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Energy efficiency of spring camelina production under an organic system in sole-cropping and intercropping cultivation

Mariusz Jerzy Stolarski [a,b,*], Michał Krzyżaniak [a,b], Ewelina Olba-Zięty [a,b], Jakub Stolarski [a]

[a] University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Department of Genetics Plant Breeding and Bioresource Engineering, Plac Łódzki 3, Olsztyn 10-724, Poland
[b] University of Warmia and Mazury in Olsztyn, Centre for Bioeconomy and Renewable Energies, Plac Łódzki 3, Olsztyn 10-724, Poland

A R T I C L E I N F O

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A B S T R A C T

Camelina and spelt are crop species enjoying a renaissance in recent years. This three-year study (2022–2024) conducted in north-eastern Poland aimed to determine the energy inputs, the amount of accumulated energy, and the energy efficiency of the production of seed and straw of spring camelina and spring spelt cultivated under an organic system in sole-cropping and intercropping. In the energy inputs, direct energy carriers, exploitation of fixed assets, consumption of materials and human labor are considered. Total energy inputs for the production of sole-cropped camelina amounted to an average of 10.60 GJ ha^{-1}. In comparison, the energy inputs for spelt were 15.3 % higher, while camelina intercropped with spelt had energy inputs that were 30.4 % higher than those of sole-cropped camelina. The total biomass energy value (seeds and straw) for spelt (an average of 103.85 GJ ha^{-1}) was 9 % higher than the average value of this characteristic for sole-cropped camelina, and for camelina intercropped with spelt (an average of 95 GJ ha^{-1}). The total energy ratio values for sole-cropped camelina averaged 8.98, whereas sole-cropped spelt and camelina intercropped with spelt were 5.5 % and 22.2 % lower, respectively. Camelina cultivated under an organic system proved to be an interesting species in terms of energy efficiency indices for both sole-cropping and intercropping, although spelt had an advantage over camelina in intercropping.

1. Introduction

In recent years, increasing attention has been paid to crop diversification in agriculture due to its resulting benefits. Potential benefits include an overall increase in soil fertility, increased resistance to pests, diseases and weeds, increased crop yields, improved crop quality, and reduced environmental stresses (Zanetti et al., 2021, 2024; Codina-Pascual et al., 2024). Therefore, there has been a return to the cultivation of older (partly forgotten) crop species. One such species is camelina (*Camelina sativa* L.) (Crantz), which belongs to the group of oil-bearing crops that are enjoying a renaissance (Gesch, 2014; Berti et al., 2016; Zanetti et al., 2017, 2021; Bakhshi et al., 2021; Wang et al., 2022), is of particular interest. Camelina is characterized by low energy inputs for the production, extensive environmental adaptability, relatively high resistance to pests and diseases, and the potential for multi-directional use of the seeds, oil and residual biomass (straw, cake) for the production of bioproducts and biofuels (Zanetti et al., 2013, 2021; Keshavarz-Afshar et al., 2015; Karlsson Potter et al., 2023). Camelina oil has interesting properties compared with other oil crops typically cultivated in Poland, such as rapeseed or flax. Compared with rapeseed, camelina shows a considerably higher linolenic acid content, which, however, is lower than in flax. However, the oxidative stability of camelina oil is higher than that of flax, as confirmed by long-term storage tests. Camelina oil is distinguished from all typically cultivated oil crops by a high content of gondoic acid, which is used in the chemical industry as a bio-based polymer, surfactant and lubricant due to its high molecular weight and unsaturation (Biermann et al., 2021). Therefore, camelina has also been the subject of many basic research studies assessing the impact of various stress conditions, e.g. drought, irrigation, salinity, or electromagnetic waves, on this species (Teimoori et al., 2023; Fereidooni et al., 2024; Heidari and Hosseini, 2024; Khashayarfard et al., 2024; Seyed Hassan Pour et al., 2024). For the group of cereal

* Corresponding author at: University of Warmia and Mazury in Olsztyn, Faculty of Agriculture and Forestry, Department of Genetics Plant Breeding and Bioresource Engineering, Plac Łódzki 3, Olsztyn 10-724, Poland.
E-mail address: mariusz.stolarski@uwm.edu.pl (M.J. Stolarski).

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crops, a species that has been enjoying a renaissance is spelt (*Triticum spelta* L.) (Jankovic et al., 2015; Vojnov et al., 2020; Wiwart et al., 2023; Wanic et al., 2024). The cultivation of various crop species, including the older and currently less common ones, in various combinations including sole-cropping, intercropping, mixed cropping, double-cropping and relay-cropping, or grown as intermediate crops, contributes to a reduction in monocultures of typical cereal and oil-bearing crop species, reduces the need for fertilizers and plant protection products, limits the development of diseases and pests, and can therefore offer an interesting alternative to farmers (Berti et al., 2015, 2017a,b; Zanetti et al., 2021; Gesch et al., 2022; Fares and Mamine, 2023; Yang et al., 2024; Pagani et al., 2024; Marcheva et al., 2024; Wanic et al., 2024). Spelt is characterized by a higher protein content (up to 17 %) in the grain than that of the common wheat that is typically cultivated in Poland (Ratajczak et al., 2020). In addition, it is characterized by higher digestibility, higher Zn, Fe, Cu, Mo, and B, and phytosterol contents (Suchowilska et al., 2012). The presence of a hard adherent hull also protects spelt seeds against fungi and the accumulation of pollutants, mycotoxins and insect damage.

Consequently, there has been growing interest in the production of niche plant species and the multidirectional use of their biomass. Research work and implementations regarding the production and use of camelina and spelt biomass are promising. It should be stressed, however, that a very important aspect in assessing the validity of the production of these species is the assessment of energy inputs and energy efficiency of biomass yields, including the seeds and straw. This is important because the energy inputs incurred in the production and energy efficiency are not affected by market turbulences related to changes in input prices (as is the case when assessing economic efficiency). For this reason, energy efficiency indices, such as energy input, energy output, energy ratio or energy intensity, are more stable in time and space and, therefore, offer reliable opportunities for comparing different technologies of the production of selected annual or perennial crop species. The energy inputs related to biomass production are primarily determined by the crop species, the farming system and the cultivation technology applied, including mainly the inputs (fuels, mineral or organic fertilizers, plant protection products, seeds, etc.) and the agricultural operations used (Budzyński et al., 2015; Dubis et al., 2019; Jankowski et al., 2016, 2021, 2022; Stolarski et al., 2017, 2024). In turn, the energy balance of the production of a particular crop species is determined, on the one hand, by the yield of biomass harvested and the energy accumulated in it and, on the other hand, by the inputs incurred, including primarily mineral fertilization, in particular nitrogen (Jankowski et al., 2015; Stolarski et al., 2019). It was demonstrated, under a conventional camelina cultivation technology, that nitrogen fertilizers accounted for 32–80 % of the total energy inputs (Keshavarz-Afshar et al., 2015; Stolarski et al., 2019; Jankowski and Sokólski, 2021). Therefore, an important challenge is to search for opportunities to increase the yield-enhancing potential of the crop while using different forms of cultivation and reducing, or completely limiting, the use of mineral nitrogen fertilizers. Such opportunities are offered by the organic production of selected species under both sole-cropping and intercropping systems. For this reason, the novelty of the present study was to respond to the challenge of assessing the energy efficiency of the organic cultivation of sole-cropped and intercropped camelina. Therefore, the aim of the three-year study presented in this manuscript was to determine: (i) the energy inputs, (ii) the amount of accumulated energy, and (iii) the energy efficiency of the production of seeds and straw of spring camelina and spring spelt, sole-cropped and intercropped under an organic system.

