy incurred in rapeseed production. In this case, the calculations were based on the same values for the three years studied. However, it was statistically proven that fertilization with digestate (D-FS) and progressive N rates (AN-FS) significantly differentiated the energy incurred in rapeseed production, which increased progressively with increasing N rates (N_f) and in the treatment with N applied alone (AN-FS). Digestate addition and reduced N rates enabled the decreasing energy intensity of winter rapeseed production.

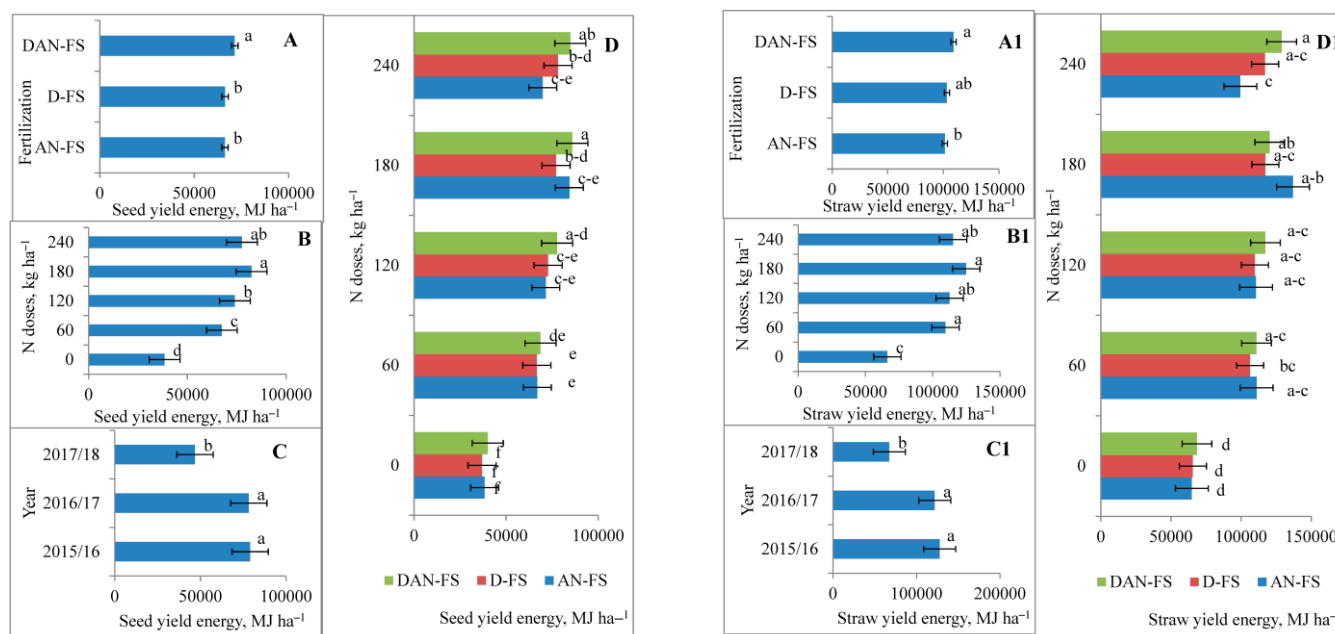


Figure 3. Seed energy yield (left) and straw energy yield (right) in response to nitrogen fertilization systems. Bars with the same letters indicate a lack of significant differences between experimental treatments using Tukey's test; the vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS × N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

