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Energy Optimization in Different Production Technologies of Winter Triticale Grain

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Abstract: This article presents the results of a field experiment investigating the energy efficiency of grain produced by a semi-dwarf genotype of winter triticale at different levels of agricultural inputs. The energy efficiency of winter triticale grain production was evaluated in two low-input and two high-input cultivation practices that differed in the rate of nitrogen fertilizer (split application) and disease control. The energy inputs associated with the production of winter triticale grain at low levels of agricultural inputs were determined to be 14.5 to 14.7 GJ ha^{-1}. Higher levels of agricultural inputs increased the demand for energy in grain production by 25% on average. The energy output of grain peaked (163.3 GJ ha^{-1}) in response to a fertilizer rate of 120 kg ha^{-1} applied in a split ratio of 50:50 (BBCH 27/32) and two fungicide treatments (BBCH 31 and 39). The energy output of grain from the remaining cultivation regimes was 3–13% lower. The energy efficiency ratio was highest in the low-input cultivation regime with a nitrogen rate of 90 kg ha^{-1} split into two applications (60 and 30 kg ha^{-1} for BBCH 27 and 32, respectively), seed dressing with fungicide (thiram and tebuconazole) and one fungicide treatment (azoxystrobin) (BBCH 39).

Keywords: *Triticosecale*; agricultural operations; energy input; energy output; energy gain; energy efficiency ratio

Citation: Szempliński, W.; Dubis, B.; Lachutta, K.M.; Jankowski, K.J. Energy Optimization in Different Production Technologies of Winter Triticale Grain. *Energies* **2021**, *14*, 1003. https://doi.org/10.3390/en14041003

Academic Editor: Luigi Pari
Received: 4 January 2021
Accepted: 11 February 2021
Published: 14 February 2021

1. Introduction

Triticale (× *Triticosecale* Wittm.) is an interspecific hybrid of wheat (*Triticum* ssp.) and rye (*Secale* ssp.). Triticale has considerable genetic potential [1,2], and modern cultivars are characterized by higher grain yields and lower disease susceptibility than wheat [3–7]. Triticale has low soil, water and fertilizer requirements, and it is relatively resistant to drought, low temperatures and fungal diseases [8–14]. The global production of triticale reached 12.8 million Mg in 2018. Nearly 90% of the global output is produced in Europe, mainly Poland (4.08 million Mg), Germany (19.3 million Mg), France (1.38 million Mg) and Belarus (1.02 million Mg) [15]. Due to its high protein content and favorable amino acid profile, triticale grain is used mainly in the feed industry [16–19] and, to a smaller extent, in the food processing industry [20–26]. However, the future potential of global triticale grain production will be largely determined by its processing suitability in the baking industry [24,27–31].

Triticale is a cereal species with high energy potential [32–37]. Triticale grain can be converted to chemicals, biomaterials, biocomponents and energy in biorefineries [38,39]. Triticale is abundant in starch and cellulose, and it can be used in the production of biofuels [20,34], and triticale straw can be directly incinerated [38,40]. Triticale grain can be processed into biogas during anaerobic digestion [41,42], and bioethanol can be obtained from grain [33,43–49] and/or straw [35,50]. Triticale grain is particularly suited for bioethanol production due to its high starch content (650–680 g kg^{-1} dry matter, DM) and somewhat lower protein content 125 g kg^{-1} DM) [51], as well as high amylolytic activity which speeds up starch hydrolysis and digestion [11,44]. The production of 1 ton of bioethanol requires 2.78 to 3.38 Mg of triticale grain [49,52]. The efficiency of bioethanol derived from triticale is determined by the productivity of cultivars [11,53] and growing conditions as well as agronomic factors, mostly nitrogen fertilization [40,45,53–55].

Triticale has lower agronomic needs, in particular lower nitrogen requirements, than other cereals, and its biomass is particularly suitable for energy generation because relatively low nitrogen fertilizer rates (i) decrease protein content and increase bioethanol yields per unit area [46], and (ii) improve the energy efficiency of biomass production [56]. The energy efficiency of agricultural production has to be increased to combat climate change and the energy crisis. Effective energy use is one of the key priorities of sustainable agriculture [57,58]. Patterson [59] defines energy efficiency as the ratio of energy outputs to energy inputs. The demand for energy in the production process and the volume of energy accumulated in biomass are two important components of the energy balance, which determine not only energy efficiency, but also the eco-efficiency of agricultural production [60]. Agricultural production systems characterized by higher energy efficiency are more environmentally friendly [61–64]. Agrotechnologies with lower energy efficiency increase the consumption of non-renewable energy resources [65] and contribute to greenhouse gas emissions [66–69].

Energy efficiency is determined by the intensity of agricultural inputs [48,49,70,71]. The demand for energy can be reduced by optimizing agricultural operations and deploying production technologies that are best suited to the cultivated crops and local conditions [72]. Nitrogen fertilization and disease control are very important agronomic factors in the production of winter triticale grain [4,73–77]. Nitrogen fertilizers have a large share of energy inputs due to the high value of energy stored in chemical bonds [49,58,62]. For this reason, efficient nitrogen use not only increases agricultural profits, but also reduces local pollutant emissions and greenhouse gas emissions, and improves global food security [51,78,79]. High nitrogen use efficiency is a key prerequisite for high energy efficiency in agriculture. In cereal production, nitrogen use efficiency can be improved by introducing high-yielding and nitrogen-efficient cultivars (hybrid, dwarf, semi-dwarf), adapting nitrogen fertilizer rates to the nutritional requirements of the produced crops, or applying nitrogen in split rates in different stages of plant development [48,49,80]. Similarly to fertilizers, plant protection products are also highly energy-intensive inputs in agricultural production [69], but they considerably boost the yield potential of crops [74,76]. Plant protection products do not induce significant changes in energy inputs [49,81], but they considerably improve energy outputs by increasing biomass yields [82–84].

