www.nature.com/scientificreports

scientific reports

OPEN

Energy balance in nitrogen and sulfur management strategies for oilseed radish

Krzysztof Józef Jankowski & Artur Szatkowski

This article analyzes the effects of different rates of nitrogen (0, 30, 60, 90, and 120 kg N ha^{-1}) and sulfur (0, 15, 30 kg S ha^{-1}) fertilizers on energy balance in oilseed radish biomass production. Energy inputs (EI) were determined at 6.8–7.1 GJ ha^{-1}. Nitrogen application increased EI by 34% (30 kg ha^{-1}) and 135% (120 kg ha^{-1}). The energy output of seeds and total biomass peaked after the application of 60 kg N ha^{-1} + 15 kg S ha^{-1} and 30 kg N ha^{-1} + 15 kg S ha^{-1}, respectively. The energy gain from seeds and total biomass peaked in response to 30 kg N ha^{-1} + 15 kg S ha^{-1}. The energy efficiency ratio (EER) of seeds peaked in response to 15 kg S ha^{-1} (without N fertilization). The EER of total biomass was highest in the absence of N and S fertilization. Nitrogen decreased the EER of seeds and total biomass by 47% and 56%, respectively. The N-induced decrease in the EER was reduced by 4–8% (seeds) and 4–10% (total biomass) when S was applied.

Keywords *Raphanus sativus* L., Fertilization, Biomass yield, Energy inputs, Energy output, Energy gain and energy efficiency ratio

Crude oil is one of the leading energy sources worldwide with a 31% share of global primary energy consumption[1]. Between 2011 and 2021, oil consumption increased at an annual rate of 0.7%[2]. According to Shafiee and Topal[3], global oil reserves will be depleted more rapidly than other sources of non-renewable fossil fuels (coal and gas). This problem can be addressed through sustainable fossil fuel mining, improved energy efficiency in transport, and the development of alternative fuels[4–6]. In addition to petroleum and diesel oil, alternative fuels are and will be the main sources of energy in the transport sector[7,8]. The share of oil in global transport is expected to decrease from the present value of 94% to around 82–85% by 2040/2050[2,9] or even to around 40% in a sustainable development scenario[10]. Flexible-fuel vehicles that can run on more than one type of fuel have been proposed as a solution to the anticipated fossil fuel crisis. At present, ethanol and biodiesel are the most popular alternative fuels for flexible-fuel vehicles[7]. Global bioethanol and biodiesel production reached 127 and 38 billion L, respectively, in 2023. According to the International Energy Agency[11], the global demand for biofuels will increase from the present value of 165 billion L to 260 billion L in 2028 (by 58%). The world's leading bioethanol producers are the USA (61 billion L), Brazil (31 billion L), and China (11 billion L). In turn, biodiesel is supplied mainly by the European Union (EU) (13 billion L), USA (7 billion L), and Brazil (6 billion L)[12]. The efforts to increase biofuel production were initiated mainly by the EU countries and the USA to mitigate the adverse effects of climate change[13]. In addition, Europe's decoupling from Russian fossil fuels further prompted the EU countries to develop alternative energy sources, including biofuels[14]. The EU has met its target of increasing the share of renewable energy in transport to 10% by 2020[15], and in 2018, its energy policy for 2020–2030 was revised to guarantee food security and biodiversity in the face of adverse changes in land use[16]. The aim of the new energy policy is to decrease the share of biofuels derived from food crops (cereals, sugar crops, oilseed crops) and promote the use of non-food crops in energy production. Palm oil has been classified as a biofuel feedstock that significantly increases the risk of indirect land-use change (ILUC), and palm oil-based biofuels will be gradually phased out in the EU by 2030[13]. According to the European Commission, palm oil-based biofuels must be phased out to prevent deforestation and ILUC. Soybean oil has been also labeled as a high ILUC-risk, and some EU countries are planning to phase out soybean oil as biofuel feedstock[13]. The EU Regulation on deforestation-free products (EUDR)[17] was introduced in 2023 as part of the European Green Deal. The aim of the EUDR is to ensure that consumption and agricultural expansion in the EU do not contribute to global deforestation and forest degradation. According to the EUDR, operators and traders who place agricultural commodities on the EU market must be able to prove that these products did not originate from recently deforested land and have not contributed to forest degradation. The list of agricultural products

Faculty of Agriculture and Forestry, Department of Agrotechnology and Agribusiness, University of Warmia and Mazury in Olsztyn, Oczapowskiego 8, Olsztyn 10-719, Poland. email: krzysztof.jankowski@uwm.edu.pl

associated with the ILUC risk includes soybeans [*Glycine max* (L.) Merr.], palm oil, rubber, cocoa, and coffee[17]. At present, palm oil and soybean oil have a combined 14% share of biofuel feedstocks in the EU[18]. If the relevant restrictions are not imposed, palm oil and soybean oil could account for 36% of biodiesel feedstocks in the EU by 2030[13]. According to Heimann et al.[13], if only palm oil is phased out, the share of rapeseed oil and soybean oil on the EU biofuel market could increase to 41% and 20%, respectively. If both palm oil and soybean oil are phased out, nearly half of European biodiesel production (49%) will rely on rapeseed oil. The share of other oils, including sunflower oil (*Helianthus annuus* L.), will also increase, and their imports will have to be doubled in the EU[13]. Ukraine is the world's largest supplier of sunflower oil with a 27% share of the global market[19]. The significance of rapeseed oil will increase in all EU biofuel market scenarios analyzed by Heimann et al.[13]. The demand for rapeseed oil in the EU petrochemical sector can be met by (i) increasing the area under oilseed rape (*Brassica napus* L.) or (ii) increasing rapeseed oil imports from non-EU countries. An increase in the area under oilseed rape could be difficult to achieve due to current limitations on its proportion in crop rotation (a high share of oilseed rape in crop rotation increases the risk of disease and decreases yields). In addition, oilseed rape and wheat (*Triticum aestivum* L.) have similar soil requirements, and increased competition between these crops could undermine the supply of wheat which plays a key role in global food security[20–23]. In turn, seed/oil imports could be very expensive because the cost of oil production accounts for 75–80% of total biodiesel production costs[24,25].

Oilseed crops of the family *Brassicaceae* offer a promising alternative in biofuel production. Species of the genus *Brassica* are well adapted to the European climate and have much lower soil requirements than oilseed rape[26,27]. *Brassicas* can be cultivated on marginal land[27,28], which rules out competition with wheat. Oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) is a *Brassica* crop that is well-suited to the agroecological conditions of Europe and can be grown on marginal soils[29,30]. In Eastern Europe, oilseed radish yields are 10% higher than winter camelina [*Camelina sativa* (L.) Crantz] yields, 16–20% higher than spring camelina, spring oilseed rape, and oil flax (*Linum usitatissimum* L.) yields, and 24% higher than white mustard (*Sinapis alba* L.) yields[31]. In Central-Eastern Europe, oilseed radish yields exceed field mustard (*Brassica rapa* L.) and spring camelina yields by 5%, and spring oilseed rape and Indian mustard [*Brassica juncea* (L.) Czern.] yields by 19–28%[32]. The crude fat content of oilseed radish seeds ranges from 284 to 398 g kg^{-1} dry matter (DM)[30–35]. Oilseed radish oil is abundant in oleic (C18:1), erucic (C22:1), and eicosenoic (C20:1) acids (19–35%, 18–46%, and 3–11%, respectively)[35–40]. Oilseed radish oil cannot be used in food production due to a high content of C22:1 which increases the risk of congestive heart failure[41]. However, oilseed radish oil is highly abundant in very-long-chain fatty acids, and it constitutes a valuable resource for oleochemical[40] and petrochemical industries[34–36,38,42–45]. Biodiesel produced from oilseed radish oil meets the standards of the American Society for Testing and Materials and EU norms[38]. Oilseed radish biodiesel does not compromise the performance of diesel engines, and the performance of engines running on diesel oil and soybean biodiesel was comparable to that of engines supplied with oilseed radish biodiesel. Oilseed radish biodiesel is also 24% cheaper to produce than soybean biodiesel[38].

Oilseed radish has numerous advantages, including (i) a short growing season (90–120 days), (ii) low agronomic requirements, (iii) low cultivation costs, and (iii) high oil yields and easy oil extraction[46,47]. However, similarly to other spring *Brassica* oilseed crops, oilseed radish is characterized by a high demand for nitrogen (N)[48–50] and low N fertilizer use efficiency (NFUE)[51]. Oilseed radish and winter oilseed rape have similar N requirements which are estimated at 50–60 kg N per 1 Mg of seeds and the corresponding straw yield[52]. However, spring *Brassica* oilseed crops are characterized by much lower NFUE than winter oilseed rape[30,53–56].

Nitrogen fertilizer use efficiency is a very important parameter because N fertilizer is the most energy-intensive input in modern production technologies of agricultural biomass. Mineral fertilizers have a high share of total energy inputs (EI) in the cultivation technology of cereals[57,58], oilseed crops[59–63], and perennial lignocellulosic energy crops[64–67]. The high EI associated with mineral fertilization result mainly from the high energy equivalent of fertilizer production rather than fertilizer transport and application in the field[63]. The demand for N fertilizers can be decreased by improving NFUE[60,68]. In agricultural practice, the effectiveness of N fertilization can be improved by harnessing the synergistic effects of combined N and sulfur (S) fertilization[69–71]. Sulfur enhances N metabolism[72–74], and it can be easily incorporated into the fertilization regime of *Brassica* oilseed crops which have a high demand for S[75]. Oilseed crops of the family *Brassicaceae* require 15–20 kg S to produce 1 Mg of seeds and the corresponding straw yield[76]. In a study by Sokólski et al.[56], S fertilization increased the NFUE of crambe by 22–39%. Similar observations were made in camelina, white mustard, Indian mustard, and field mustard[54,77–81]. By improving NFUE due to S application, it is possible to increase the energy efficiency ratio (EER) of the cultiuvation technology[62,63]. In the work of Jankowski and Sokólski[62] and Jankowski et al.[63], S applied to camelina and crambe induced an 8% and 3–17% increase in the EER of seed production, respectively.