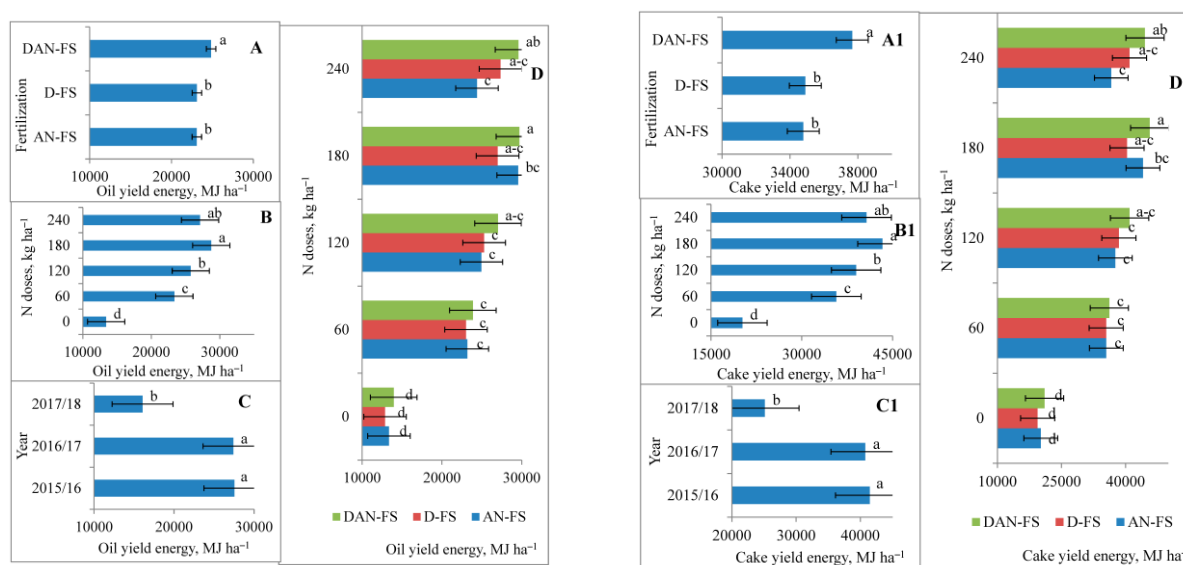


Figure 4. Oil energy yield (left) and cake energy yield (right) in response to nitrogen fertilization systems. Bars with the same letters indicate a lack of significant differences between experimental

treatments using Tukey's test; the vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS $\times$ N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

The highest energy efficiency index (E_e) calculated for the sum of seed and straw yields was obtained in the combined digestate and nitrogen (DAN-FS) system (8.15) and was on average 8.28% higher than that observed in the other combinations. When varying N fertilization rates (AN-FS) were used, the highest energy efficiency index (E_e) was obtained after applying 60 kg N ha⁻¹ (9.97) and was 39.52% higher than that observed for the least favorable variant, i.e., with nitrogen fertilization at a rate of 240 kg ha⁻¹. A significant interaction was demonstrated when combining the study factors. In this case, the most favorable energy efficiency index (E_e) (on average 10.44) was obtained in the variant using only D-FS digestate corresponding to a nitrogen dose of 60 kg ha⁻¹ (this was 5.5 t ha of digestate supplemented with 20 kg N ha⁻¹, 10 kg P₂O₅ ha, and 15 kg K₂O ha⁻¹). The least favorable results were obtained in each fertilization system (FS) in combination with the nitrogen fertilization variant in the amount corresponding to 180 and 240 kg ha⁻¹ (Figure 5, Table S3). The second analyzed energy efficiency indicator is R_e , which is calculated for the total yield of straw, oil, and oilcakes. The highest energy efficiency index (R_e) was obtained in the system of fertilization with digestate only (D-FS) and combined doses of digestate and nitrogen (DAN-FS) (7.75 and 7.40, respectively) and was on average 9.91% higher than that observed in the variant with nitrogen fertilization only (AN-FS). When using differentiated N fertilization rates (AN-FS), the highest energy efficiency index (R_e) was obtained after applying 60 kg N ha⁻¹ (9.50) and was 39.79% higher than that observed for the least favorable variant, i.e., with nitrogen fertilization at a dose of 240 kg ha⁻¹. A significant interaction was demonstrated when combining the study factors. In this case, the most favorable energy efficiency index (R_e) (on average 9.94) was obtained in the variant using D-FS digestate only, corresponding to a nitrogen dose of 60 kg ha⁻¹. The least favorable results were obtained in each fertilization system (FS) in combination with the nitrogen fertilization variant in the amount corresponding to 180 and 240 kg ha⁻¹. The best results were obtained in the 2015/16 and 2016/17 seasons, when favorable meteorological conditions occurred. Straw accounted for 64% of the energy in the biomass, whereas oil and oilcake accounted for 22% and 14%, respectively (Figure S2). In total, the biomass of these three components yielded as much as 163,552 MJ ha⁻¹, which made the average energy efficiency ratio reach $R_E = 7.32$ (Figure 5, Table S3).