2. Materials and methods

2.1. Field experiment

A field experiment was conducted in north-eastern Poland (N:53°59’31’’ E:20°32’84’’) on an organic farm. In three consecutive years (2022, 2023, 2024), the experiment was established on plots with an area of 9 m^2 each (width 1.5 m x length 6.0 m). The experiment cultivated spring spelt (the Oliwia variety bred at the Poznań University of Life Sciences, Poland) and spring spelt (the Wirtas variety, bred at the University of Warmia and Mazury in Olsztyn, Poland) under the sole-cropping and intercropping systems. Each species was cultivated under a sole-cropping and intercropping system in four replications, each year in a randomized block design. Sowing standards and dates, as well as crop harvest dates, are provided in Table 1. The experiment was carried out on brown soil, i.e., Eutric Cambisol, which was made from loamy sand resting on sandy loam. The mineral nitrogen content of the soil was 115 kg ha^{-1}, the organic carbon content was 1.76 %, the P_2O_5 content was 7.4 mg 100 g^{-1} soil, the K_2O content was 10.5 mg 100 g^{-1} of soil, and the pH value was 6.6.

It should be stressed that in each successive year of the study (2022, 2023, 2024), the average air temperature for the crop growing season (April-August) was 0.5, 1.6 and 1.9 ℃ higher, respectively, compared with the multi-year period (1991–2021), averaging 15.0 ℃. In contrast, in terms of the amount and distribution of precipitation, the year 2022 was decidedly the most favorable, with the sum of precipitation for the crop growing season amounting to 390 mm and being 11 % higher compared with the multi-year period value. A very similar amount of precipitation (386 mm) was noted in the growing season of 2024. However, its distribution was very unfavorable for plant growth and development because approximately 72 % of this precipitation occurred at the end of July and in August when plants had already completed their development. In contrast, precipitation was very low in the first three key months (April-June) of 2024. The situation was even worse in 2023, when the total precipitation for the crop growing season was only 258 mm, i.e., 27 % lower than the multi-year value. Moreover, the distribution of precipitation was very unfavorable, with a particularly large precipitation deficit noted in May 2023 (only 27 % of the multi-year value). In addition, as much as 49 % of precipitation occurred at the end of July and in August, when the plants were already finishing their development. This experiment applied no additional plant irrigation.

2.2. Energy input

In all the years of the study, the same traditional tillage system was applied for the production of camelina and spelt under sole-cropping and intercropping system. All the crops were cultivated under organic systems, i.e., no plant protection products or mineral fertilizers were used. It was assumed that cow manure would be applied at 40 Mg ha^{-1} once every four years in the ongoing crop rotation and that agricultural lacustrine lime, which is permitted in organic cultivation, would be applied at 7 Mg ha^{-1}. Therefore, analyses took into account 25 % of the energy inputs resulting from the application of manure and lime (Table 2). Each year, plowing was performed to a depth of 20 cm. The soil was then additionally tilled with a tillage unit, and seeds were sown in alternating rows. During the growing season, mechanical weeding was applied twice. The analyses assumed that all the species cultivated under both sole-cropping and intercropping systems were harvested in

Table 1
General information on the field experiment.

Year	Sowing date	Crop harvest date	Sowing standard under sole-cropping system (kg ha^{-1})		Sowing standard under intercropping system (kg ha^{-1})	
			Camelina	Spelt	Camelina	Spelt
2022	13 April	24 August	7.0	190.0	6.0	158.3
2023	14 April	23 August				
2024	11 April	31 July				

Table 2
Data on the camelina and spelt production technology.

Operation	Tractors / Combine harvester			Machinery		Operating period[a]	Comments
	Name	Mass (kg)	Power (kW) (max/used)	Name	Mass (kg)	(h ha^{-1})	
Manure application	Case Maxum 140	5845	103.0/61.8	Pichon M945 spreader	5300	1.9	every 4 years manure at 40 Mg ha^{-1}, i.e. an average of 10 Mg ha^{-1} y^{-1}, with an operating time of 0.48 h ha^{-1} y^{-1}
Lime application	Case Maxum 140	5845	103.0/61.8	Pichon M945 spreader	5300	0.9	every 4 years, lime at 7 Mg ha^{-1}, i.e. an average of 1.750 Mg ha^{-1} y^{-1}, with an operating time of 0.23 h ha^{-1} y^{-1}
Ploughing	Case Maxum 140	5845	103.0/77.3	Maschio Gaspardo plough, Siro Pas S 3–1 D95	1270	1.0	4-furrow plough, ploughing depth of 20 cm
Pre-sowing tillage	Case Maxum 140	5845	103.0/56.7	Batyra tilling unit	1500	0.9	operating width of 3 m
Sowing[b]	Case Maxum 140	5845	103.0/77.3	Kverneland Amazone seed drill	900	0.9	operating width of 3 m
Mechanical weeding (x2)	Case Maxum 140	5845	103.0/51.5	PRESSIUS weeding harrow	1450	1.0	operating width of 7.5 m
Harvesting	Class Mercator 75	6000	77.0/69.3	-	-	1.0	working width 3.6 m
Seed transport	Case Maxum 140	5845	103.0/51.5	Gromar tractor trailer	1870	0.2	load capacity of 7 Mg
Seed separation	-	-	-	PETKUS separation line	8530	1.3–3.6	average efficiency of 0.8 Mg h^{-1}, electricity consumption of 15.16 kWh h^{-1}

[a] human labor time was longer by 0.1 h ha^{-1} in each production operation due to the preparation of machinery for work
[b] the operating time in the intercropping cultivation of camelina and spelt was twice as long (x2) due to the separate sowing of seeds of these species

one stage with a Class Mercator 75 combine harvester. The harvested seeds were transported to the farm, whereas the straw remained in the field. After harvesting intercropped camelina and spelt, the seeds of the two species were separated from each other using a separation line.

The total energy inputs (GJ ha^{-1}) for the production of the species under study (camelina and spelt) under the sole-cropping system and under the intercropping system were determined based on the sum of inputs from four basic energy sources, i.e., direct energy carriers (diesel fuel), exploitation of fixed assets (tractors, combine harvester and other machines), consumption of materials (manure, lime, seeds) and human labor. The total energy input for the production of seeds and straw of the species under study, cultivated under the sole-cropping system and under the intercropping system, was calculated based on the quantity of materials consumed and the energy intensity of their production. The calculations adopted, after Neeft et al., (2011) and Szeptycki and Wójcicki, (2003), the following energy conversion coefficients: diesel fuel (43.1 MJ kg^{-1}), manure (0.3 MJ kg^{-1}), lime (1.97 MJ kg^{-1} CaO), camelina seeds (12 MJ kg^{-1}), spelt seeds (9 MJ kg^{-1}), tractors and combine harvester (125 MJ kg^{-1}), machinery (110 MJ kg^{-1}), and human labor (60 MJ $hour^{-1}$).