In the literature, oilseed radish is described mainly as a valuable resource for biodiesel production. However, the energy balance of oilseed radish cultivation, including the energy output (EO) of seeds and the EI associated with the production technology, has not been thoroughly investigated to date. There are no published data on the effect of N fertilization, the most energy-intensive agricultural operation, on the energy balance of oilseed radish cultivation or potential improvements in the energy balance resulting from combined N and S fertilization. The present study fills in this knowledge gap by providing information about (i) the energy balance in the cultivation technology of oilseed radish, and (ii) the most energy-efficient method of managing N and S in oilseed radish cultivation. The research hypothesis states that the synergistic effects of N and S fertilization should improve energy efficiency in the cultivation technology of oilseed radish.

The aim of this study was to determine the effect of N and S fertilization on biomass yields (seeds, straw), EI, EO, energy gain (EG), and the EER of oilseed radish grown in a large-area farm in north-eastern Poland. The energy balance of oilseed radish cultivation was determined in two biomass production variants. The energy potential of seeds which can be used in the production of biodiesel (oil) and animal feed (fat-free seed residues) was determined in the first variant. In this variant, straw was chopped during harvest and left to decompose naturally in the field. The energy potential of total biomass (seeds and straw) which can be used in the production of liquid biofuels (oil), solid biofuels (straw), and animal feed (fat-free seed residues) was determined in the second variant.

Materials and methods

Field experiment

The seed and straw yields of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) were determined during a small-area field experiment conducted in the Agricultural Experiment Station (AES) in Bałcyny (53°35'46.4" N, 19°51'19.5" E, elevation 137 m) in north-eastern Poland between 2020 and 2022. The AES is a part of the University of Warmia and Mazury in Olsztyn. Five N fertilizer rates (0, 30, 60, 90, 120 kg ha^{-1}) and three S fertilizer rates (0, 15, 30 kg ha^{-1}) were applied in the experiment. Nitrogen rates of up to 90 kg ha^{-1} were applied once in BBCH stage 00 (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie[82]). The N rate of 120 kg N ha^{-1} was split into two applications: 90 kg ha^{-1} in BBCH 00 and 30 kg ha^{-1} in BBCH 12–13. Nitrogen was applied as ammonium nitrate (34% N). Sulfur was applied in BBCH stage 00 as potassium sulfate (18% S, 50% K_2O).

The experiment had a randomized block design (RBD) with three replications. Plot size was 15 m^2 (10 by 1.5 m). Winter wheat was the preceding crop. The experiment was established on Haplic Luvisol originating from boulder clay[83]. The chemical properties of soil (pH, humus content, content of plant-available fertilizer macronutrients), analytical methods, and weather conditions were described by Szatkowski et al.[30]. Agronomic treatments are presented in detail in Table S1.

Energy input analysis

Diesel oil consumption, labor, and the performance of agricultural machines and devices were measured directly in a field with an area of 85 ha in the AES in Bałcyny (own measurements, Table S2). The field is situated at a distance of 1.2 km from the AES (and this distance was included in the energy efficiency analysis). The experiment involved tractors and machines that are used in agricultural production in the AES in Bałcyny. The EI associated with the cultivation technology of oilseed radish were determined based on the energy indicators proposed by Wójcicki[84] and Fore et al.[85] (Table 1). The total EI were calculated by summing up the EI associated with diesel oil consumption, human labor, fixed assets (tractors and machines), and agricultural materials (seeds, fertilizers, and pesticides) (Eq. 1). Agricultural operations (tillage, sowing, mineral fertilization, chemical crop protection, seed harvest and transport, straw harvest and transport) and energy fluxes (labor, diesel oil, tractors and machines, agricultural materials) were included in the structure of EI associated with the cultivation technology of oilseed radish.

$$\mathrm{EI} = \mathrm{EI_d} + \mathrm{EI_f} + \mathrm{EI_m} + \mathrm{EI_l} \tag{1}$$

where: EI - total energy inputs for oilseed radish production (GJ ha^{-1}), EI_d - energy input for diesel oil consumption (GJ ha^{-1}), EI_f - energy input for fixed assets (GJ ha^{-1}), EI_m - energy input for materials (GJ ha^{-1}), EI_l - energy input for human labor (GJ ha^{-1}).

Biomass yields

The fresh matter yield (FMY) of seeds and straw was determined directly after harvest. The moisture content of biomass was determined by drying 1 kg samples of seeds and straw from each plot at a temperature of 105 °C in a ventilated oven FD 53 (Binder GmbH, Tuttlingen, Germany) until constant weight (Eq. 2). The dry matter yield (DMY) of seeds and straw was calculated with the use of Eq. 3.

$$\mathrm{W} = \frac{(\mathrm{M_w} - \mathrm{M_d})}{\mathrm{M_w}} \times 100 \tag{2}$$

where: W - moisture content (%), M_w – wet sample weight, before drying (g), M_d – dry sample weight, after drying (g).

Source	Unit	Input	References
Labor	MJ $hour^{-1}$	80	Wójcicki[95]
Tractors	MJ kg^{-1}	125	Wójcicki[95]
Machines	MJ kg^{-1}	110	Wójcicki[95]
Diesel oil	MJ kg^{-1}	48	Wójcicki[95]
Seeds	MJ kg^{-1}	12	Wójcicki[95]
N	MJ kg^{-1}	77	Wójcicki[95]
P_2O_5	MJ kg^{-1}	15	Wójcicki[95]
K_2O	MJ kg^{-1}	10	Wójcicki[95]
S	MJ kg^{-1}	8.9	Fore et al.[96]
Pesticides	MJ kg^{-1} active ingredient	300	Wójcicki[95]

Table 1. Energy equivalents of inputs associated with the cultivation technology of oilseed radish.

$$\mathrm{DMY} = \frac{\mathrm{FMY} \times \mathrm{DM}}{100} \quad (3)$$

where: DMY – dry matter yield (Mg ha^{-1}), FMY – fresh matter yield (Mg ha^{-1}), DM – dry matter content (%).

Energy output analysis

The higher heating value (HHV) of seeds and straw was determined by adiabatic combustion in a calorimeter C 6000 (IKA-Werke GmbH & CO. KG, Staufen, Germany) with the use of a dynamic method. The lower heating value (LHV) was calculated according to the method proposed by Kopetz et al.[86] (Eq. 4). The EO was calculated as the product of FMY and LHV (Eq. 5), and it was determined separately for seeds and for total biomass (seeds and straw).

$$\mathrm{LHV} = \frac{\mathrm{HHV} \times (100 - \mathrm{W})}{100} - \mathrm{W} \times 0.0244 \quad (4)$$

where: LHV - lower heating value of seeds or straw determined on a wet basis (MJ kg^{-1}), HHV - higher heating value of seeds or straw determined on a dry basis (MJ kg^{-1}), W - moisture content of seeds or straw (%), 0.0244 - correction coefficient for water vaporization enthalpy (MJ kg^{-1} per 1% moisture content).

$$\mathrm{EO}\ (\mathrm{GJ\,ha^{-1}}) = \mathrm{LHV}\ (\mathrm{GJ\,Mg^{-1}}) \times \mathrm{FMY}\ (\mathrm{Mg\,ha^{-1}}) \quad (5)$$

Energy gain and the energy efficiency ratio

The energy efficiency of the cultivation technology of oilseed radish was determined based on EG and the EER (Eqs. 6 and 7, respectively). Energy efficiency parameters were calculated separately for seeds and for total biomass (seeds and straw).

$$\mathrm{EG}\ (\mathrm{GJ\,ha^{-1}}) = \mathrm{EO}\ (\mathrm{GJ\,ha^{-1}}) - \mathrm{EI}\ (\mathrm{GJ\,ha^{-1}}) \quad (6)$$

$$\mathrm{EER} = \frac{\mathrm{EO}\ (\mathrm{GJ\ ha^{-1}})}{\mathrm{EI}\ (\mathrm{GJ\ ha^{-1}})} \quad (7)$$

Statistical analysis

The values of DMY, EO, EG, and EER were processed by repeated measures analysis of variance (ANOVA), where the rates of N and S fertilizers were the fixed factors, and years and replications were the repeated factors. Treatment means were compared in Tukey's honest significant difference (HSD) test at $p \leq 0.05$. All analyses were performed in the Statistica 13.3 program[87].

Results

Energy inputs

The demand for energy in oilseed radish cultivation without N fertilization was determined at 6.8–7.1 GJ ha^{-1} (Fig. 1). Nitrogen rates of 30, 60, 90, and 120 kg ha^{-1} increased EI by 34%, 68%, 101%, and 135%, respectively. On average, every increase in the N rate by 30 kg ha^{-1} increased EI associated with the cultivation technology of oilseed radish by 2.30–2.38 GJ ha^{-1}. Energy inputs reached 16.2–16.5 GJ ha^{-1} in the cultivation technology with the highest N rate (120 kg ha^{-1}) (Fig. 1). Energy inputs were lower by 0.5 GJ ha^{-1} in the biomass production variant where only seeds were harvested (Table 2). The inclusion of S in the fertilization regime increased EI by 0.15–0.26 (15 kg S ha^{-1}) and 0.28–0.31 GJ ha^{-1} (30 kg S ha^{-1}), i.e. by 1–4% (Fig. 1).

Mineral fertilization was the most energy-intensive operation in oilseed radish cultivation (28–31% of total EI for 0 kg N ha^{-1} and 69–70% for 120 kg N ha^{-1}). The remaining farming operations had a much smaller share of total EI. Tillage accounted for 13–31%, sowing for 4–10%, chemical crop protection for 4–10%, seed harvest and transport for 6–14%, and straw harvest and transport for 3–8% of total EI. An increase in N and S rates induced differences in the share of agricultural operations in total EI, but it did not change the order in which agricultural operations were ranked (Table 2).