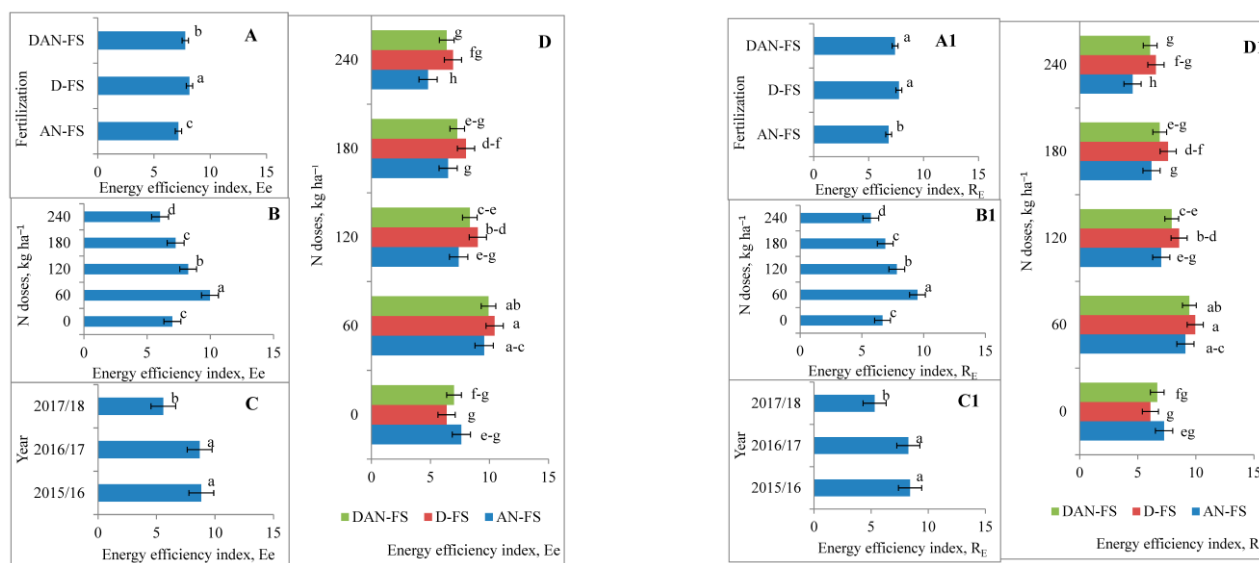


Figure 5. Energy efficiency indices, E_e (left) and R_E (right), in response to nitrogen fertilization systems. Bars with the same letters indicate a lack of significant differences between experimental treatments using Tukey's test; the vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS $\times$ N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

The structure of energy inputs spent on winter rapeseed production included a very high share of direct energy carriers (fuels) (43.31% on average) as well as raw materials and consumables (38.73% on average), with a particularly large contribution of nitrogen fertilizers (45.23% on average in materials and production inputs) (Figure 6, Tables S4–S6). Energy inputs were relatively higher in the treatment with mineral fertilization (NPK) applied alone. Using digestate alone or as an additive to NPK fertilization reduced the energy content of raw materials and production materials. Pesticides and foliar fertilizers were major players in this group, accounting for 36.35% on average of the total energy in production inputs and materials. The largest energy inputs in winter rapeseed cultivation were for soil tillage and plant protection (42.92% on average), followed by harvesting and transport (36.51%) (Figures S3 and S4). Fertilization with digestate using a slurry tanker alone accounted for on average 13.7% of the energy expended on mechanical treatments. Mineral fertilization, on the other hand, required an average of 6.2% of the energy consumed on treatments.

Numerous significant correlations were found in this study (Table 4). Seed, straw, oil, and oilcake yields were highly correlated. The yields of these biomass components were significantly correlated with the energy inputs for their production. Energy efficiency indicators were significantly highly correlated with the above-mentioned traits as well.

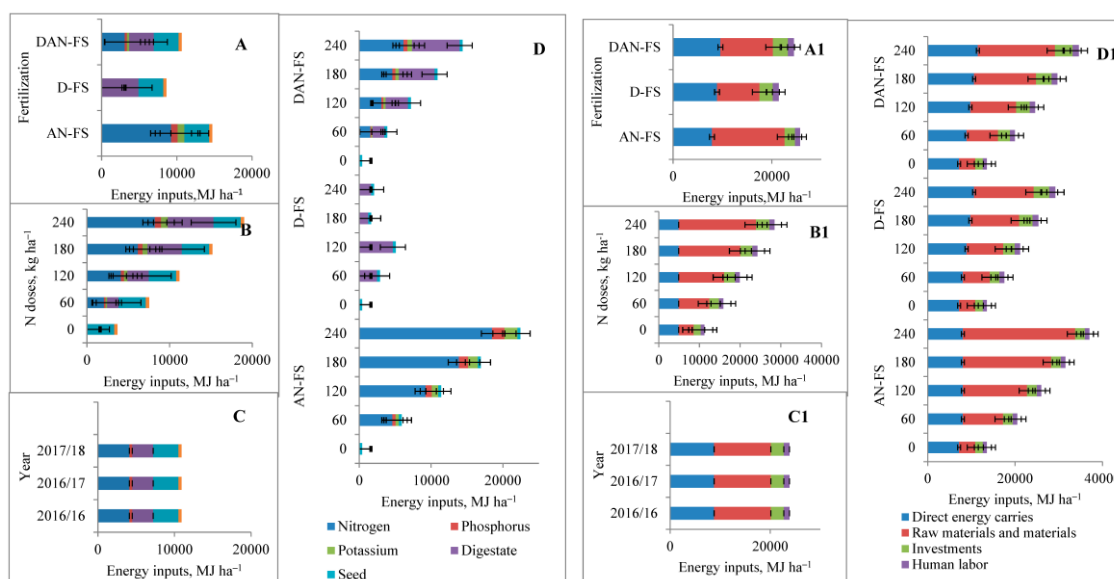


Figure 6. Structure of the energy inputs in the cultivation and raw materials and materials of winter rape. The vertical bar in each column shows the standard error (SE) of the mean for the treatments. Legend: (A,A1)—fertilization systems; (B,B1)—nitrogen doses; (C,C1)—years; (D,D1)—FS × N interaction; AN—AN-FS, nitrogen mineral fertilization system (ammonium nitrate); D—D-FS, digestate-based (N) fertilization system; DAN—DAN-FS, mixed fertilization system consisting of $\frac{2}{3}$ digestate N and $\frac{1}{3}$ ammonium nitrate.