2.3. Biomass yield and energy efficiency indices

In the successive years of the study, at the time of harvesting the camelina and spelt crops, the seeds and straw collected from the plots were weighed, and the obtained yield was converted into an area of 1 ha (Mg ha^{-1}). When harvesting the crops, seed and straw samples were collected for laboratory analyses. The laboratory determined the moisture content (%) in a dryer and the higher heating value (HHV) using a bomb calorimeter for the seeds and straw. Based on the yield of seeds and straw (Mg ha^{-1} d.m.) as well as their HHV (GJ Mg^{-1} d.m.), the total biomass yield energy value (GJ ha^{-1}) was calculated. In the next step, based on the difference between the total biomass yield energy value and the total input for their production, the accumulated energy gain (GJ ha^{-1}) was calculated. Another index was the energy intensity (GJ Mg^{-1} d.m. seeds or straw), which was calculated as the ratio of total energy input to the yield of seeds or straw. Diesel fuel consumption was also determined in relation to the seeds (kg^{-1} d.m.) and straw produced (kg^{-1} d.m.). Another index was the energy efficiency ratio of seeds or straw production (as well as their total value), which was calculated as the ratio of the yield energy value (energy output) to total energy input for its production (energy input).

2.4. Statistical analysis

The normality of the characteristics under study was checked using the Shapiro-Wilk test. The statistical analysis was conducted based on a three-factor analysis of variance to determine the effect of the crop species (factor A), the cultivation method (factor B), and the year (factor Y), and all the interactions between these main factors on the seed yield, straw yield, seed yield energy value, straw yield energy value, total yield energy value, energy gain, seed energy intensity, fuel consumption for seed, fuel consumption for straw, seed energy ratio, straw energy ratio and total energy ratio. For all characteristics under study, the arithmetical averages and the standard error were calculated. Using Tukey's multi-comparison honest significance test (HSD), homogeneous groups were determined at a significance level of $P < 0.05$. In addition, a similarity analysis was conducted for the species under study, and the indices were analyzed. A multidimensional cluster analysis was applied, agglomeration was carried out using Ward's method, and Euclidean distances were used as a measure of distance. The cut-off significance was adopted based on the Sneath criterion at levels of 33 % and 66 %. All statistical analyses were conducted using STATISTICA 13 software (TIBCO Software Inc.).

3. Results and discussion

3.1. Biomass yield and its energy value

The yields of seeds and straw varied significantly ($P < 0.001$) depending on the species, the cultivation method and the year of the study (Table 3). The highest average yield of seeds from three years of the study (2.28 Mg ha^{-1} d.m.) was obtained from spelt cultivated under the sole-cropping system (Table 4). The average yield of camelina seeds cultivated under the sole-cropping system was lower and amounted to 1.46 Mg ha^{-1} d.m. In contrast, the average yield from intercropping

Table 3
The results of analysis of variance (ANOVA) – *P* values for the studied attributes.

Source of variation	df	Seed yield	Straw yield	Seed yield energy value	Straw yield energy value	Total yield energy value	Energy gain	Seed energy intensity	Straw energy intensity	Fuel consumption for seed	Fuel consumption for straw	Seed energy ratio	Straw energy ratio	Total energy ratio
Species (A)	1	< 0.001*	< 0.001*	0.259	< 0.001*	0.008*	0.012*	0.106	0.106	0.009*	0.001*	0.939	0.037*	0.257
Cultivation method (B)	1	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	0.010*	0.030*	0.007*	0.011*	< 0.001*	< 0.001*	< 0.001*
Year (Y)	2	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	0.001*	< 0.001*	0.002*	< 0.001	< 0.001*	< 0.001*	< 0.001*
AB	1	0.429	0.118	0.522	0.128	0.235	0.183	0.214	0.128	0.109	0.044*	0.171	0.013*	0.036*
AY	2	< 0.001*	0.210	< 0.001*	0.208	0.002*	0.002*	0.178	0.707	0.254	0.856	< 0.001*	0.341	0.008*
BY	2	0.120	0.385	0.196	0.406	0.248	0.236	0.128	0.993	0.091	0.984	0.153	0.148	0.119
ABY	2	0.048*	0.008*	0.083	0.008*	0.157	0.157	0.166	0.013	0.128	0.017*	0.080	0.008*	0.163
Error	36													

*significant values ($P < 0.05$)

cultivation of these two species was 1.76 Mg ha^{-1} d.m., with the yield of spelt amounting to 67 % and the yield of camelina to 33 %. The weather conditions in the cultivation years under study had a significant effect on crop yields, with the highest yields obtained in 2022, when the amount and distribution of precipitation were most favorable, and air temperatures were slightly higher compared with the multi-year period values. Under these conditions, spelt yielded at a rate of 4 Mg ha^{-1} d.m., and camelina at a rate of 1.5 Mg ha^{-1} d.m. In contrast, the yield from intercropping cultivation was 2.9 Mg ha^{-1} d.m., with the proportion of spelt dominating again. Moreover, in another study, the yield of camelina seeds with no fertilization was, on average, 1.43 Mg ha^{-1} d.m., and ranged from 1.04 to 1.87 Mg ha^{-1} d.m., which was close to the results obtained in the present study (Stolarski et al., 2019). Even more previous studies (Schillinger et al., 2012; Berti et al., 2016; Zanetti et al., 2017) have shown that the yield of camelina seeds was, on average, approximately 1.5 Mg ha^{-1} d.m. It should be noted, however, that with the appropriate technology applied and under optimum environmental conditions, as much as approximately 3 Mg ha^{-1} d.m. of seeds were obtained, which unfortunately could not be achieved in the present study conducted under organic cultivation system. In contrast, under Polish conditions, the average yield of camelina cultivated traditionally on a large scale amounted to approximately 1.1 Mg ha^{-1} d.m. (Stolarski et al., 2018). In another study conducted in Poland (Jankowski and Sokólski, 2021), the yield of camelina seeds with no nitrogen fertilization was, on average, 1.26 Mg ha^{-1} d.m., with the maximum value of 2.24 Mg ha^{-1} d.m., when applying fertilization at a rate of 160 kg ha^{-1} N, and 30 kg ha^{-1} S. It follows from the literature data that camelina is well adapted to various agro-ecological conditions, and is cultivated in Asia, Europe and the Americas. However, depending on the agro-ecological conditions and the technology applied, the yields of camelina seeds ranged widely from 0.6 Mg to over 3 Mg ha^{-1} d.m. in Europe (Stolarski et al., 2018; Jankowski et al., 2015, 2019; Załuski et al., 2020; Zanetti et al., 2021; Hryhoriv et al., 2022,2023) and the USA (Pavlista et al., 2012; Wysocki et al., 2013; Sintim et al., 2015; Schillinger, 2019), in South America from 1.4 to 2.4 Mg ha^{-1} d.m. (Solis et al., 2013), whereas in Canada, it ranged from 1.6 to 3.3 Mg ha^{-1} d.m. (Gugel and Falk, 2006; Urbaniak et al., 2009; Jiang et al., 2013). The yields of spelt also varied and ranged from 1.8 to 2.5 Mg ha^{-1} (Bavec et al., 2012), from 2.5 to 3.8 Mg ha^{-1} (Vojnov et al., 2020) and from 2.2 to 5.6 Mg ha^{-1} (Dolijanović et al., 2022), depending on the above-mentioned conditions, with these being at higher levels than the yields of camelina. Therefore, the relationships between these species were consistent with the results of the present study. Unfortunately, the cultivation of camelina intercropped with spelt did not yield better results than the sole cropping system, yet, in future studies, it may be worth considering other indices related to environmental aspects which could favor this type of solution. Especially because, in organic farming, camelina can bring many benefits, e.g. improved soil structure, reduced erosion and the promotion of biodiversity (Berti et al., 2017a). In addition, it can be assumed that, for spelt, organic cultivation may have reduced its yield due to the incomplete supply of nutrients, as compared with its production under conventional systems in which high mineral fertilization is applied, as a rule, at different stages of development.