Agricultural materials and diesel oil consumption accounted for 33–71% and 20–48% of total EI in oilseed radish cultivation (Table 3). The share of agricultural materials in the overall structure of EI increased with a rise in the N rate (from 33 to 35% for 0 kg N ha^{-1} to 50–71% for 120 kg N ha^{-1}). In turn, the share of diesel oil consumption in total EI decreased with a rise in the N rate (from 48 to 46% for 0 kg N ha^{-1} to 21–20% for 120 kg N ha^{-1}). The EI associated with labor, tractors and agricultural machines accounted for 2–4% and 7–16% of total EI, respectively. The low share of labor and machinery in total EI can be attributed to the fact that the experiment was conducted on a large-area farm (approx. 2000 ha) with the use of high-performance agricultural machines. Chemically-bound energy accumulated in mineral fertilizers accounted for 88–98% of EI associated with fertilization. Fertilizer application (tractors and machines, diesel oil consumption, labor) accounted for 2% (90–120 N ha^{-1}) to 12% (0–30 kg N ha^{-1}) of EI associated with fertilization (Table 3).

Biomass and energy yield (energy output)

Seed and straw yields in the production of oilseed radish in north-east Poland were determined at 0.69–1.02 and 7.4–9.2 Mg ha^{-1} DM, respectively (Figs. 2 and 3). Seed yields peaked in response to 120 kg N ha^{-1} and 15 kg S ha^{-1}. The S rate of 15 kg ha^{-1} was particularly effective in improving seed yields (by 7–10%) in treatments supplied with ≤60 kg N ha^{-1}. In plots fertilized with 90 and 120 kg N ha^{-1}, the application of 15 kg S ha^{-1} increased seed yields by 1% and 5%, respectively. In turn, the highest straw yields were noted when oilseed radish

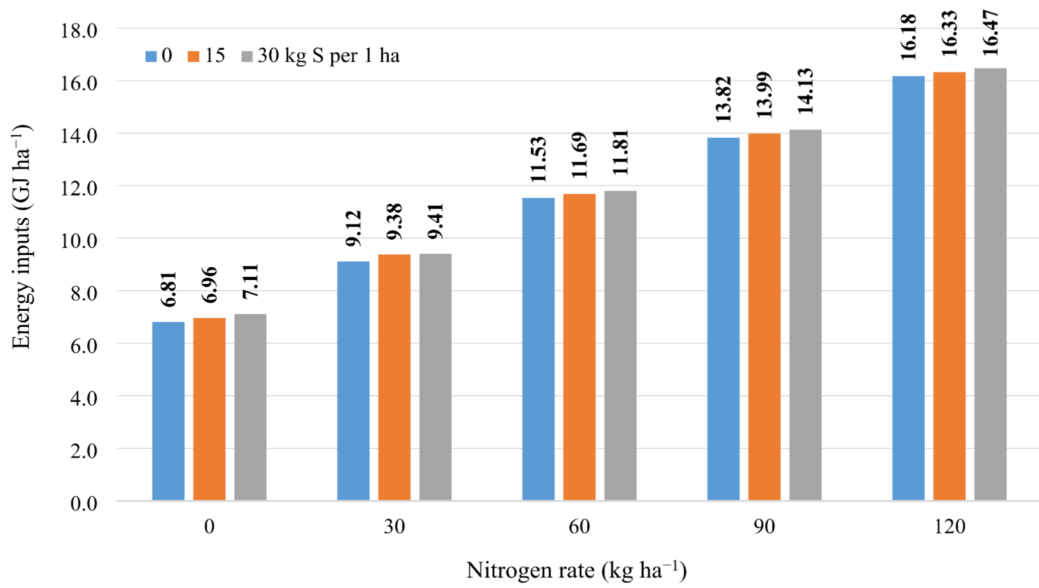

Fig. 1. Energy inputs associated with the cultivation technology of oilseed radish (seed and straw harvest), across years.

Farming operation	Nitrogen rate (kg ha^{-1})														
	0			30			60			90			120		
	Sulfur rate (kg ha^{-1})														
	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
MJ ha^{-1}															
Tillage	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117	2117
Sowing	666	666	666	666	666	666	666	666	666	666	666	666	666	666	666
Mineral fertilization	1893	2057	2190	4203	4367	4500	6513	6677	6810	8823	8987	9120	11,163	11,327	11,460
Chemical crop protection	681	681	681	681	681	681	681	681	681	681	681	681	681	681	681
Seed harvest and transport	933	933	933	933	1027	933	1027	1027	1027	1027	1027	1027	1027	1027	1027
Straw harvest and transport	523	509	523	523	523	509	523	523	509	509	509	523	523	509	523
%															
Tillage	31.1	30.4	29.8	23.2	22.6	22.5	18.4	18.1	17.9	15.3	15.1	15.0	13.1	13.0	12.9
Sowing	9.8	9.6	9.4	7.3	7.1	7.1	5.8	5.7	5.6	4.8	4.8	4.7	4.1	4.1	4.0
Mineral fertilization	27.8	29.5	30.8	46.1	46.5	47.8	56.5	57.1	57.7	63.8	64.2	64.5	69.0	69.4	69.6
Chemical crop protection	10.0	9.8	9.6	7.5	7.3	7.2	5.9	5.8	5.8	4.9	4.9	4.8	4.2	4.2	4.1
Seed harvest and transport	13.7	13.4	13.1	10.2	10.9	9.9	8.9	8.8	8.7	7.4	7.3	7.3	6.3	6.3	6.2
Straw harvest and transport	7.7	7.3	7.4	5.7	5.6	5.4	4.5	4.5	4.3	3.7	3.6	3.7	3.2	3.1	3.2

Table 2. Structure of energy inputs in the cultivation technology of oilseed radish per farming operation, across years.

was supplied with 30 kg N ha^{-1} and 15 kg S ha^{-1} (Fig. 3). In treatments without N fertilization, the application of S decreased straw yields by 3%. Sulfur induced the greatest increase in straw yields (14%) in plots supplied with 30 kg N ha^{-1}. A further increase in the N rate decreased the yield-forming effect of S (60 and 90 kg N ha^{-1}) or decreased straw yields (120 kg N ha^{-1}) (Fig. 3).

The EO of seeds peaked in response to 60 kg N ha^{-1} and 15 kg S ha^{-1} (Table 4). The S rate of 15 kg ha^{-1} had a positive impact on the EO of seeds only in treatments supplied with ≤60 kg N ha^{-1}. Nitrogen rates higher than 60 kg N ha^{-1} did not induce significant changes in the EO of seeds, regardless of the S rate. The EO of total biomass (seeds and straw) peaked (164.4 GJ ha^{-1}) in response to 30 kg N ha^{-1} and 15 kg S ha^{-1}. A further increase in the N rate did not induce significant differences in the EO of seeds and straw, regardless of the S rate (Table 4).

Farming operation	Nitrogen rate (kg ha^{-1})														
	0			30			60			90			120		
	Sulfur rate (kg ha^{-1})														
	0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
MJ ha^{-1}															
Labor	249	250	251	249	253	250	252	253	252	251	252	253	253	254	255
Tractors and machines	1097	1102	1107	1097	1127	1102	1116	1127	1122	1111	1122	1127	1127	1132	1137
Diesel oil	3254	3265	3272	3254	3344	3264	3326	3344	3336	3319	3336	3344	3344	3354	3361
Agricultural materials, including:	2213	2347	2480	4523	4657	4790	6833	6967	7100	9143	9277	9410	11,453	11,587	11,720
seeds	192	192	192	192	192	192	192	192	192	192	192	192	192	192	192
fertilizers	1675	1809	1942	3985	4119	4252	6295	6429	6562	8605	8739	8872	10,915	11,049	11,182
pesticides	346	346	346	346	346	346	346	346	346	346	346	346	346	346	346
%															
Labor	3.7	3.6	3.5	2.7	2.7	2.7	2.2	2.2	2.1	1.8	1.8	1.8	1.6	1.6	1.5
Tractors and machines	16.1	15.8	15.6	12.0	12.0	11.7	9.7	9.6	9.5	8.0	8.0	8.0	7.0	6.9	6.9
Diesel oil	47.8	46.9	46.0	35.7	35.6	34.7	28.9	28.6	28.2	24.0	23.9	23.7	20.7	20.5	20.4
Agricultural materials, including:	32.5	33.7	34.9	49.6	49.6	50.9	59.3	59.6	60.1	66.1	66.3	66.6	70.8	71.0	71.1
seeds	2.8	2.8	2.7	2.1	2.0	2.0	1.7	1.6	1.6	1.4	1.4	1.4	1.2	1.2	1.2
fertilizers	24.6	26.0	27.3	43.7	43.9	45.2	54.6	55.0	55.6	62.2	62.5	62.8	67.5	67.7	67.9
pesticides	5.1	5.0	4.9	3.8	3.7	3.7	3.0	3.0	2.9	2.5	2.5	2.5	2.1	2.1	2.1

Table 3. Structure of energy inputs in the cultivation technology of oilseed radish by energy fluxes, across years.