Table 4. Pearson correlation coefficients between the studied features.

Variables (n = 180)	Straw Yield	Oil Yield	Cake Yield	Production of Seed and Straw	Energy Efficiency Index E_e	Energy Efficiency Index R_e
Seed yield	0.95 [†] $p = 0.000$	0.99 $p = 0.000$	0.99 $p = 0.000$	0.43 $p = 0.003$	0.59 $p = 0.003$	0.57 $p = 0.000$
Straw yield	1.000	0.96 $p = 0.000$	0.96 $p = 0.003$	0.34 $p = 0.023$	0.67 $p = 0.003$	0.67 $p = 0.003$
Oil yield		1.000	0.99 $p = 0.000$	0.44 $p = 0.003$	0.58 $p = 0.000$	0.56 $p = 0.000$
Cake yield			1.000	0.44 $p = 0.000$	0.59 $p = 0.000$	0.59 $p = 0.000$
Production of seed and straw				1.000	0.42 $p = 0.004$	0.42 $p = 0.004$

[†] All values represent significant differences ($p \geq 0.05 = 0.146$).

4. Discussion

This paper presents the results of a production, quality, and energy assessment of winter oilseed rape production, assuming an equal production effect of digestate N and mineral fertilizer N. A field experiment conducted with three fertilizer treatments (without digestate, with digestate, and NPK fertilization + digestate from a biogas plant) against five nitrogen rates (from 0 to 240 kg N ha⁻¹) enabled the determination of the yields of winter rapeseed seeds, straw, oil, and oilcake. The energy inputs of biomass components and the energy inputs for rapeseed seed and straw production were calculated as well. These calculations enabled us to compute the energy efficiency ratios, E_e (seed + straw) and R_e (oil + oilcake + straw), which indicate the technological efficiency of winter rapeseed production.

The literature survey conducted in this work and the results obtained from the conducted series of field experiments prove that high yields of winter rapeseed products (seeds, straw, oil, oilcake) can be obtained after ensuring

1. Appropriate field stand (responsible for soil fertility);
2. A sufficiently large dose of nitrogen (ensuring the desired yields of oil, oilcake, and straw and optimal energy intensity in winter rapeseed production);
3. A dose of digestate from a biogas plant appropriately matched to the nitrogen dose, which has a positive effect on the quantity and quality of the crop as well as on the energy efficiency of winter rapeseed production [3,4,15,24,29,32–34,38,43].

4.1. Digestate and Specific Yield Traits of Winter Oilseed Rape

The maximum seed yields of rapeseed, averaged over three growing seasons, were 3.26 t ha⁻¹ for the ammonium nitrate system (AN-FS), 3.32 t ha⁻¹ for the digestate system (D-FS) and 3.66 t ha⁻¹ for the mixed system (DAN-FS). The optimum N doses were 170, 186 and 189 kg N ha⁻¹ (Figure S1). The EU-27 average seed yield in 2023 was 3.16 t ha⁻¹, and in Poland, it was 3.24 t ha⁻¹ [11]. The yield obtained in the conducted experiment was not high, and this was the result of poor wintering conditions for rapeseed and the drastic drought that occurred in 2018. Drought covered the entire spring vegetation of rapeseed. The period from rosette to flowering (BBCH 30 to BBCH 60) is critical for biomass production by plants and the development of yield structure components [21,51]. The decline in this particular growing season affected all studied yield categories. For seeds, it averaged 30%. The $Y_{\max}$ values for the average seed yield in 2016 and 2018 were 3.64 t ha⁻¹ for AN-FS, 3.91 t ha⁻¹ for D-FS and 4.17 t ha⁻¹ for the DAN-FS. The respective N_{op} doses were 150.6, 179.7 and 186.7 kg N ha⁻¹. The seed yields obtained in the AN system were above the average value recorded in Poland in 2003–2013 in field experiments with mineral N and were obtained for an N_{op} of 150 kg N ha⁻¹ [52].

Analysis of the average N_{op} doses for individual crop categories in the studied case showed higher values in the FSs with digestate. For AN, this value was 157.2; for D, it was 183.6; and for DA, it was 198.5 kg N ha⁻¹. The difference between the N_{op} -AN and N_{op} values for the pure digestate systems was associated with increased yield and a greater difference with AN effects. The general scheme of digestate operation is illustrated for the seed field (Figure S5). This figure clearly shows the beneficial effect of N from digestate at high N doses. This beneficial effect of N from digestate confirms the results of a number of field experiments [36,53]. This effect is likely due to two factors. The first is that N forms in the digestate, which contains a highly ammonium nitrogen. The second important characteristic is the narrow C:N ratio, which, in turn, determines the release of N not only from the digestate organic matter but also from native soil organic matter [54–56].

The research hypothesis of the conducted field experiments assumed the same N productivity from digestate as ammonium nitrate (AN). This mineral N carrier is used in Poland as a standard source of this nutrient in winter oilseed rapeseed production [52]. The only mineral N carrier competitive with AN is calcium ammonium nitrate [19,22].