The yields of sole-cropped camelina and spelt straw were more leveled and amounted to 2.81 and 3.15 Mg ha^{-1} d.m., respectively (Table 4). In contrast, the yield from intercropping cultivation was 2.94 Mg ha^{-1}, with the yield of spelt straw amounting to 64 % d.m. and the yield of camelina straw to 36 % d.m. For the years of the study, similar relationships were noted for the yield of seeds, and the highest yields of straw from the cultivation under both sole-cropping and intercropping systems were obtained in 2022. In another study, the yield of camelina straw with no fertilization was lower (an average of 1.96 Mg ha^{-1} d.m.) and ranged from 1.29 to 2.72 Mg ha^{-1} d.m. (Stolarski et al., 2019). A large variation in the yield of camelina straw was also noted in a previous study (Stolarski et al., 2018). In another study conducted in Poland (Jankowski and Sokólski, 2021), the yield of camelina straw with no

Table 4
The yield and energy value of the yield of sole-cropped and intercropped camelina and spelt.

Species and sowing system	Year	Seeds yield (Mg ha^{-1} d.m.)	Straw yield (Mg ha^{-1} d.m.)	Seed yield energy value (GJ ha^{-1})	Straw yield energy value (GJ ha^{-1})	Total yield energy value (GJ ha^{-1})
Camelina sole	2022	1.47 ± 0.26 bc	3.68 ± 0.42 ab	41.27 ± 7.40	71.04 ± 8.13 ab	112.31 ± 14.82
Camelina sole	2023	1.69 ± 0.98 bc	2.79 ± 0.64 abcd	47.40 ± 27.51	53.91 ± 12.35 abcd	101.31 ± 39.60
Camelina sole	2024	1.22 ± 0.38 bcd	1.95 ± 0.65 cde	34.23 ± 10.77	37.80 ± 12.54 cde	72.04 ± 21.80
Camelina sole	Mean	1.46 ± 0.60 B	2.81 ± 0.90 A	40.97 ± 16.87	54.25 ± 17.42 AB	95.22 ± 30.54 AB
Spelt sole	2022	4.06 ± 0.40 a	3.88 ± 0.57 a	75.74 ± 7.47	75.29 ± 11.03 a	151.03 ± 7.99
Spelt sole	2023	1.44 ± 0.65 bc	2.58 ± 1.01 bcd	26.90 ± 12.24	50.08 ± 19.55 bcd	76.97 ± 31.55
Spelt sole	2024	1.34 ± 0.37 bcd	2.99 ± 0.71 abc	25.19 ± 6.99	58.35 ± 13.89 abc	83.55 ± 18.57
Spelt sole	Mean	2.28 ± 1.39 A	3.15 ± 0.91 A	42.61 ± 25.86	61.24 ± 17.61 A	103.85 ± 40.06 A
Camelina inter	2022	0.73 ± 0.33 cd	1.19 ± 0.05 d	20.32 ± 9.06	22.99 ± 1.04 e	43.31 ± 8.57
Camelina inter	2023	0.38 ± 0.24 d	0.93 ± 0.14 d	10.46 ± 6.59	18.02 ± 2.65 e	28.48 ± 8.08
Camelina inter	2024	0.63 ± 0.17 cd	1.07 ± 0.27 d	17.40 ± 4.84	20.64 ± 5.22 e	38.04 ± 9.53
Camelina inter	Mean	0.58 ± 0.28 C	1.06 ± 0.19 C	16.06 ± 7.70	20.55 ± 3.76 C	36.61 ± 10.18 C
Spelt inter	2022	2.16 ± 0.67 b	2.78 ± 0.13 abcd	40.16 ± 12.42	53.95 ± 2.43 abcd	94.11 ± 11.46
Spelt inter	2023	0.66 ± 0.26 cd	1.64 ± 0.24 cd	12.34 ± 4.88	31.76 ± 4.68 de	44.09 ± 9.44
Spelt inter	2024	0.71 ± 0.32 cd	1.21 ± 0.31 d	13.31 ± 5.9 0	23.60 ± 5.97 e	36.91 ± 11.72
Spelt inter	Mean	1.18 ± 0.83 C	1.88 ± 0.72 B	21.94 ± 15.47	36.44 ± 14.02 C	58.37 ± 28.35 C
Camelina + Spelt inter	2022	2.89 ± 0.99 X	3.97 ± 0.18 X	60.48 ± 21.44 X	76.94 ± 3.47 X	137.42 ± 19.96 X
Camelina + Spelt inter	2023	1.04 ± 0.38 Y	2.57 ± 0.38 Y	22.80 ± 8.92 Y	49.78 ± 7.33 Y	72.58 ± 15.57 Y
Camelina + Spelt inter	2024	1.34 ± 0.48 Y	2.28 ± 0.58 Y	30.71 ± 10.53 Y	44.24 ± 11.2 Y	74.95 ± 21.16 Y
Camelina + Spelt inter	Mean	1.76 ± 1.04 AB	2.94 ± 0.86 A	38.00 ± 21.55	56.99 ± 16.58 AB	94.98 ± 35.78 AB

±standard deviation; A,B,C – homogeneous groups (hg) on average for the species under sole-cropping and intercropping system; a,b,c,d – hg for the interaction of the species × cultivation method × year; X,Y – hg for the years in the intercropping cultivation of camelina and spelt; Tukey's test ($P < 0.05$).

nitrogen fertilization amounted to an average of 2.28 Mg ha^{-1} d.m., with the maximum value amounting to 3.30 Mg ha^{-1} d.m. with mineral fertilization applied. The literature data show that the yields of camelina straw most frequently ranged from less than 2 to more than 3 Mg ha^{-1} d.m. (Krzyżaniak et al., 2019; Załuski et al., 2020), but 4.5 Mg ha^{-1} d.m. of camelina straw was also obtained (Jankowski et al., 2019). It should also be noted that nitrogen fertilization increased the yield of straw to a lesser extent than it increased the yield of seeds (Malhi et al., 2014; Jankowski et al., 2019), which may explain the relatively high yields of straw of camelina cultivated under the organic system in the present study.