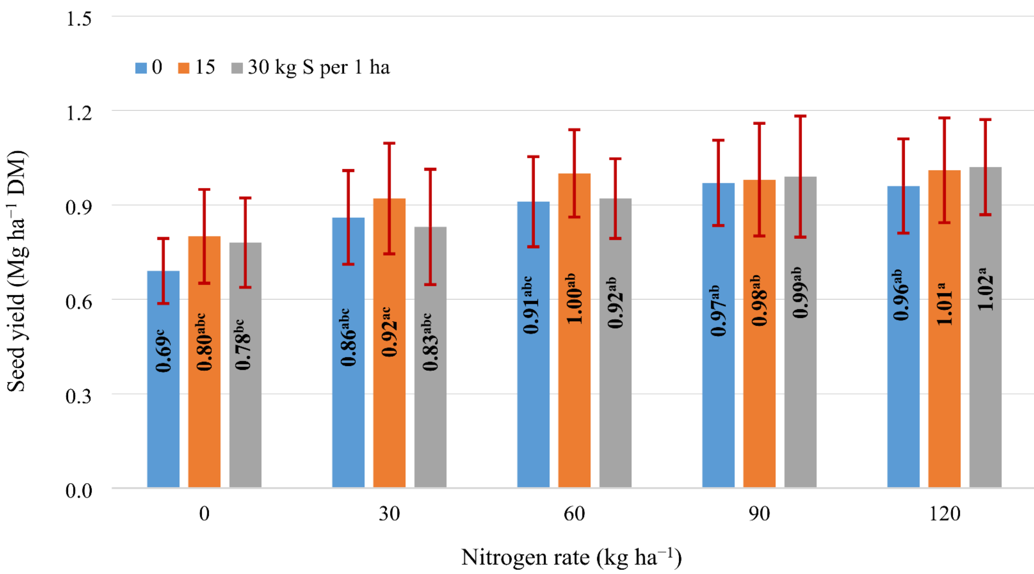

Fig. 2. Seed yields in the cultivation technology of oilseed radish, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey`s test; $n = 9$.

Energy gain and the energy efficiency ratio

The EG of oilseed radish was determined at 10.6–16.7 GJ ha^{-1} (seeds) and 117.6–155.0 GJ ha^{-1} (seeds and straw). In both biomass production variants (seeds only or seeds and straw), EG peaked in response to 30 kg N ha^{-1} and 15 kg S ha^{-1} (Table 4).

The EER of seeds ranged from 1.68 to 3.43. The highest value of this parameter was noted in treatments supplied with 15 kg S ha^{-1} (without N fertilization). Nitrogen fertilization decreased the EER of seeds by 15% (30 kg N ha^{-1}), 28% (60 kg N ha^{-1}), 38% (90 kg N ha^{-1}), and 47% (120 kg N ha^{-1}). The application of 15 kg S ha^{-1} reduced the N-induced decrease in the EER of seeds by 4–8%. The EER of total biomass (seeds and straw) was 5- to 7-fold higher than the EER of seeds. The EER of total biomass was significantly differentiated by N fertilization, and it was highest in the cultivation technology without N or S fertilization. Nitrogen applied at 30,

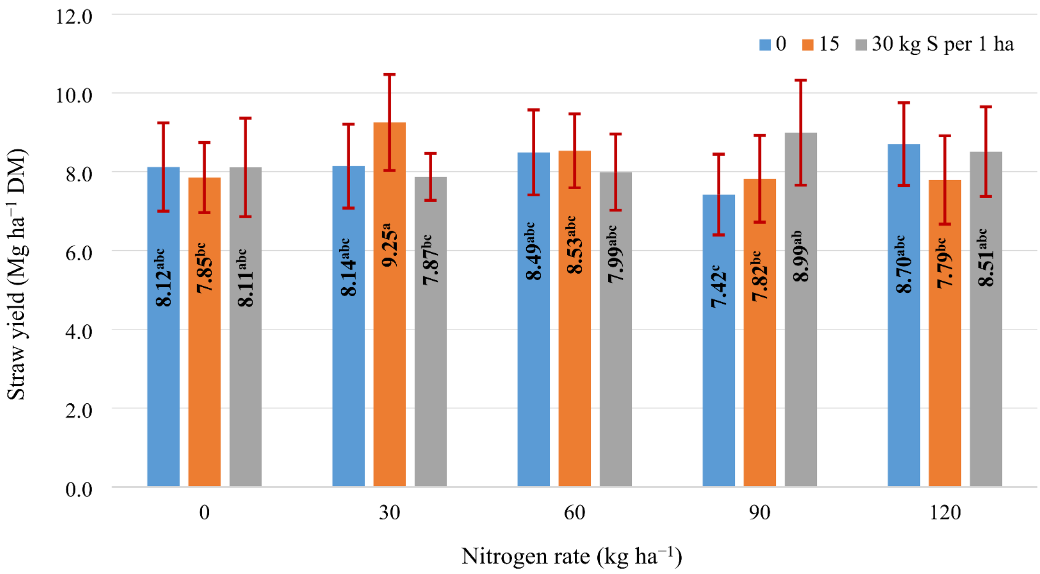

Fig. 3. Straw yields in the cultivation technology of oilseed radish, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey`s test; $n = 9$.

60, 90, and 120 kg ha^{-1} decreased the EER by 21%, 38%, 50%, and 56%, respectively. The N-induced decrease in the EER was reduced by 4–10% when S was incorporated into the fertilization plan of oilseed radish (Table 4).

Discussion
Energy inputs
The demand for energy in the cultivation technology of oilseed radish is determined by the energy intensity of agricultural materials, mainly N fertilizers[88,89], (present study: Tables 2 and 3). The EI in cultivation technologies without N or with very low N rates (< 10 kg N ha^{-1}) range from 6.7[88] to 7.1 GJ ha^{-1} (present study: Fig. 1). The demand for energy in cultivation technologies with N rates that are optimal for the agroecological conditions in Europe (90–120 kg ha^{-1}) has been determined in the range of 12–16 (present study: Fig. 1) to even 22.1 GJ ha^{-1}[89]. In north-eastern Poland, oilseed radish has similar energy requirements to other spring *Brassica* oilseed crops, including oilseed rape (14.3–18.2 GJ ha^{-1})[90–92], white mustard (13.2–14.2 GJ ha^{-1})[90–92], Indian mustard (10.8–13.4 GJ ha^{-1})[90,91], camelina (5.2–17.6 GJ ha^{-1})[62,91,92], crambe (5.7–15.0 GJ ha^{-1})[63,91], and oil flax (12.1 GJ ha^{-1})[92].

Mineral fertilizers play the key role in the structure of EI associated with oilseed radish cultivation, regardless of the energy intensity of the seed production technology. In cultivation technologies with low N rates, the share of mineral fertilization in total EI ranges from 28–31% (present study: Table 2) to 33%[88]. In the current study, an increase in the N rate to 30, 60, 90, and 120 kg $^{-1}$ increased EI in seed production by 34%, 68%, 101%, and 135%, respectively. Due to the N-induced increase in EI, mineral fertilization accounted for 69–70% of total EI at the optimal N rate. In other studies, higher N rates exerted similar effects on total EI in the production of spring *Brassica* oilseed crops (camelina and crambe)[62,63]. According to Jankowski and Sokólski[62], an increase in the N rate in spring camelina cultivation by 40, 80, 120, and 160 kg ha^{-1} increased total EI in seed production by 59%, 118%, 177%, and 236%, respectively. In crambe, total EI increased by 41%, 81%, 122%, and 163% when the N rate was increased by 30, 60, 90, and 120 kg N ha^{-1}, respectively[63]. In spring *Brassica* oilseed crops (camelina, crambe, rapeseed, white mustard, Indian mustard, oil flax) supplied with optimal N rates, mineral fertilizers accounted for 52–75% of total EI[62,63,90,91].

Biomass and energy yield (energy output)
In a 20-year study conducted in western Poland by Toboła and Muśnicki[32], the average seed yield of oilseed radish ranged from 0.41 to 2.56 Mg ha^{-1} (1.11 Mg ha^{-1} on average), and was comparable to that noted in camelina and crambe crambe (1.05 and 1.38 Mg ha^{-1}, respectively). Oilseed radish was characterized by lower variation in seed yields across years (52%) than camelina and crambe (74% and 65%, respectively)[32]. In the present study, seed yields were determined in the range of 0.69–1.02 Mg ha^{-1}. Similar results (0.63–1.00 Mg ha^{-1}) were reported in oilseed radish cultivated in Lithuania[33,93]. Seed yields were considerably higher in Ukraine and Russia (1.4–1.6 and 1.6–2.4 Mg ha^{-1}, respectively)[31,52,94]. In the current experiment, a significant increase in seed yields (32%) was noted up to 120 kg N ha^{-1} and 15 kg S ha^{-1}. Nitrogen induced a similar increase (37%) in crambe seed yields[63]. In turn, the N-induced increase in seed yields was twice higher in camelina (65%)[62]. In north-eastern Poland, the greatest increase in the seed yields of camelina (2.24 Mg ha^{-1} DM) and crambe (1.78 Mg ha^{-1} DM) was observed in response to 160 kg N ha^{-1} + 30 kg S ha^{-1} and 120 kg N ha^{-1} + 30 kg S ha^{-1}, respectively[62,63]. It should also be noted that crambe and camelina responded differently to combined S and N fertilization than oilseed radish[62,63, present study: Table 4]. In camelina, S significantly increased seed yields (by 5–12%)