A comparative analysis of the effect of digestate nitrogen versus AN, i.e., the calculation of the Nitrogen Fertilizer Replacement Value (FRV), was determined for five basic winter rapeseed yield indices (Figures S5–S9). The value of this indicator was not calculated as in the commonly used procedure for yields and comparable doses [57]. Simple, averaged calculations were performed for the maximum yields in the tested fertilization system. Such a procedure allows for a realistic assessment of the tested fertilization system, which is, after all, the goal of this type of field study [58]. Table 5 summarizes two cardinal indices defining the maximum yield value ($Y_{\max}$) for the optimal respective N dose (N_{op}).

Table 5. Summary of cardinal indicators of winter oilseed rape yield categories and respective Nitrogen Fertilizer Replacement Values ¹.

Fertilization Systems—FSs	Cardinal Indices, Units	Yield Category				
		Seed SEY	Straw STY	Biomass, TB	Crude Oil COY	Oilcake CAKEY
Ammonium nitrate, AN	N _{op} , kg N ha ^{−1}	169.8	146.5	149.6	164.0	156.3
	Y _{max} , t ha ^{−1}	3.26	8.52	11.76	1.42	1.714
	NFRV, %	100	100	100	100	100
Digestate, D	N _{op} , kg N ha ^{−1}	185.7	181.8	181.3	184.1	185.2
	Y _{max} , t ha ^{−1}	3.32	8.56	11.88	1.47	1.835
	NFRV, %	102	100	101	104	107
Mix	N _{op} , kg N ha ^{−1}	188.7	200.0	196.7	190.0	203.7
² / ₃ D + ¹ / ₃ AN	Y _{max} , t ha ^{−1}	3.66	9.21	12.74	1.59	2.086
DAN	NFRV, %	112	108	108	112	122

¹ The calculations are based on the regression models presented in Figures S5–S9.

The summary of indicators, presented in Table 5, clearly indicates that, regardless of the winter rapeseed yield category under evaluation, N from digestate slightly exceeded the yield-forming effect of N from mineral fertilizer. The largest difference in favor of digestate was noted for oilcake (+7 percentage points). A significantly greater effect, and this for each of the yield categories under assessment, was achieved in the mixed fertilization variant—DAN. For seed and crude oil yields, the NFRV values for this FS exceeded the mineral N action by 12 pps, and for oilcake, as much as 22 pps. The NFRV values for digestate, as research shows, range widely, from approximately 55% to almost 200% [59]. The results obtained in the conducted study exceed 100%, raising the question of the causes. Two aspects of assessing the effect of N from digestate should be considered. The first, observed in experiments with increasing N doses, is an increase in the NFRV value for digestate. In the presented case, an even greater increase was noted for the mixed system, in which digestate constituted ²/₃ of the N source. As can be seen in Figure 7, the curves are linear, but the growth dynamics (slope) for DAN-FS were almost 27% greater compared to D-FS. The obtained linear trend confirms the results observed, documented for natural fertilizers manure and digestate [60]. However, studies on manure have shown that at low doses of N, the index values fall well below 100% [57]. In the case discussed, even at a dose of 60 kg N ha^{−1}, the index values were at the level of 100%, at least. This specific effect was also confirmed for other yield categories in the conducted research, except for straw. The phenomenon obtained can be explained by the increasing input of organic matter into soils with a high concentration of N-NH₄ and a narrow C:N ratio, which accelerates the mineralization and transformation of organic N compounds in the soil. Furthermore, a greater increase was observed in soils with low humus content and slightly acidic soil pH [58,60].

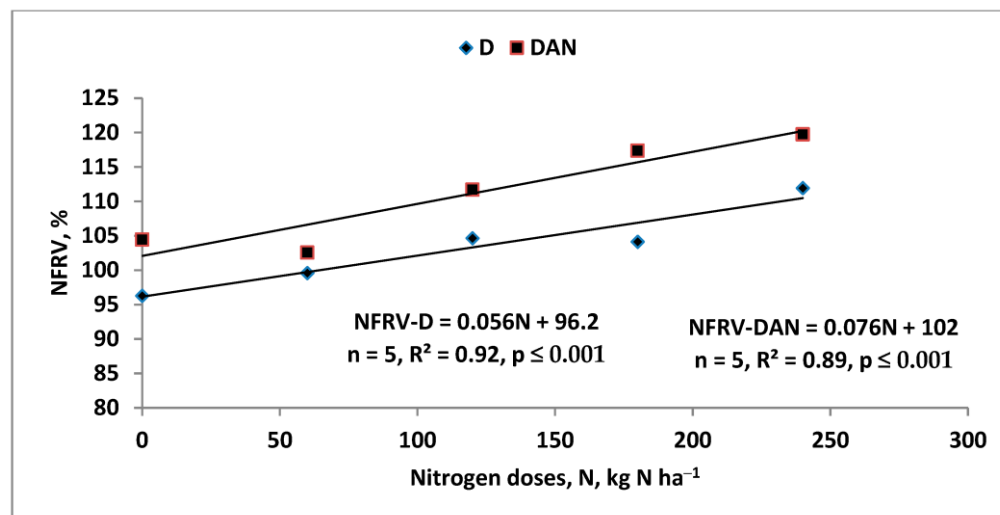


Figure 7. Trends in the indicator Nitrogen Fertilization Replacement Value for two fertilization systems with digestate against the progressing nitrogen doses—assessed for seed yield.