The energy value of the yield of seeds or the yield of straw varied significantly, mainly depending on the cultivation method and the year of the study, and, for the energy value of straw, also on the interaction of all the factors. In contrast, the total yield energy value varied significantly, depending on the three main experimental factors (Table 3). Despite the lower yield of seeds, the average energy value of camelina seeds (40.97 GJ ha^{-1}) was close to the energy value of spelt seeds (42.61 GJ ha^{-1}) (Table 4). This was due to the considerably higher HHV of camelina seeds (an average of 27.86 GJ Mg^{-1} d.m.) compared with that of spelt seeds (an average of 18.70 GJ Mg^{-1} d.m.). The higher HHV for camelina seeds resulted from their considerably higher oil content compared with spelt seeds. However, the energy value of the seeds from intercropping cultivation of these two species was slightly lower and amounted to an average of 38.0 GJ ha^{-1}, with the energy value of spelt seeds amounting to 58 % and of camelina seeds to 42 %. The energy value of spelt straw (an average of 61.24 GJ ha^{-1}) was nearly 13 % higher than the average value of this characteristic for camelina straw. The total biomass energy value (seeds and straw) for spelt (an average of 103.85 GJ ha^{-1}) was 9 % higher than the average value of this characteristic for sole-cropped camelina, and for camelina intercropped with spelt (an average of 95 GJ ha^{-1}). The highest total biomass energy values were obtained in 2022 for spelt cultivated under the sole-cropping system (151 GJ ha^{-1}). For camelina, the biomass energy value was 112 GJ ha^{-1}, while camelina intercropped with spelt produced a value of 137 GJ ha^{-1}.

A low energy value of camelina seeds alone was obtained in another three-year study (Keshavarz-Afshar and Chen, 2015), with it amounting to an average of 24.0 GJ ha^{-1} and ranging from 11.7 to 31.7 GJ ha^{-1}. A similar result was noted in a study by Keshavarz-Afshar et al., (2015), in which the energy value of camelina seeds was, on average, 19.0 GJ ha^{-1}. It should be stressed, however, that this value increased with an increase in the nitrogen fertilization rate from 0 to 90 kg N ha^{-1} and was higher for conventional tillage than for a no-tillage system. In another study conducted in Poland, the seed energy value for camelina with no fertilization was higher and amounted to an average of 39.4 GJ ha^{-1}, whereas for straw, it was an average of 36.3 GJ ha^{-1} (Stolarski et al., 2019). Consequently, in the cited study, the total biomass energy value for camelina with no fertilization was, on average, 75.8 GJ ha^{-1}, while ranging from 52.3 to 88.0 GJ ha^{-1}. In another study conducted in Poland (Jankowski and Sokólski, 2021), the total biomass energy value for camelina with no fertilization was, on average, 61.5 GJ ha^{-1}, and for the seeds alone, the value of this index was 28.4 GJ ha^{-1}. It should, therefore, be concluded that higher total biomass energy values were obtained in the organic cultivation of camelina than in the study cited above. In contrast, in another three-year, large-scale study, the highest average total biomass energy value for conventionally cultivated camelina was 79.5 GJ ha^{-1} (Stolarski et al., 2018). However, when applying an optimum technology of production and mineral fertilization, the value of this index increased to 97.1 GJ ha^{-1}, of which the seed energy value amounted to 52.9 GJ ha^{-1}, i.e., 54.5 % (Jankowski and Sokólski, 2021). This index should be considered to be high, as under conventional medium-input production technology, the seed energy value for camelina ranged from 24 to 36 GJ ha^{-1} (Berti et al., 2015; Keshavarz-Afshar and Chen, 2015; Keshavarz-Afshar et al., 2015).

3.2. Energy inputs

In the sole-cropping cultivation of camelina and spelt and in the intercropping cultivation of these two species, the same cultivation and crop harvesting technology was applied in the individual years of the cultivation. Therefore, the energy inputs incurred for most production stages (the use of manure, lime spreading, plowing, pre-sowing tillage, mechanical weeding, harvesting, and the transport of seeds) were, on average, the same (Fig. 1). In contrast, variation in energy inputs was noted for the sowing, as in the case of sole-cropping cultivation of camelina, it was 1.04 GJ ha^{-1}. For the sole-cropped cultivation of spelt and the intercropping of camelina and spelt, the energy inputs were higher and amounted to 2.66 and 3.50 GJ ha^{-1}, respectively, with this increase resulting from the higher weight of the seeds sown, and for the intercropping cultivation, also from the double number of sowing operations. In addition, for the intercropping cultivation, additional

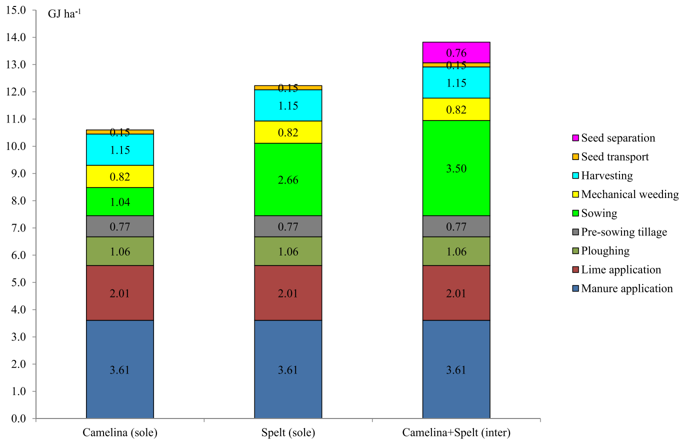

Fig. 1. Energy inputs in the organic cultivation of sole-cropped and intercropped camelina and spelt.

energy inputs were linked to the separation of seeds after harvest. Therefore, the total energy inputs in the organic production of camelina cultivated under the sole-cropping system amounted, on average, to 10.60 GJ ha^{-1}. As for the cultivation of spelt under the sole-cropping system, the energy inputs (12.23 GJ ha^{-1}) were 15.3 % higher, and under intercropping cultivation of camelina with spelt, the value of this index (13.82 GJ ha^{-1}) was 30.4 % higher compared with the sole-cropping cultivation of camelina. In the structure of energy inputs, in each cultivation variant under analysis, the use of manure at a rate from 26 % to 34 % was dominant for the intercropping cultivation and sole-cropping cultivation of spelt, respectively. For sole-cropping cultivation of camelina, the application of lime ranked second (19 %). For the sole-cropping cultivation of spelt and the intercropping cultivation of camelina with spelt, the sowing operation ranked second at 22 and 25 %, respectively, with the application of lime ranking third (15–16 %) in the structure of energy inputs.

In another study, energy inputs for the production of camelina cultivated under a sole-cropping system and with no fertilization were close to the results of the present study and amounted to an average of 10.11 GJ ha^{-1} (Stolarski et al., 2019). The application of mineral fertilization at a rate of 60 or 120 kg ha^{-1} N in the cited study obviously increased the energy inputs to 13.2 and 16.2 GJ ha^{-1}. Jankowski and Sokólski, (2021) demonstrated that the energy inputs in the production of camelina with no fertilization were very low and only amounted to 5.1 GJ ha^{-1}, and when applying maximum fertilization with N (160 kg ha^{-1}) and S (30 kg ha^{-1}), these increased to 17.7 GJ ha^{-1}. With the application of 100 kg ha^{-1} N, the energy inputs for camelina production amounted to nearly 14 GJ ha^{-1} (Stolarski et al., 2018). In another study (Bielski et al., 2014), the energy inputs related to camelina production (12.8 GJ ha^{-1}) were lower than those of other studied oil-bearing crop species. The literature data show that the energy inputs related to camelina cultivation on large-area farms in North America ranged from 6 to 8 GJ ha^{-1} (Berti et al., 2015; Keshavarz-Afshar and Chen, 2015; Keshavarz-Afshar et al., 2015), and were lower than those under European conditions, amounting to 12–16 GJ ha^{-1} (Stolarski et al., 2018, 2019; Jankowski and Sokólski, 2021). Furthermore, it was demonstrated that nitrogen mineral fertilization had the decidedly highest proportion (frequently over 60 %) in the structure of the total energy inputs for the production (Budzyński et al., 2015; Stolarski et al., 2018, 2019; Jankowski and Sokólski, 2021). Consequently, energy inputs in production technologies without mineral nitrogen fertilization are generally low. The present study applied manure and lime fertilization, which contributed to an increase in energy inputs. Therefore, the energy inputs for the production of camelina under an organic system were lower than those under conventional systems, which applied high levels of minerals, especially nitrogen and fertilization. However, they were also comparable and sometimes even higher than those under conventional cultivation, especially when low nitrogen fertilization was applied. This increase in inputs in organic cultivation was due to the use of manure and liming. However, as a rule, organic cultivation is characterized by a lower adverse impact on the natural environment compared with conventional cultivation.