Indicator		Nitrogen rate (kg ha^{-1})														
		0			30			60			90			120		
		Sulfur rate (kg ha^{-1})														
		0	15	30	0	15	30	0	15	30	0	15	30	0	15	30
Energy output (GJ ha^{-1})	seeds	18.9 ± 2.9^{b}	22.2 ± 4.2^{ab}	21.7 ± 4.0^{ab}	23.9 ± 4.2^{ab}	25.6 ± 4.9^{ab}	22.9 ± 5.1^{ab}	25.2 ± 4.0^{ab}	27.7 ± 3.9^{a}	25.4 ± 3.6^{ab}	26.8 ± 3.8^{a}	27.0 ± 4.9^{a}	27.3 ± 5.3^{a}	26.3 ± 4.1^{a}	27.7 ± 4.6^{a}	27.9 ± 4.1^{a}
	seeds and straw	143.1 ± 19.6^{ab}	139.2 ± 15.40^{ab}	144.3 ± 21.80^{ab}	145.2 ± 18.4^{ab}	164.4 ± 21.7^{a}	139.5 ± 10.1^{ab}	151.1 ± 18.9^{ab}	153.2 ± 16.3^{ab}	142.2 ± 16.9^{ab}	131.4 ± 18.0^{b}	138.7 ± 19.5^{ab}	159.9 ± 23.9^{a}	153.5 ± 18.0^{ab}	139.0 ± 19.7^{ab}	151.5 ± 110.0^{ab}
Energy gain (GJ ha^{-1})	seeds	12.6 ± 2.9^{ab}	15.7 ± 4.2^{ab}	15.1 ± 4.0^{ab}	15.3 ± 4.2^{ab}	16.7 ± 4.9^{a}	14.0 ± 5.1^{ab}	14.2 ± 4.0^{ab}	16.5 ± 3.9^{a}	14.1 ± 3.6^{ab}	13.4 ± 3.8^{ab}	13.5 ± 4.9^{ab}	13.7 ± 5.3^{ab}	10.6 ± 4.1^{b}	11.9 ± 4.6^{ab}	11.9 ± 4.1^{ab}
	seeds and straw	136.3 ± 19.6^{ab}	132.2 ± 15.2^{ab}	137.2 ± 21.8^{ab}	136.1 ± 18.4^{ab}	155.0 ± 21.7^{a}	130.1 ± 10.1^{ab}	139.6 ± 18.9^{ab}	141.5 ± 16.3^{ab}	130.4 ± 16.9^{ab}	117.6 ± 18.0^{b}	124.7 ± 19.5^{ab}	145.7 ± 23.9^{ab}	137.3 ± 18.0^{ab}	122.7 ± 19.7^{ab}	135.0 ± 110.0^{ab}
Energy efficiency ratio	seeds	3.00 ± 0.46^{ab}	3.43 ± 0.65^{a}	3.29 ± 0.60^{ab}	2.78 ± 0.48^{ab}	2.89 ± 0.56^{ab}	2.58 ± 0.57^{ab}	2.29 ± 0.36^{ab}	2.48 ± 0.35^{ab}	2.25 ± 0.35^{ab}	2.01 ± 0.28^{ab}	2.00 ± 0.36^{ab}	2.01 ± 0.39^{ab}	1.68 ± 0.26^{b}	1.75 ± 0.29^{b}	1.75 ± 0.26^{b}
	seeds and straw	21.00 ± 2.88^{a}	19.98 ± 2.22^{a}	20.29 ± 3.07^{a}	15.91 ± 2.01^{abc}	17.52 ± 2.31^{ab}	14.83 ± 1.08^{abcd}	13.11 ± 1.64^{bcd}	13.10 ± 1.39^{bcd}	12.04 ± 1.43^{bcd}	9.51 ± 1.30^{cd}	9.92 ± 1.39^{cd}	11.31 ± 1.69^{bcd}	9.49 ± 1.11^{cd}	8.51 ± 1.20^{d}	9.20 ± 1.21^{cd}

Table 4. Energy efficiency indicators in the cultivation technology of oilseed radish, across years. Means with the same letters do not differ significantly at $p \leq 0.05$ in Tukey`s test; $n = 9$.

only in treatments supplied with ≥120 kg N ha^{-1}. Sulfur was not productive in plots fertilized with ≤80 kg N ha^{-1}[162]. In crambe, S increased seed yields when combined with N rates of ≥60 kg N ha^{-1}[163]. In the present study, the greatest increase in seed yields (7–10%) was observed when 15 kg S ha^{-1} was applied in combination with ≤60 kg N ha^{-1}. In treatments with higher N rates (90 and 120 kg ha^{-1}), the application of 15 kg S ha^{-1} increased seed yields by only 1% and 5%, respectively.

In oilseed radish, straw yields range from 3.1 to 5.6[95] to 7.4–9.2 Mg ha^{-1} DM (present study: Fig. 2). White mustard and spring oilseed rape are the only spring *Brassica* oilseed crops with similar straw yields to oilseed radish[90,96]. In Poland, the straw yields of the remaining *Brassica* oilseed crops (camelina, crambe, Indian mustard, oil flax) do not exceed 4.5 Mg ha^{-1} DM[62,63,90,92,97,98]. In this study, straw yields peaked in response to 30 kg N ha^{-1} and 15 kg S ha^{-1}. In spring *Brassica* oilseed crops, N fertilization exerts a more ambiguous influence on straw yields than seed yields. In the work of Stolarski et al.[98], the N rate did not differentiate straw yields in crambe or camelina. In turn, Jankowski and Sokólski[62] found that straw yields in spring camelina peaked in response to 80 kg N ha^{-1} + 30 kg S ha^{-1} or 120 kg N ha^{-1} + 0 kg S ha^{-1} (increase of 45% relative to the production technology without N and S fertilization). In crambe, straw yields increased by 13–29% after the application of ≥60 kg N ha^{-1}[163]. Sulfur fertilization increased straw yields in crambe (by 5–26%) only in treatments supplied with ≤90 kg N ha^{-1}. When the N rate was increased to 120 kg ha^{-1}, S induced a significant decrease (1–7%) in the straw yields of crambe[63]. In the present study, the straw yields of oilseed radish decreased by 3% when S was applied in the absence of N fertilization. Sulfur induced the greatest increase in straw yields (14%) in plots supplied with 30 kg N ha^{-1}. A further increase in the N rate decreased the yield-forming effect of S (60 and 90 kg N ha^{-1}) or decreased straw yields (120 kg N ha^{-1}).

The EO of oilseed radish seeds ranges from 18.8[88] to 27.7 GJ ha^{-1} (present study: Table 4). The EO of seeds and straw was determined in the range of 56.7[88] to even 164.4 GJ ha^{-1} (present study: Table 4). In *Brassica* oilseed crops, the EO of seeds is influenced mainly by N fertilization, provided that N contributes to increasing seed yi elds[59,60,62,99–102]. In the current study, N increased the EO of oilseed radish seeds by 38% relative to the control treatment (18.9 GJ ha^{-1}). The EO of seeds peaked (27.7 GJ ha^{-1}) in response to 60 kg N ha^{-1} and 15 kg S ha^{-1}. A further increase in the N rate (> 60 kg N ha^{-1}) had no effect on the EO of seeds, regardless of S fertilization. Other studies of spring *Brassica* oilseed crops also demonstrated that N fertilization has a positive influence on the EO of seeds[62,63,101,103]. In the work of Jankowski et al.[63], the application of 120 kg N ha^{-1} increased the EO of crambe seeds by 43% relative to the control treatment (26.13 GJ ha^{-1}). In camelina, higher N rates increased the EO of seeds by 20%[101] to even 64–71%[62,103]. According to Jankowski and Sokólski[62] and Jankowski et al.[63], S should be incorporated into the fertilization plans of crambe and camelina. The EO of crambe seeds peaked (40.56 GJ ha^{-1}) in response to 120 kg N ha^{-1} and 30 kg S ha^{-1}[163]. In turn, the greatest increase in the EO of camelina seeds (52.89 GJ ha^{-1}) was observed after the application of 160 kg N ha^{-1} and 30 kg S ha^{-1}[162].

The present study demonstrated that the EO of total biomass (seeds and straw) is strongly affected by N and S rates. The EO of oilseed radish straw peaked (164.4 GJ ha^{-1}) in response to 30 kg N ha^{-1} and 15 kg S ha^{-1}. Stolarski et al.[101], Jankowski and Sokólski[62], and Jankowski et al.[63] also found that N and S fertilization enhanced the EO of biomass in other spring *Brassica* oilseed crops. In crambe and camelina, the EO of biomass increased significantly after the application of 90 kg N ha^{-1} (crambe)[63] and 60–120 kg N ha^{-1} (camelina)[62,101]. In both crambe and camelina, higher N rates (> 80–90 kg N ha^{-1}) exerted a positive effect on the EO of seeds and straw in treatments that were additionally supplied with S[62,63]. In this study, no significant improvement in the EO of oilseed radish biomass was observed in response to S application at N rates higher than 30 kg ha^{-1}.

Energy gain and the energy efficiency ratio

Siqueira et al.[88] and Akdemir et al.[104] found that EG in the production of oilseed radish seeds in Turkey ranged from 12.1 do 18.5 GJ ha^{-1}. Energy gain was similar in the production of oilseed radish seeds in the present experiment (10.6–16.7 GJ ha^{-1}). In Europe, EG is generally lower in the production of oilseed radish seeds than other spring *Brassica* oilseed crops. The EG in the production of crambe, white mustard, and camelina seeds was determined at 19–26[63], 27[90], and 13–35 GJ ha^{-1}[162], respectively. In oilseed crops of the family *Brassicaceae*, the highest EG was noted in winter oilseed rape seeds (from 40 to 62 to even 99–126 GJ ha^{-1})[59,90,99,100,105]. The EG from *Brassica* oilseed crops is much higher when the energy value of straw is included in the analysis[59,62,63,88,90]. In the work of Siqueira et al.[88] and in the present study (Table 4), the EG from the total biomass of oilseed radish was 4 to 10 times higher than the EG from seeds only. In other spring *Brassica* oilseed crops, the EG from total biomass was 2.4 (crambe and camelina) to 5 times (white mustard) higher than the EG from seeds only[62,63,90]. The EG from winter oilseed rape increased by 231–268% when straw was included in the analysis[59,90]. The proportional increase in the EG from total biomass relative to the EG from seeds only is much greater in winter oilseed rape than in spring *Brassica* oilseed crops because winter oilseed rape is characterized by higher values of the harvest index[106–108]. In the present study, the average EG from the total biomass of oilseed radish reached 135 GJ ha^{-1}, which is similar to the values noted in white mustard (135 GJ ha^{-1}) and much higher than the values reported in crambe (50–58 GJ ha^{-1}), camelina (51–71 GJ ha^{-1}), and Indian mustard (86 GJ ha^{-1})[62,63,90,97]. In the current study, the EG from the total biomass of oilseed radish was 7–36% higher than that achieved in high-input production technologies of winter oilseed rape seeds[90,99,100]. These observations indicate that oilseed radish seeds and straw produced in north-eastern Poland constitute a competitive source of bioenergy relative to winter oilseed rape seeds.