4.2. Digestate and Energetic Balance in Winter Oilseed Production

The results obtained show that the energy value of seeds, straw, oil, and oilcake depended significantly on fertilization with both fertilizer N and biogas digestate (Figures 3 and 4, Table S3). Theoretically, the amount of energy obtained is the product of the yield and the appropriate energy coefficient for a given component (see: Materials and Methods, Section 2). On average, over the three years of this study, the energy value of the seed yield was 68,022 MJ ha⁻¹ (2.71 t ha⁻¹), that of straw reached 105,676 MJ ha⁻¹ (7.43 t ha⁻¹), that of oilcake was 35,788 MJ ha⁻¹ (1.57 t ha⁻¹), and that of oil was 23,678 MJ ha⁻¹ (1.24 t ha⁻¹). Jankowski et al. [4] proved that winter rapeseed, with a seed yield of 5.36 t ha⁻¹, produced the highest amount of effective energy accumulated in oil, which amounted to 55.6 GJ ha⁻¹. In turn, the energy value of straw harvested from 1 ha of winter rapeseed was reported to reach 187.8 GJ [4]. These values are, therefore, comparable to those achieved in the present experiment, where the contribution of straw, oil, and oilcake accounted for 64%, 22%, and 14% of the energy in biomass, respectively. The total biomass of these three components yielded as much as 163,552 MJ ha⁻¹. In the study by Jankowski et al. [4], the share of energy accumulated in winter rapeseed biomass was 60% in straw, 18% in oil and 22% in oilcake. Lohosha et al. [38] claim that an analysis of energy consumption per 1 ha of corn grown for grain in Ukraine shows that the lowest values were observed in the control variant (without fertilizer application)—47.3 GJ ha⁻¹. The highest consumption of total energy of 61.2 GJ ha⁻¹ was observed in the variant where mineral fertilizer at the rate of N₉₀P₉₀K₉₀ and digestate-based bio-organic fertilizer “Efluent” (55.0 t ha⁻¹) were applied in the soil, which exceeded the control in terms of this indicator by 29.4%. A similar situation was observed in the variants with vegetable crops. When the nutrition background increased, energy consumption also grew proportionally. Thus, in the variants of carrot cultivation, the highest energy consumption was observed on the sites where mineral fertilizer was applied in the soil at the rate of N₉₀P₉₀K₉₀ = 70.4 GJ ha⁻¹ and combined with digestate (at the rate of 55.0 t ha⁻¹) = 77.3 GJ ha⁻¹, which was 12.1–18.9 GJ ha⁻¹ more compared to the control (58.3 GJ ha⁻¹). The maximum energy consumption was observed when growing red beet. Thus, in non-fertilized variants, it amounted to 75.7–78.6 GJ ha⁻¹, while an increased nutrition background led to an increase in energy consumption by 9.7–32.0 GJ ha⁻¹, depending on the form and rates of fertilizers. In general, the energy efficiency of the digestate-based bio-organic fertilizer “Efluent” applied directly under corn grown for grain, carrot and red beet is

quite high, because the energy efficiency ratio significantly exceeded the unit, which indicates the energy efficiency of the crop cultivation technology that was studied [38].

The components of a classic economic or energy balance are inputs and outputs. The net balance sheet, as well as the calculated efficiency indicators, allow for the assessment of input efficiency [61]. In this paper, two assumptions related to the use of digestate as a N carrier in rapeseed production are key: (i) reduction in N fertilization costs, (ii) increase in yield(s) as a result of the so-called prolonged action of digestate (Section 4.1).

In the discussed data, the energy inputs for winter rapeseed production amounted to 23,863 MJ ha⁻¹ on average (Figure S1, Table S3). In the structure of energy inputs, the share of direct energy carriers (fuels) was 36.8% on average, and that of raw materials and other consumables was 47.5% on average. The use of N fertilizers alone accounted for 36.2% of the energy contained in the materials and production means (Figure 5, Tables S4–S6). Pesticides and foliar fertilizers also had a large share in this group, averaging 29.1%. Among the cultivation measures, the highest energy inputs were for tillage and plant protection (33.3% on average), followed by harvesting and transport (36.5%). Fertilization with digestate alone, using a slurry tanker, accounted for 13.7% of the energy input on average, while NPK fertilization accounted for 31.12% of the energy incurred for the treatments. Our results fully confirmed the burden of N on rapeseed production, which on average in the AN-FS system accounted for 39% (Figure S4a). In the mixed rapeseed production system (DAN-FS), N fertilization costs decreased to 18% and, compared to D-FS, where the source of nitrogen was digestate, by 6% (Figure S4b,c). Research conducted by Jankowski et al. [4] showed that energy inputs for the production of 1 ha of winter rapeseed amounted to 26.29 GJ and that the most energy-intensive process appeared to be mineral fertilization, which accounted for 79% of the energy input. Other agricultural operations had the following shares in the total energy inputs in winter rapeseed production: seed and straw harvesting—9%, tillage—6%, pest control—4%, and sowing—2% [4]. The literature on the subject provides numerous reports indicating that mineral fertilization (59–80%) and energy carriers—fuel (12–30%) are the most energy-intensive components in plant production [1–3].