3.3. Energy gain and energy intensity

Energy gain varied significantly, depending on the three main experimental factors, i.e., the species, the cultivation method, the year and the interaction between the species and the year of the study (Table 3). Energy gain from the sole-cropping spelt cultivation (an average of 91.62 GJ ha^{-1}) was 8.3 % higher than the average value of this characteristic for sole-cropped camelina (an average of 84.62 GJ ha^{-1}), and 12.5 % higher than camelina intercropped with spelt (Table 5). The highest energy gain value was obtained in 2022 for spelt sown as a single crop (138.8 GJ ha^{-1}), whereas for camelina sown as a single crop, the value was 101.7 GJ ha^{-1}, and for camelina intercropped with spelt, it was 123.6 GJ ha^{-1}.

In another study, energy gain from camelina production with no fertilization was lower and amounted to an average of 65.7 GJ ha^{-1}, ranging from 42.2 to 77.9 GJ ha^{-1} (Stolarski et al., 2019). Jankowski and Sokólski, (2021) also obtained similar energy gain from camelina production with no fertilization (56.4 GJ ha^{-1}), whereas when applying N fertilization (120 kg ha^{-1}) and S fertilization (30 kg ha^{-1}), the value increased to 80.8 GJ ha^{-1}. In turn, on a large scale, the highest average energy gain from conventional camelina cultivation was 64.4 GJ ha^{-1} (Stolarski et al., 2018). In other studies, the value of this index was even lower: 59.2 GJ ha^{-1} (Bielski et al., 2014), or 18.3 GJ ha^{-1} (Keshavarz-Afshar and Chen, 2015) and 14.9 GJ ha^{-1} (Keshavarz-Afshar et al., 2015).

The energy intensity of the production of seeds and straw varied significantly depending on the cultivation method and year. For straw, it also depended on the interaction of all three experimental factors (Table 3). Energy intensity of the production of sole-cropped camelina (an average of 8.11 GJ Mg^{-1} d.m.) was 7.3 % higher than the average value of this characteristic for sole-cropped spelt (an average of 7.56 GJ Mg^{-1} d.m.), and 22 % lower than that of camelina intercropped with spelt (Table 5). In contrast, the energy intensity of the production of sole-cropped camelina (an average of 4.34 GJ Mg^{-1} d.m.) was only 0.9 % higher, compared with the average value of this characteristic for sole-cropped spelt and 14 % lower compared with camelina intercropped with spelt. Similar relationships between the species under study were also found for the consumption of diesel fuel for the production of seeds and straw, with the average diesel fuel consumption for the production of 1 kg of seeds (an average range of 0.6–0.9 kg^{-1} d.m.) being approximately twice as high compared with this index obtained for straw (an average range of 0.3–0.4 kg^{-1} d.m.).

In another study, the average energy intensity of camelina seed production with no fertilization was lower, as it amounted to an average of 6.8 GJ Mg^{-1}, with the value of this index, however, ranging widely from 4.9 to 8.9 GJ ha^{-1} (Stolarski et al., 2019). Therefore, the upper values of this index were close to the values obtained in the present study for cultivation under an organic system. Very low energy intensity values (an average of 2.7 GJ Mg^{-1}) were obtained in a study which did not apply nitrogen fertilization (Keshavarz-Afshar et al., 2015). However, when nitrogen fertilization was applied at rates of 45 and 90 kg ha^{-1}, the values of this index increased to 6.3 and 7.7 GJ Mg^{-1}, respectively. In contrast, in a large-scale experiment under traditional production technology, with fertilization applied (100 kg ha^{-1} N), the energy intensity of camelina seeds was considerably higher at 12.0 GJ Mg^{-1} (Stolarski et al., 2018). The energy intensity of camelina straw production in the cited experiment ranged from 5.5 to 6.4 GJ Mg^{-1}.

Table 5
Energy gain, energy intensity and diesel fuel consumption in the production of sole-cropped and intercropped camelina and spelt.

Species and sowing system	Year	Energy gain (GJ ha^{-1})	Energy intensity of seeds yield (GJ Mg^{-1} d.m.)	Energy intensity of straw yield (GJ Mg^{-1} d.m.)	Diesel fuel consumption for seeds (kg kg^{-1} d.m.)	Diesel fuel consumption for straw (kg kg^{-1} d.m.)
Camelina sole	2022	101.71 ± 14.82	7.37 ± 1.33	2.91 ± 0.33 b	0.07 ± 0.01	0.03 ± 0.00 bc
Camelina sole	2023	90.71 ± 39.60	7.60 ± 3.20	3.94 ± 0.82 ab	0.07 ± 0.03	0.04 ± 0.01 abc
Camelina sole	2024	61.44 ± 21.80	9.35 ± 2.90	6.16 ± 2.97 a	0.09 ± 0.03	0.06 ± 0.03 a
Camelina sole	Mean	84.62 ± 30.54 AB	8.11 ± 2.53	4.34 ± 2.15	0.07 ± 0.02	0.04 ± 0.02
Spelt sole	2022	138.8 ± 7.99	3.04 ± 0.30	3.21 ± 0.52 ab	0.02 ± 0.01	0.03 ± 0.01 bc
Spelt sole	2023	64.74 ± 31.55	10.06 ± 4.54	5.40 ± 2.25 ab	0.08 ± 0.04	0.04 ± 0.02 abc
Spelt sole	2024	71.32 ± 18.57	9.57 ± 2.28	4.29 ± 1.12 ab	0.08 ± 0.02	0.03 ± 0.01 bc
Spelt sole	Mean	91.62 ± 40.06 A	7.56 ± 4.27	4.30 ± 1.63	0.06 ± 0.03	0.03 ± 0.01
Camelina inter	2022	29.48 ± 8.57	9.83 ± 4.28	5.24 ± 0.24 ab	0.09 ± 0.04	0.05 ± 0.01 abc
Camelina inter	2023	15.14 ± 8.08	21.01 ± 11.8	6.53 ± 1.03 a	0.21 ± 0.12	0.06 ± 0.01 a
Camelina inter	2024	24.62 ± 9.53	10.2 ± 2.96	5.98 ± 1.78 ab	0.10 ± 0.03	0.06 ± 0.02 a
Camelina inter	Mean	23.08 ± 10.07 C	13.68 ± 8.64	5.92 ± 1.21	0.13 ± 0.09	0.06 ± 0.01
Spelt inter	2022	80.29 ± 11.46	3.78 ± 1.15	2.73 ± 0.12 b	0.03 ± 0.01	0.02 ± 0.01 c
Spelt inter	2023	30.75 ± 9.44	12.53 ± 4.96	4.56 ± 0.72 ab	0.10 ± 0.04	0.04 ± 0.01 abc
Spelt inter	2024	23.49 ± 11.72	12.45 ± 6.65	6.47 ± 1.92 ab	0.10 ± 0.05	0.05 ± 0.02 abc
Spelt inter	Mean	44.84 ± 28.15 C	9.58 ± 6.13	4.59 ± 1.92	0.08 ± 0.05	0.04 ± 0.02
Camelina + Spelt inter	2022	123.6 ± 19.96 X	5.22 ± 1.76 Y	3.49 ± 0.16 Y	0.04 ± 0.01 Y	0.03 ± 0.01 Y
Camelina + Spelt inter	2023	59.23 ± 15.57 Y	14.7 ± 6.76 X	5.28 ± 0.83 X	0.13 ± 0.06 X	0.05 ± 0.01 X
Camelina + Spelt inter	2024	61.53 ± 21.16 Y	11.18 ± 4.51 X	6.24 ± 1.86 X	0.10 ± 0.04 X	0.05 ± 0.02 X
Camelina + Spelt inter	Mean	81.45 ± 35.59 AB	10.36 ± 5.96	5.00 ± 1.60	0.09 ± 0.05	0.04 ± 0.01