Nitrogen fertilization significantly increases EG in the cultivation of *Brassica* oilseed crops by exerting a positive impact on FMYand DMY. The extent to which N fertilization affects EG is determined by NFUE, i.e. the yield-forming effect of N[63]. In the present study, EG in oilseed radish cultivation peaked in response to 30 kg N ha^{-1} and 15 kg S ha^{-1} in both biomass production variants. In the work of Stolarski et al.[101] and Jankowski et al.[63], the EG from crambe seeds or total biomass (seeds and straw) produced in north-eastern Poland was not significantly differentiated by N fertilization. Jankowski et al.[63] found that EG in the production of crambe seeds and total biomass increased only after S was incorporated into the fertilization regime. Energy gain peaked in response to 60 kg N ha^{-1} and 30 kg S ha^{-1} (seeds) or 90 kg N ha^{-1} and 30 kg S ha^{-1} (total biomass)[63]. Jankowski and Sokólski[62] also reported a strong relationship between EG and N and S rates in camelina cultivation. An increase in the N rate to 160 kg ha^{-1} induced a gradual increase in the EG from camelina seeds in treatments that were additionally supplied with 30 kg S ha^{-1}. The highest EG from camelina biomass was noted in response to 80 kg N ha^{-1} and 30 kg S ha^{-1}[62]. According to Groth et al.[99], indicates that in winter oilseed rape cultivation, the relationship between N and S fertilization and EG subject to a cultivar's yield potential. In open-pollinated and semi-dwarf hybrid cultivars, the EG from seed production peaked in response to 230 kg N ha^{-1} and 40 kg S ha^{-1}. In a high-yielding long-stem hybrid cultivar, the highest EG from seeds was achieved after the application of 180 kg N ha^{-1} without S fertilization[99].

The EER of oilseed radish seeds ranges from 1.6[104] to 2.8–3.4[88] (present study: Table 4). In production variants where both seeds and straw are harvested, the EER is determined in the range of 8.4–9.9[88] (present study: Table 4) to even 12–21[present study: Table 4]. An increase in EI resulting from higher rates of mineral fertilizers (mainly N) leads to a considerable decrease in the EER of crop production[109]. Jankowski et al.[63] found that an increase in the N rate from 30 to 120 kg ha^{-1} decreased the EER of crambe by 23–48% (seeds) and 25–50% (seeds and straw). The EER of camelina decreased by 17–53% (seeds) and 22–57% (seeds and straw) when the N rate was increased from 40 to 160 kg ha^{-1}[62]. In the present study, a similar decrease in the EER of oilseed radish seeds and total biomass (by 15–47% and 21–56%, respectively) was observed when the N rate was increased from 30 to 120 kg ha^{-1}. The application of 15 kg S ha^{-1} in treatments supplied with N decreased the EER of oilseed radish seeds by 4–8%, but had no effect on the EER of total biomass. The EER of oilseed radish seeds peaked after the application 15 kg S ha^{-1} without N fertilization. The EER of total biomass was highest in the absence of N and S fertilization. In camelina and crambe, the EER of seeds and total biomass was also highest in treatments without N and S fertilization[62,63].

Conclusions

The demand for energy in the cultivation technology of oilseed radish ranged from 6.8 to 7.1 (0 kg N ha^{-1}) to 16.2–16.5 GJ ha^{-1} (120 kg N ha^{-1}). Nitrogen and S fertilization increased EI by 34–135% and 1–4%, respectively. Mineral fertilizers had a 57–70% share of total EI in the cultivation technology of oilseed radish, where chemically-bound energy accumulated in fertilizers accounted for 88–98% and fertilizer application accounted for 2–12% of that value. The above implies that in oilseed radish cultivation, a significant decrease in EI can be achieved only by decreasing fertilizer rates. Changes in the fertilizer application method can induce only minor differences in EI. In north-eastern Poland, the seed and straw yields of oilseed radish were determined at 0.69–1.02 and 7.4–9.2 Mg ha^{-1} DM, respectively. Seed yields peaked (1.01 Mg ha^{-1} DM) in response to 120 kg N ha^{-1} and 15 kg S ha^{-1}, whereas the highest straw yield (9.25 Mg ha^{-1} DM) was noted after the application of 30 kg N ha^{-1} and 15 kg S ha^{-1}. The EO of seeds was highest (27.7 GJ ha^{-1}) when oilseed radish was supplied with 60 kg N ha^{-1} and 15 kg S ha^{-1}. The EO of total biomass (straws and seeds) peaked (164.4 GJ ha^{-1}) in response to 30 kg N ha^{-1} and 15 kg S ha^{-1}. Energy gain in oilseed radish cultivation reached 10.6–16.7 (seeds) and 117.6–155.0 GJ ha^{-1} (seeds and straw). The EG from seeds and total biomass peaked in response to 30 kg N ha^{-1} and 15 kg S ha^{-1}. The EER of seeds ranged from 1.68 to 3.43, and it was highest when S was applied at 15 kg ha^{-1} (without N fertilization). Nitrogen fertilization decreased the EER of seeds and total biomass by 15–47% and 21–56%, respectively. The application of 15 kg S ha^{-1} reduced the N-induced decrease in the ERR of seeds and total biomass by 4–8% and 4–10%, respectively. In large-area farms, where energy is the main limiting factor, the EER of oilseed radish seeds can be improved by applying 15 kg S ha^{-1} without N fertilization, whereas the EER of total biomass (seeds and straw) can be maximized by abstaining from both N and S fertilization. In small-area farms, where land is the main limiting factor, oilseed radish should be fertilized with 30 kg N ha^{-1} and 15 kg S ha^{-1} to maximize the EG per unit area.

In the future, the energy potential of oilseed radish should be analyzed in a broader context by conducting research in regions with different climatic and soil conditions. The environmental impact of N and S fertilization, especially potential soil and groundwater pollution and greenhouse gas emissions, should also be considered in a comprehensive assessment of oilseed radish production technology. In addition, the economic analysis of radish biofuel production should be extended to include production costs, market demand, and policy support in order to estimate the actual application potential of this energy crop in the context of global trends on the biofuel market.

Data availability

All data generated or analysed during this study are included in this published article.

Received: 1 July 2024; Accepted: 14 March 2025
Published online: 21 March 2025

References

1. Ritchie, H. & Rosado, P. *Energy Mix*. https://ourworldindata.org/energy-mix?country=#energy-mix-what-sources-do-we-get-our-energy-from (2024).
2. British Petroleum. BP Energy Outlook. (2019). Edition https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf (2019).
3. Shafiee, S. & Topal, E. When will fossil fuel reserves be diminished? *Energy Policy*. **37**, 181–189 (2009).
4. Umar, M., Ji, X., Kirikkaleli, D. & Alola, A. A. The imperativeness of environmental quality in the united States transportation sector amidst biomass-fossil energy consumption and growth. *J. Clean. Prod.* **285**, 124863 (2021).