The first component of the classic input balance, in the case under discussion, concerns the energetic cost of N. The production costs of N fertilizers are extremely high because they include both the raw material for production and energy inputs. In both cases, it is natural gas, which contains methane, that is a non-renewable component [62,63]. The conducted research has shown that it is possible to completely replace ammonium nitrate with digestate (Section 4.1). Furthermore, N from digestate, as well as other nutrients, is not burdened with production or emission costs [64]. Therefore, the energy input costs for the nutrients in digestate were assumed to be zero. In the standard winter rapeseed production system, N costs are the dominant production factor [61].

The second component of the balance sheet is the energy output, which can be calculated separately or for aggregated yield categories depending on the direction of rapeseed use [3]. The $Y_{\max}$ values for the total energy output, based on the regression models, were 187,887 (real $Y_{\max}$ = 186,703) MJ ha⁻¹ for AN-FS, 189,852 (vs. 185,334) MJ ha⁻¹ for D-FS and 203,398 (vs. 203,014) MJ ha⁻¹ for DAN-FS (Figure S10). The values obtained for AN-FS and D-FS are at the same level as those reported by [61]. However, for the mixed system, DAN-FS, they were almost 9 pps higher. The trend for progressive N rates is important for the assessment of rapeseed fertilization systems with digestate (Figure S10). In both systems with the tested N carrier, energy production by rapeseed increased up to a dose of 240 kg N ha⁻¹. However, for AN-FS, a significant decrease occurred after exceeding the dose of 180 kg N ha⁻¹. Therefore, a potential environmental threat occurs only for the variant with mineral N fertilizers. Environmental hazards re-

sulting from digestate application may occur primarily during its application, particularly due to the high pH of the digestate (approximately 7.0) and the presence of ammonium N. Some authors suggest that the digestate induces N losses from the soil due to nitrate leaching or accelerated denitrification, which are responsible for the production of N oxide gases [55,64]. Considering the presented trends in the evaluated yields and energy production, a significant reduction in these losses can be assumed.

Net energy balance (NEB) showed a strong statistical relationship with rapeseed energy yield (E-P) regardless of fertilization system or N dose. This relationship is represented by the equation

$$NEB = 0.88EP - 1774.3 \text{ for } n = 15, R^2 = 0.97, p \leq 0.001$$

The NEB trends showed a strong dependence on FS (Figure 8). NEB values were significantly higher in systems with digestate, and the NFRV value calculated for this trait was 12%. Therefore, this characteristic of rapeseed production clearly confirmed the fertilizing value of N from digestate. A few highly significant facts are worth noting. First, the energy efficiency of rapeseed production was highest up to a dose of 60 kg N ha⁻¹, which indicates a N deficiency. Second, starting from this dose, there was a linear decline in the efficiency of this nutrient. Third, in the fertilization systems, the rate of decline was significantly slower.

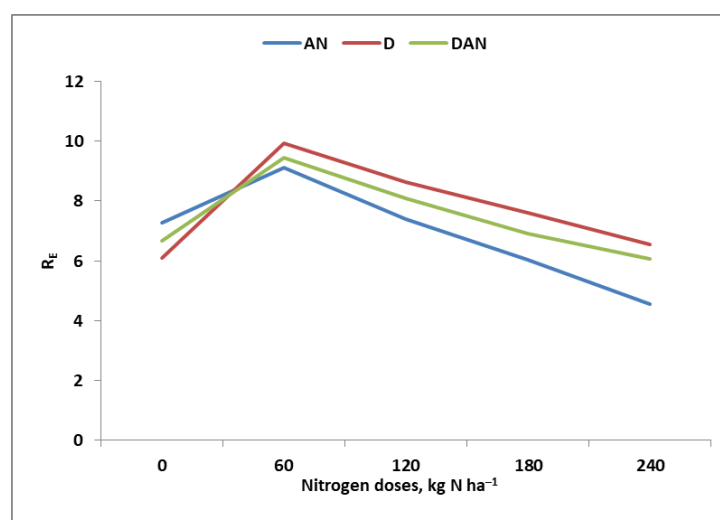


Figure 8. General patterns of the energy efficiency in winter oilseed rape in response to nitrogen sources against the background of increasing nitrogen doses.