±standard deviation; A,B,C – homogeneous groups (hg) on average for the species under sole-cropping and intercropping system; a,b,c,d – hg for the interaction of the species × cultivation method × year; X,Y – hg for the years in the intercropping cultivation of camelina and spelt; Tukey's test ($P < 0.05$).

3.4. Energy ratio

The energy ratio for seed production and the total energy ratio varied significantly depending on the cultivation method and the year, as well as on the interaction between the species and the year (Table 3). In contrast, the energy ratio for straw production varied significantly depending on the species, the cultivation method, the year and the interaction between all three main factors. In practice, the energy ratio indicates how many times more renewable energy has been stored in the biomass obtained (energy output) compared with the consumed energy from fossil fuels (energy input) for the generation of this renewable energy in the biomass. The energy ratio for the production of sole-cropped camelina seeds amounted to an average of 3.86, with this index amounting to 5.12 for straw. Therefore, the total energy ratio for camelina cultivation was an average of 8.98 (Fig. 2). For the sole-cropping of spelt, the average energy ratio values for the production of seeds and straw, and the total energy ratio values were lower, compared with those for camelina, by 9.8 %, 2.1 % and 5.5 %, respectively. In contrast, for camelina intercropped with spelt, the values of these indices were lower by 27.7 % for the seeds, by 18.0 % for straw, and by 22.2 % for the total energy ratio. It should also be noted that throughout the experiment, the highest total energy ratio value (12.35) was obtained in 2022 for sole-cropped spelt (Table 6). In addition, in the same year, the value of this indicator for sole-cropped camelina amounted to over 10.5, whereas it was nearly 10 for camelina

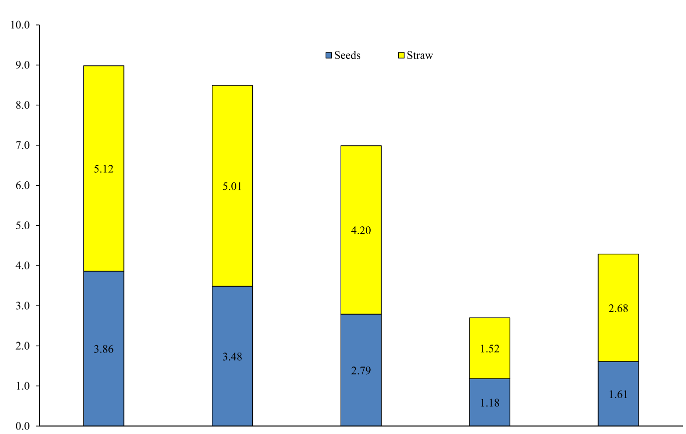

Fig. 2. Average energy ratio indices for the production of sole-cropped and intercropped camelina and spelt.

Table 6
The energy ratio for seeds and straw and the total biomass of the production of sole-cropped and intercropped camelina and spelt.

Species and sowing system	Year	Seeds	Straw	Total
Camelina sole	2022	3.89 ± 0.70	6.70 ± 0.77 a	10.59 ± 1.40
Camelina sole	2023	4.47 ± 2.59	5.08 ± 1.16 abc	9.56 ± 3.74
Camelina sole	2024	3.23 ± 1.02	3.57 ± 1.18 cd	6.79 ± 2.06
Spelt sole	2022	6.19 ± 0.61	6.16 ± 0.90 ab	12.35 ± 0.65
Spelt sole	2023	2.20 ± 1.00	4.10 ± 1.60 bc	6.29 ± 2.58
Spelt sole	2024	2.06 ± 0.57	4.77 ± 1.14 abc	6.83 ± 1.52
Camelina inter	2022	1.47 ± 0.66	1.66 ± 0.08 de	3.13 ± 0.62
Camelina inter	2023	0.78 ± 0.49	1.35 ± 0.20 e	2.13 ± 0.61
Camelina inter	2024	1.30 ± 0.36	1.54 ± 0.39 de	2.83 ± 0.71
Spelt inter	2022	2.91 ± 0.90	3.9 ± 0.18 cd	6.81 ± 0.83
Spelt inter	2023	0.92 ± 0.37	2.38 ± 0.35 de	3.30 ± 0.71
Spelt inter	2024	0.99 ± 0.44	1.76 ± 0.45 de	2.75 ± 0.87
Camelina + Spelt inter	2022	4.38 ± 1.55 X	5.57 ± 0.25 X	9.94 ± 1.44 X
Camelina + Spelt inter	2023	1.71 ± 0.67 Y	3.73 ± 0.55 Y	5.44 ± 1.17 Y
Camelina + Spelt inter	2024	2.29 ± 0.78 Y	3.30 ± 0.83 Y	5.58 ± 1.58 Y

±standard deviation; a,b,c,d – homogeneous groups (hg) for the interaction of the species × cultivation method × year; X,Y – hg for the years in the intercropping cultivation of camelina and spelt; Tukey's test ($P < 0.05$).

intercropped with spelt.