5. Guo, X., Liang, C., Umar, M. & Mirza, N. The impact of fossil fuel divestments and energy transitions on mutual funds performance. *Technol. Forecast. Soc. Change*. **176**, 121429 (2022).
6. Holechek, J. L., Geli, H. M. & Sawalhah, M. N. Valdez R. A global assessment: can renewable energy replace fossil fuels by 2050? *Sustainability* **14**, 4792 (2022).
7. Ghadikolaei, M. A. et al. Why is the world not yet ready to use alternative fuel vehicles? *Heliyon* **7**, e07527 (2021).
8. Sandaka, B. P. & Kumar, J. Alternative vehicular fuels for environmental decarbonization: A critical review of challenges in using electricity, hydrogen, and biofuels as a sustainable vehicular fuel. *Chem. Eng. J. Adv.* **14**, 100442 (2023).
9. Energy Information Administration (EIA). International Energy Outlook 2019 with Projections to 2050. https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf (2019).
10. International Energy Agency (IEA). Energy Technology Perspectives (2020). https://www.iea.org/reports/energy-technology-perspectives-2020 (2020).
11. International Energy Agency (IEA). Global biofuel demand, historical, main and accelerated case, 2016–2028. https://www.iea.org/data-and-statistics/charts/global-biofuel-demand-historical-main-and-accelerated-case-2016-2028 (2023).
12. OECD-FAO. *Agricultural Outlook* (OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, 2018–2027). https://stats.oecd.org/index.aspx?queryid=84952#(2024).
13. Heimann, T. et al. Phasing out palm and soy oil biodiesel in the EU: what is the benefit? *GCB Bioenergy*. **16**, e13115 (2023).
14. Zhang, Q. et al. EU-Russia energy decoupling in combination with the updated NDCs impacts on global fossil energy trade and carbon emissions. *Appl. Energy*. **356**, 122415 (2024).
15. Directive 2009/28/EC & Directive /28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Off. J. Europ. Union* (2009).
16. Directive 2018/2001. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *Off. J. Europ. Union.* (2018).
17. Regulation 2023/1115. Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the union market and the export from the union of certain commodities and products associated with deforestation and forest degradation and repealing regulation (EU) 995/2010. *Official J. Europ Union* (2023).
18. United States Department of Agriculture. *Biofuels Annual.* (2023). https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_The%20Hague_European%20Union_E42023-0033
19. Faostat. *Food and Agriculture Organization Corporate Statistical Database*. (2024). http://www.apps.fao.org
20. Braun, H. J., Atlin, G., Payne, T. & Reynolds, M. P. Multi-location testing as a tool to identify plant response to global climate change. In *Climate Change and Crop Production* (ed Reynolds, M. P.) 115–138 (CABI, 2010).
21. Alexandratos, N. & Bruinsma, J. *World Agriculture towards 2030/2050: The 2012 Revision*. (FAO, 2012).
22. Riaz, M. W. et al. Effects of heat stress on growth, physiology of plants, yield and grain quality of different spring wheat (*Triticum aestivum* L.) genotypes. *Sustainability* **13**, 2972 (2021).
23. Khalid, A., Hameed, A. & Tahir, M. F. Wheat quality: A review on chemical composition, nutritional attributes, grain anatomy, types, classification, and function of seed storage proteins in bread making quality. *Front. Nutr.* **10**, 1053196 (2023).
24. McIntosh, C., Smith, S. & Withers, R. Energy balance of -on-farm production and extraction of plant oil for fuel in the united States' inland Northwest. *Energy Agric.* **3**, 155–166 (1984).
25. Mizik, T. & Gyarmati, G. Economic and sustainability of biodiesel production—a systematic literature review. *Clean. Technol.* **3**, 19–36 (2021).
26. Schillaci, C. et al. Assessing marginality of camelina (*C. sativa* L. Crantz) in rotation with barley production in Southern Europe: A modelling approach. *Agric. Ecosyst. Environ.* **357**, 108677 (2023).
27. Zanetti, F. et al. The opportunities and potential of camelina in marginal land in Europe. *Ind. Crops Prod.* **211**, 118224 (2024).
28. Von Cossel, M. et al. Marginal agricultural land low-input systems for biomass production. *Energies* **12**, 3123 (2019).
29. Tsytsiura, Y. The influence of agroecological and Agrotechnological factors on the generative development of oilseed radish (*Raphanus sativus Var. Oleifera* Metzg). *Agron. Res.* **4**, 842–880 (2022).
30. Szatkowski, A., Antoszkiewicz, Z., Purwin, C. & Jankowski, K. J. Oilseed radish: nitrogen and sulfur management strategies for seeds yield and quality. A case study in Poland. *Agriculture* **14**, 755 (2024).
31. Prakhova, T. Y., Prakhov, V. A., Brazhnikov, V. N. & Brazhnikova, O. F. Oil seed crops-biodiversity, value and productivity. *Vol Reg. Farm.* **3**, 18–23 (2019).
32. Toboła, P. & Muśnicki, C. Yielding variability of spring sown oilseed crops of cruciferous family. *Rośliny Oleiste-Oilseed Crops*. **20**, 93–100 (1999). [in Polish].
33. Ražukas, A. & Nedzinskienė, T. L. Pašarinių Ridikų (*Raphanus sativus* L. *Var. Oleiformis* Pers) 'VB Gausiai' auginimas Sėklai Ir Žaliai Masei. *Žemdirbzstė – Agric.* **95**, 86–92 (2008). [in Lithuanian].
34. Faria, D. et al. Extraction of radish seed oil (*Raphanus sativus* L.) and evaluation of its potential in biodiesel production. *AIMS Energy*. **6**, 551–565 (2018).
35. Stevanato, N. & Silva, C. Radish seed oil: Ultrasound-assisted extraction using ethanol as solvent and assessment of its potential for ester production. *Ind. Crops Prod.* **132**, 283–291 (2019).
36. Valle, P. W. P. A., Rezende, T. F., Souza, R. A., Fortes, I. C. P. & Pasa, V. M. D. Combination of fractional factorial and Doehlert experimental designs in biodiesel production: Ethanolysis of *Raphanus sativus* L. Var. *Oleiferus* Stokes oil catalyzed by sodium ethoxide. *Energ. Fuel.* **23**, 5219–5227 (2009).
37. Valle, P., Velez, A., Hegel, P., Mabe, G. & Brignole, E. A. Biodiesel production using supercritical alcohols with a non-edible vegetable oil in a batch reactor. *J. Supercrit Fluids*. **54**, 61–70 (2010).
38. Chammoun, N., Geller, D. P. & Das, K. C. Fuel properties, performance testing and economic feasibility of *Raphanus sativus* (oilseed radish) biodiesel. *Ind. Crop Prod.* **45**, 155–159 (2013).
39. Silva, S. B., Garcia, V. A. S., Arroyo, P. A. & Silva, C. Ultrasound-assisted extraction of radish seed oil with Methyl acetate for biodiesel production. *Can. J. Chem. Eng.* **95**, 2142–2147 (2017).
40. Polaczek, K. & Kurańska, M. Hemp seed oil and oilseed radish oil as new sources of Raw materials for the synthesis of bio-polyols for open-cell polyurethane foams. *Materials* **24**, 8891 (2022).
41. Knutsen, H. K. et al. Erucic acid in feed and food. *EFSA J.* **14**, 173 (2016).
42. Silveira Junior, E. G. et al. Biodiesel production from non-edible forage turnip oil by extruded catalyst. *Ind. Crops Prod.* **139**, 111503 (2019).
43. Ramos, M., Dias, A. P., Puna, J. F., Gomes, J. & Bordado, J. C. Biodiesel production processes and sustainable Raw materials. *Energies* **12**, 4408 (2019).
44. Ravikumar, V. et al. Production of *Raphanus sativus* biodiesel and its performance assessment in a thermal barrier-coated agriculture sector diesel engine. *Energy Technol.* **11**, 2300235 (2023).
45. Stevanato, N., de Mello, B. T. F., Saldaña, M. D. A., Cardozo-Filho, L. & Silva, C. Production of Ethyl esters from forage radish seed: an integrated sequential route using pressurized ethanol and Ethyl acetate. *Fuel* **332**, 126075 (2023).
46. Jankowski, K., Bielski, S. & Szempliński, W. Industrial crops. In *Agricultural Crops* (ed Szempliński, W.) 306–446 (Publishing House of the University of Warmia and Mazury in Olsztyn, 2012).
47. Kołodziejczyk, M. & Kulig, B. Oilseed radish. In *Plant Cultivation–III* (ed Kotecki, A.) 393–399 (Publishing House of the Wrocław University of Environmental and Life Sciences, 2020).