Analysis of rapeseed yields, considered in five categories, as well as gross and net energy production, supported by efficiency indicators, confirmed the high fertilizer value of digestate. The present study showed that the most favorable energy efficiency ratio, $E_e = 10.44$ (seeds + straw), was achieved under the combined use of digestate (5.5 m³ ha⁻¹) and N doses of 40 kg ha⁻¹ (Figure 5, Table S3). The second analyzed energy efficiency coefficient, i.e., R_E (straw + oil + cake), was also highly beneficial in DAN-FS (5.5 m³ ha⁻¹) and with N rates of 40 kg ha⁻¹, and it ranged up to 9.94 (Figure 5, Table S3). Bielski et al. [3] showed that the energy efficiency ratio of winter rapeseed seed and straw production was 5.5. In turn, Ozturk [16] calculated the energy efficiency ratio of seeds and straw at 7.3. In the study by Jankowski et al. [4], the energy efficiency ratio of winter rapeseed seeds and straw was determined at 11.96. The production of brassica oilseeds for energy purposes is advantageous when other fat-free biomass components are also used and processed into solid fuel (straw briquettes and a mixture of straw and oilcake) [65]. Jankowski et al. [4] also claimed that the use of winter rapeseed for energy production

purposes is justified only when the entire biomass is converted into liquid fuel (oil) and solid fuel (cake and/or straw).

It can, therefore, be concluded that digestate from agricultural biogas plants meets the requirements of an economy known as the Circular Economy [66,67].

5. Conclusions

The presented study findings indicate that the complete replacement of mineral nitrogen fertilizer (ammonium nitrate) allows for the obtaining of comparable yields of winter oilseed rape. Partial replacement of mineral N fertilizer with digestate can generate higher yields of seeds, straw, oilcake, and oil. Nitrogen Fertilization Replacement Values ranged from 100% for seed yield to 108% for oilcake yield. In the mixed variant, the range was from 108% to 122%, respectively. The addition of digestate (D-FS) to a N fertilization system (AN-FS) through proper NPK balancing significantly reduces the energy intensity of rapeseed production, primarily by reducing the energy-intensive N using the synthetic fertilizer. Applying excessively high doses of mineral N fertilizer is unjustified in terms of N use by winter rapeseed. This phenomenon is confirmed by the calculation of energy inputs for seed production, which were the least favorable under the highest tested nitrogen rate, i.e., 240 kg ha⁻¹. The balanced addition of digestate in the amount of 8.3 and 15.6 m³ ha⁻¹ to nitrogen doses of 40 and 80 kg ha⁻¹, respectively, is compensated for by the yields of winter rapeseed seeds, straw, oil, and oilcake, which translates into favorable energy efficiency indicators.

Overall, based on the results of the field experiment carried out on a podzolized lessive soil (Albic Luvisol) in the West Pomeranian climatic region in Poland and calculations conducted, it is recommended that winter rapeseed biomass should be used entirely for liquid fuel (oil) and solid fuel (oilcake and/or straw) production. Digestate generated in biogas plants and appropriately balanced in terms of micronutrient composition is recommended for use near biogas plants together with NPK fertilizers in winter rapeseed production. The use of digestate on its own is an important element of the economic concept of the Circular Economy.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en19030865/s1>, Figure S1: The influence of nitrogen doses and digestate fertilization on energy value of winter oilseed rape production; Figure S2: The percentage share of biomass components in the total energy intensity of the biomass; Figure S3: Energy inputs and their structure in winter rape; Figure S4: The structure of energy inputs in winter rapeseed production—averaged over nitrogen doses; Figure S5: Regression model of the oilcake yield of winter oilseed rape in response to nitrogen doses and against a background of three fertilization systems (FSs); Figure S6: Regression model of the seed yield of winter oilseed rape in response to nitrogen doses and against a background of three fertilization systems (FSs); Figure S7: Regression model of the straw yield of winter oilseed rape in response to nitrogen doses and against a background of three fertilization systems (FSs); Figure S8: Regression model of the total biomass of winter oilseed rape in response to nitrogen doses and against a background of three fertilization systems (FSs); Figure S9: Regression model of the crude oil yield of winter oilseed rape in response to nitrogen doses and against a background of three fertilization systems (FSs); Figure S10: General scheme of winter oilseed rape response to nitrogen sources against the background of increasing nitrogen doses—on the example of crude oil yield. Table S1: Basic characteristics of the topsoil physical and chemical properties in subsequent growing seasons; Table S2: Yield of seed, straw, oilcake and oil of winter rape production; Table S3: Energy intensity of yield of seed, straw, oilcake, and oil and energy efficiency index E_e and R_e of winter oilseed rape production; Table S4: Energy inputs and their structure in winter oilseed rape; Table S5: Structure of

the energy inputs in the cultivation of winter rape; Table S6: Structure of the energy inputs in the raw materials and materials in production of winter rape.

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Abbreviations

AN	Ammonium nitrate
D	Digestate
FS	Fertilization system

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