In another study (Stolarski et al., 2019), the average energy ratio for the production of camelina seeds with no fertilization was close (an average of 3.9) to the results presented in this manuscript while being lower for straw (3.6). Therefore, the total energy ratio for the production of camelina (an average of 7.5, or a maximum of 8.7) in the cited study was lower compared with the average and maximum values obtained for sole-cropped camelina in this study. In contrast, high energy ratio values for the production of camelina seeds (an average of 10.4) were obtained in a study applying no nitrogen fertilization (Keshavarz-Afshar et al., 2015). The index decreased with an increase in the nitrogen fertilization rate to 4.4 and 3.7. Jankowski and Sokólski, (2021) also demonstrated a relatively high energy ratio (5.6) for the production of camelina seeds with no fertilization, with this index increasing to 12.1 after straw was taken into account. The application of different mineral fertilization variants significantly reduced the energy ratio, both for the seeds alone (2.64) and for the total camelina biomass (5.23). An even lower energy ratio for camelina seed production (2.0) was obtained in a large-scale experiment that applied a traditional production technology (Stolarski et al., 2018). After taking straw into account, the total biomass energy ratio for camelina averaged 4.8, which was lower than the value obtained in the present study for camelina cultivated organically under the sole-cropping system. It should also be added that the energy ratio value for the production of oil-bearing and cereal crops, as well as other species (including perennials), varies greatly in practice, depending on multiple biotic and abiotic factors (Budzyński et al., 2015; Dubis et al., 2019; Jankowski et al., 2016, 2021, 2022; Stolarski et al., 2017, 2024). Based on the current study, it can be concluded that organic camelina cultivation under a sole cropping system and intercropped with spelt may be interesting in terms of energy efficiency, but the impact of climatic conditions (and especially the amount and distribution of precipitation) may play a key role. It should also be stressed that the results of the current study may be helpful in making decisions about the future directions of agricultural production, especially with regard to the implementation of the European Green Deal concept, in which organic production will be preferred due to the reduction in (and abandonment of) the use of chemical plant protection products and mineral fertilizers. Moreover, the objectives set for European agriculture include reducing plant nutrient losses by at least 50 %, which is expected to result in a reduction in fertilizer use by at least 20 %, while ensuring that the soil fertility has not deteriorated. Another objective is to designate at least 25 % of arable land for organic farming by 2030. For these objectives to be achieved, research is needed to optimize the implementation of these objectives through the selection of plants, cultivation methods or organic cultivation conditions. Therefore, the current study is designed to meet these challenges.

3.5. Cluster analysis for the production of camelina and spelt

Cluster analysis for the fourteen examined characteristics demonstrated that for a cut-off of 2/3 D_{max}, and when increasing accuracy to 1/3 D_{max}, two separate clusters were formed (Fig. 3a). One of the clusters included indices related to energy inputs, diesel fuel consumption and energy intensity. In contrast, the other nine characteristics under analysis formed the second cluster. In turn, the species studied (camelina and spelt), and their cultivation methods (sole-cropping and intercropping) at a cut-off of 2/3 D_{max} formed two main clusters (Fig. 3b). One of the clusters included camelina and spelt cultivated under the sole-cropping system and together under the intercropping system. The second cluster contained intercropped camelina and intercropped spelt. However, when the accuracy of the analysis was increased (at a cut-off of 1/3 D_{max}), four clusters were distinguished. Sole-cropped camelina and spelt formed a single common cluster, whereas the other three variants formed their own independent clusters.

4. Conclusions

In general, the present three-year study conducted under an organic system under conditions of north-eastern Poland did not obtain such high yields of biomass (seeds and straw) or the energy values of spring camelina or spring spelt as the conventional cultivation of these species. However, the study demonstrated the validity of intercropping cultivation of these two species. It should also be added that the results obtained were largely affected by climatic conditions, in particular, low precipitation that was poorly distributed over the growing season. In this regard, the best year was 2022, when the highest total biomass yield, total biomass energy value, energy gain and energy ratio were obtained for camelina and spelt cultivated under both sole-cropping and intercropping systems. Energy inputs for the cultivation of sole-cropped camelina were lower than those for the cultivation of sole-cropped spelt and those for the intercropped cultivation of these two species. The above-mentioned environmental factors affected the energy value of the obtained biomass yield and the energy efficiency indices, with sole-cropped spelt exhibiting the highest average total biomass energy value. However, sole-cropped camelina exhibited the highest average total energy ratio.

The results of the present study provide farmers and researchers with valuable information on energy inputs and energy efficiency indices for the organic production of sole-cropped and intercropped camelina and spelt. This information may also be useful in other regions of the world in popularizing the cultivation of these two important species on organic farms under both sole-cropping and intercropping systems. It should be stressed, however, that due to considerable discrepancies between the

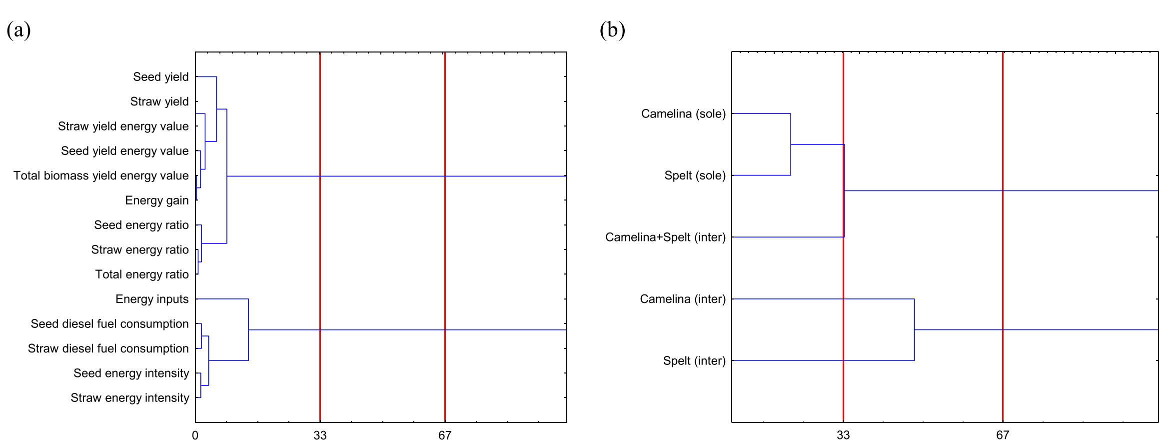

Fig. 3. A dendrogram of a hierarchical cluster analysis showing the similarities between the production indices under study (a) and the plant species under study and their cultivation methods (b). The red vertical line marks the Sneath criterion (2/3 D_{max}) and (1/3 D_{max}). D – linkage distance; D_{max} – maximum linkage distance.

years under study, further research is needed to verify them. In addition, possible improvements should be sought in terms of the crop rotation used in production technology (including the sowing rate for both species) in order to increase yields and reduce energy inputs, which could ultimately improve the energy efficiency of the production of these species. Another crucial element of further research will be an assessment of the economic and environmental efficiency of the cultivation of these two promising spring crop species on organic farms under both sole-cropping and intercropping systems. It can be concluded, however, that the results of the current study may be helpful in making decisions about the future directions of agricultural production, especially with regard to the implementation of the Green Deal concept, in which organic production will be preferred due to the reduction in (and abandonment of) the use of chemical plant protection products and mineral fertilizers. In addition, the results of the current study have confirmed that organic cultivation of camelina under a sole cropping system and intercropped with spelt may be interesting in terms of energy efficiency. However, the impact of climatic conditions (in particular, the amount and distribution of precipitation) can play a crucial role. In view of the above, a key aspect will be water management during the growing season, especially on poorer-quality soil sites with low groundwater levels.

CRediT authorship contribution statement

Krzyżaniak Michał: Writing – review & editing, Validation, Resources, Project administration, Investigation, Funding acquisition. **Stolarski Mariusz Jerzy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stolarski Jakub:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Olba-Zięty Ewelina:** Writing – review & editing, Validation, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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