48. Panwar, A. S., Verma, V. S. & Bawa, R. Growth and seed yield of radish (*Raphanus sativus*) as influenced by nitrogen and biofertilizer application. *Indian J. Agron.* **45**, 411–415 (2000).
49. Seepaul, R., Small, I. M., Marois, J., George, S. & Wright, D. L. *Brassica carinata* and *Brassica Napus* growth, nitrogen use, seed, and oil productivity constrained by post-bolting nitrogen deficiency. *Crop Sci.* **59**, 2720–2732 (2019).
50. Wen, G. et al. Optimizing nitrogen fertilization for hybrid Canola (*Brassica Napus* L.) production across Canada. *Field Crops Res.* **302**, 109048 (2023).
51. Poisson, E. et al. Seed yield components and seed quality of oilseed rape are impacted by sulfur fertilization and its interactions with nitrogen fertilization. *Front. Plant. Sci.* **10**, 458 (2019).
52. Lykhochvor, A. Yield and seed quality of spring oilseed crops. *FPUTS Agric. Aliment. Piscaria Et Zootech.* **43**, 336 (2017).
53. Gan, Y., Malhi, S. S., Brandt, S., Katepa-Mupondwa, F. & Stevenson, C. Nitrogen use efficiency and nitrogen uptake of juncea Canola under diverse environments. *Agron. J.* **100**, 285–295 (2008).
54. Kumar, M., Singh, P. K., Yadav, K. G., Chaurasiya, A. & Yadav, A. Effect of nitrogen and sulphur nutrition on growth and yield of Indian mustard (*Brassica juncea* L.) in Western UP. *J. Pharma Phytochem*. **6**, 445–448 (2017).
55. Jankowski, K. J., Sokólski, M., Kordan, B. & Camelina Yield and quality response to nitrogen and sulfur fertilization in Poland. *Ind. Crops Prod.* **141**, 111776 (2019).
56. Sokólski, M. M., Załuski, D. & Jankowski, K. Crambe: seed yield and quality in response to nitrogen and sulfur—A case study in Northeastern Poland. *Agronomy* **10**, 1436 (2020).
57. Szempliński, W., Dubis, D., Lachutta, K. & Jankowski, K. J. Energy optimization in different production technologies of winter triticale grain. *Energies* **14**, 1003 (2021).
58. Bielski, S., Marks-Bielska, R. & Wiśniewski, P. Investigation of energy and economic balance and GHG emissions in the production of different cultivars of buckwheat (*Fagopyrum esculentum* Moench): A case study in northeastern Poland. *Energies* **16**, 17 (2023).
59. Budzyński, W. S., Jankowski, K. J. & Jarocki, M. An analysis of the energy efficiency of winter rapeseed biomass under different farming technologies. A case study of a large-scale farm in Poland. *Energy* **90**, 1272–1279 (2015).
60. Keshavarz-Afshar, R., Mohammed, Y. A. & Chen, C. Energy balance and greenhouse gas emissions of dryland camelina as influenced by tillage and nitrogen. *Energy* **91**, 1057–1063 (2015).
61. Greer, K., Martins, C., White, M. & Pittelkow, C. M. Assessment of high-input soybean management in the US Midwest: balancing crop production with environmental performance. *Agric. Ecosyst. Environ.* **292**, 106811 (2020).
62. Jankowski, K. J. & Sokólski, M. Spring Camelina: effect of mineral fertilization on the energy efficiency of biomass production. *Energy* **220**, 119731 (2021).
63. Jankowski, K. J., Sokólski, M., Szatkowski, A. & Kozak, M. Crambe – Energy efficiency of biomass production and mineral fertilization. A case study in Poland. *Ind. Crops Prod.* **182**, 114918 (2022).
64. Dubis, B. et al. Biomass yield and energy balance of fodder Galega in different production technologies: an 11-year field experiment in a large-area farm in Poland. *Renew. Energy*. **154**, 813–825 (2020).
65. Dubis, B., Jankowski, K. J., Załuski, D. & Sokólski, M. M. The effect of sewage sludge fertilization on the biomass yield of giant miscanthus and the energy balance of the production process. *Energy* **206**, 11818910 (2020).
66. Bogucka, B. & Jankowski, K. J. The effect of harvest strategy on the energy potential of Jerusalem artichoke. *Ind. Crops Prod.* **177**, 114473 (2022).
67. Jankowski, K. J. et al. The effect of sewage sludge on the energy balance of cup plant biomass production. A six-year field experiment in Poland. *Energy* **276**, 127478 (2023).
68. Barłóg, P. Improving fertilizer use efficiency-Methods and strategies for the future. *Plants* **12**, 3658 (2023).
69. Salvagiotti, F., Castellarín, J. M., Miralles, D. J. & Pedrol, H. M. Sulfur fertilization improves nitrogen use efficiency in wheat by increasing nitrogen uptake. *Field Crops Res.* **113**, 170–177 (2009).
70. Galić, M., Mesić, M., Perčin, A., Šestak, I. & Zgorelec, Ž. Sulphur balance in agroecosystem. *Bulg. J. Agric. Sci.* **3**, 104–118 (2018).
71. Barczak, B., Barczak, T., Skinder, Z. & Piotrowski, R. Proportions of nitrogen and sulphur in spring rapeseeds depending on fertilization with these elements. *J. Elem.* **25**, 1385–1398 (2020).
72. Jamal, A., Moon, Y. & Abdin, M. Sulphur – a general overview and interaction with nitrogen. *Aust J. Crop Sci.* **4**, 523–529 (2010).
73. Perveen, S. et al. Assessing the potential of polymer coated Urea and sulphur fertilization on growth, physiology, yield, oil contents and nitrogen use efficiency of sunflower crop under arid environment. *Agronomy* **11**, 269 (2021).
74. Głowacka, A., Jariene, E., Flis-Olszewska, E. & Kiełtyka-Dadasiewicz, A. The effect of nitrogen and sulphur application on soybean productivity traits in temperate climates conditions. *Agronomy* **13**, 80 (2023).
75. Jankowski, K. J., Budzyński, W. S., Kijewski, Ł. & Zając, T. Biomass quality of *Brassica* oilseed crops in response to sulfur fertilization. *Agron. J.* **107**, 1377–1391 (2015).
76. Zhao, F., Evans, E. J., Bilsborrow, P. E. & Syers, J. K. Influence of sulphur and nitrogen on seed yield and quality of low glucosinolate oilseed rape (*Brassica Napus* L). *J. Sci. Food Agric.* **63**, 29–37 (1993).
77. Ahmad, A., Abraham, G., Gandotra, N., Abrol, Y. P. & Abdin, M. Z. Interactive effect of nitrogen And sulphur on growth And yield of rape-seed-mustard (*Brassica juncea* L. Czern. And Coss. And *Brassica Campestris* L.) genotypes. *J. Agron. Crop Sci.* **181**, 193–199 (1998).
78. Kovács, A. B., Kincses, I., Vágó, I., Loch, J. & Filep, T. Effect of application of nitrogen and different nitrogen-sulfur ratios on the quality and quantity of mustard seed. Commun. *Soil. Sci. Plant.* **40**, 453–561 (2009).
79. Lošák, T. et al. Effect of combined nitrogen and sulfur fertilization on yield and qualitative parameters of *Camelina sativa* [L.] Crtz. (false flax). *Acta Agric. Scand. Sect. B – Soil. Plant. Sci.* **4**, 313–321 (2011).
80. Jiang, Y., Caldwell, C. D., Falk, K. C., Lada, R. R. & MacDonald, D. Camelina yield and quality response to combined nitrogen and sulfur. *Agron. J.* **105**, 1847–1852 (2013).
81. Wysocki, D. J., Chastain, T. G., Schillinger, W. F., Guy, S. O. & Karow, R. S. Camelina: seed yield response to applied nitrogen and sulfur. *Field Crops Res.* **145**, 60–66 (2013).
82. Meier, U. Growth stages of mono- and dicotyledonous plants: BBCH Monograph. (2018). https://www.julius-kuehn.de/media/Veroeffentlichungen/bbch%20epaper%20en/page.pdf
83. IUSS Working Group WRB.World reference base for soil resources. (2022). https://eurasian-soil-portal.info/wp-content/uploads/2022/07/wrb_fourth_edition_2022-3.pdf (2022).
84. Wójcicki, Z. Equipment, materials and energy inputs in growth-oriented farmsIBMER, [in Polish]. (2000).
85. Fore, S. R., Porter, P. & Lazarus, W. Net energy balance of small-scale on-farm biodiesel production from Canola and soybean. *Biomass Bioenerg*. **35**, 2234–2244 (2021).
86. Kopetz, H., Jossart, J., Ragossnig, H. & Metschina, C. European biomass statistics. *Eur. Biomass Assoc. (AEBIOM)*, 1–73 (2007).
87. TIBCO Software Inc. Statistica (data analysis software System). *Version 13* (2017).
88. Siqueira, R., Gamero, C. A. & Boller, W. Energetic balance from biodiesel production of oilseed radish (*Raphanus sativus* L.). In *Proceedings of the International Conference of Agricultural Engineering* (Foz do Iguaçu, 2008). https://www.osti.gov/etdeweb/servlets/purl/21514432
89. Lima et al. D. C. Energetic balance of biodiesel production based on oilseed rape crop. *Magistra* **29**, 208–214 (2017).
90. Jankowski, K. J., Budzyński, W. S. & Kijewski, Ł. An analysis of energy efficiency in the production of oilseed crops of the family *Brassicaceae* in Poland. *Energy* **81**, 674–681 (2015).
91. Jankowski, K. & Budzyński, W. Energy potential oilseed crops. *Elect. J. Pol. Agric. Univ.* **6**, 2 (2003).

92. Bielski, S., Jankowski, K. & Budzyński, W. The energy efficiency of oil seed crops production and their biomass conversion into liquid fuels. *Przem Chem.* **93**, 2270–2273 (2014).
93. Nedzinskas, A. & Nedzinskienė, T. Effect of seed rate, interrow width and nitrogen fertilisation on oil radish grown for seed. *Žemdirbystė Mokslo Darbai*. **69**, 85–95 (2000).
94. Ukhanova, Y. V., Voskresensky, A. A. & Ukhanov, A. P. Comparative evaluation of the properties of vegetable oils used as bioadditives to petroleum diesel fuel. *Niva Povolzhia*. **43**, 98–105 (2017). [in Russian].
95. Pegoraro, T. et al. Use of swine wastewater in oilseed radish crop: agronomic and environmental aspects. *Semina: Ciênci Agrár.* **35**, 2931–2943 (2014).
96. Harasimowicz-Hermann, G., Wilczewski, E. & Kisielewska, W. Modelling biometric traits and straw yield of white mustard (*Sinapis Alba* L.) grown for seeds by the sowing date and meteorological factors. *Acta Sci. Pol. Agric.* **16**, 207–215 (2017).
97. Stolarski, M. J., Krzyżaniak, M., Kwiatkowski, J., Tworkowski, J. & Szczukowski, S. Energy and economic efficiency of camelina and crambe biomass production on a large-scale farm in north-eastern Poland. *Energy* **150**, 770–780 (2018).
98. Krzyżaniak, M. et al. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of central Europe. *Ind. Crops Prod.* **138**, 111443 (2019).
99. Groth, D. A., Sokólski, M. M. & Jankowski, K. J. A multi-criteria evaluation of the effectiveness of nitrogen and sulfur fertilization in different cultivars of winter rapeseed—Productivity, economic and energy balance. *Energies* **13**, 4654 (2020).
100. Sokólski, M., Jankowski, K. J., Załuski, D. & Szatkowski, A. Productivity, energy and economic balance in the production of different cultivars of winter oilseed rape. A case study in north-eastern Poland. *Agronomy* **10**, 508 (2020).
101. Stolarski, M. et al. Camelina and crambe production–Energy efficiency indices depending on nitrogen fertilizer application. *Ind. Crops Prod.* **137**, 386–395 (2019).
102. Rabiee, M., Majidian, M., Alizadeh, M. R. & Kavoosi, M. Evaluation of energy use efficiency and greenhouse gas emission in rapeseed (*Brassica Napus* L.) production in paddy fields of Guilan Province of Iran. *Energy* **217**, 119411 (2021).
103. Keshavarz-Afshar, R. & Chen, C. Intensification of dryland cropping systems for bio-feedstock production: energy analysis of camelina. *Bioenerg Res.* **8**, 1877–1884 (2015).
104. Akdemir, S., Ismailla, J. S. & Mavruk, A. An analysis of energy use and input costs for radish production in Turkey. *Sci. Papers Ser. Manag Econ. Eng. Agric. Rural Develop*. **23**, 13–20 (2023).
105. Jankowski, K. J., Sokólski, M. & Załuski, D. Winter oilseed rape: agronomic management in different tillage systems and energy balance. *Energy* **277**, 127590 (2023).
106. Gan, Y., Malhi, S. S., Kutcher, H. R., Brandt, S. & Katepa-Mupondwa, F. Optimizing the production of *Brassica juncea* Canola in comparison with other *Brassica* species, in different soil-climatic zones. *Project Code: CARP*, **11** (2008).
107. Lu, K. et al. A combination of genome-wide association and transcriptome analysis reveals candidate genes controlling harvest index-related traits in *Brassica Napus*. *Sci. Rep.* **6**, 36452 (2016).
108. Li, J. et al. Research advances on harvest index of *Brassica Napus* L. *Chin. J. Oil Crop Sci.* **40**, 640 (2018).
109. Paris, B. et al. Energy use in open-field agriculture in the EU: A critical review recommending energy efficiency measures and renewable energy sources adoption. *Renew. Sustain. Energy Rev.* **158**, 112098 (2022).

Acknowledgements
The results presented in this paper were obtained as part of a comprehensive study financed by the University of Warmia and Mazury in Olsztyn (grant No. 30.610.013–110). The study was funded by the Minister of Science under the Regional Initiative of Excellence Program. The authors would like to thank the staff of the AES in Bałcyny for technical support during the experiment.

Author contributions
Conceptualization (K.J.J and A. S.); methodology (K.J.J and A. S.); software (K.J.J and A. S.); validation (K.J.J and A. S.); formal analysis (K.J.J.); investigation (K.J.J and A. S.); resources (K.J.J and A. S.); data curation (K.J.J and A. S.); writing - original draft preparation (K.J.J and A. S.); writing - review and editing (K.J.J.); visualization (K.J.J and A. S.); supervision (K.J.J.); project administration (K.J.J and A. S.); funding acquisition (K.J.J and A. S.).

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-94537-6.

Correspondence and requests for materials should be addressed to K.J.J.