The aim of this study was to evaluate the energy efficiency (energy inputs, energy output, energy gain and energy efficiency ratio) of grain production in a semi-dwarf genotype of winter triticale at four levels of agricultural inputs. Triticale was grown in a field experiment in a large farm in north-eastern Poland.

2. Materials and Methods

A field experiment was conducted in 2008–2011 in the Agricultural Experiment Station in Bałcyny in north-eastern Poland (53°35′46.4′′ N, 19°51′19.5′′ E, elevation 137 m). The experimental treatments were four levels of agricultural inputs in the production of a semi-dwarf genotype of winter triticale (× *Triticosecale* Wittm.) cv. Alekto, which differed in the spring nitrogen rate (split application) and fungal disease control (Table 1). The experiment had a randomized block design (RBD) with three replications. Plot size was 15 m^2 (10 by 1.5 m). In each year of the study, the preceding crop was winter rapeseed (*Brassica napus* L.). Each year, the experiment was established on *Haplic Luvisol* (LV-ha) originating from boulder clay [85]. Soil was disc harrowed and deep plowed after the harvest of the preceding crop. Sowing was preceded by tillage and harrowing. Fertilizers were applied before sowing at 70 kg ha^{-1} P_2O_5 (enriched superphosphate—40% P_2O_5) and 100 kg ha^{-1} K_2O (potash salt—60% K_2O). Each year, the seeds of semi-dwarf winter triticale cv. Alekto were dressed with thiram and tebuconazole and sown with a row seeder in late September at 400 germinating kernels per 1 m2, to a depth of 3.0 cm. During the autumn growing seasons, in stage Biologische Bundesanstalt, Bundessortenamt and Chemical Industry (BBCH) 14–15 [86], weeds were controlled with 1600 g ha^{-1} prosulfocarb, 50 g ha^{-1} diflufenican, 250 g ha^{-1} isoproturon and 3.75 g ha^{-1} chlorosulfuron. In the stage BBCH 31, ethephon (growth regulator) was applied at 480 g ha^{-1}. Winter triticale was harvested at physiological maturity (BBCH 89) using a small-plot harvester (7–10 August).

Table 1. Levels of agricultural inputs in the production of a semi-dwarf genotype of winter triticale (2008–2011).

Farming Operation	Date (BBCH Scale)	Levels of Agricultural Inputs			
		Low Input		High Input	
		A	B	C	D
N fertilizer (kg ha^{-1})	27	90	60	60	90
	32	0	30	60	60
Fungicides	31	none	none	125 g ha^{-1} flusilazole + 250 g ha^{-1} carbendazim	125 g ha^{-1} flusilazole + 250 g ha^{-1} carbendazim
	39	none	250 g ha^{-1} azoxystrobin	72 g ha^{-1} flutriafol + 72 g ha^{-1} epoxiconazole	none

BBCH—Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [86].

Energy inputs were divided into categories based on the respective agricultural operations and energy fluxes (Equation (1)).

$$\text{Energy inputs} = E_{i\ \text{diesel}} + E_{i\ \text{fixed assets}} + E_{i\ \text{materials}} + E_{i\ \text{human labor}} \quad (1)$$

where:

Energy inputs—total energy inputs (GJ ha^{-1}),
$E_{i\ \text{diesel}}$—energy input for diesel fuel consumption (GJ ha^{-1}),
$E_{i\ \text{fixed}}$—energy input for fixed assets (GJ ha^{-1}),
$E_{i\ \text{materials}}$—energy input for materials (GJ ha^{-1}),
$E_{i\ \text{human labor}}$—energy input for labor (GJ ha^{-1}).

The energy inputs for labor, tractor and machine operation, fuel consumption and materials were determined based on energy consumption and energy indicators per unit area in crop production (Table 2).

The higher heating value (HHV) of winter triticale grain was estimated by adiabatic combustion in a calorimeter (IKA C 2000, USA) with the use of a dynamic method. The lower heating value (LHV) was calculated based on the moisture content of freshly harvested grain [87] (Equation (2)).

$$\text{LHV} = \frac{\text{HHV} \times (100 - \text{W})}{100} - \text{WC} \times 0.0244 \quad (2)$$

where:

Table 2. Energy equivalence of inputs in the production technology [88].

Input	Unit	Energy Equivalent
Labor	MJ hour^{-1}	40
Tractors	MJ kg^{-1}	125
Machines	MJ kg^{-1}	110
Diesel oil	MJ kg^{-1}	48
Seeds	MJ kg^{-1}	9
N	MJ kg^{-1}	77
P_2O_5	MJ kg^{-1}	15
K_2O	MJ kg^{-1}	10
Pesticides	MJ kg^{-1} active ingredient	300

LHV—lower heating value of grain fresh matter (MJ kg^{-1}),
HHV—higher heating value of grain dry matter (MJ kg^{-1}),

MC—moisture content of freshly harvested grain (%),

0.0244—correction coefficient for water vaporization enthalpy (MJ kg^{-1} per 1% moisture content).

The energy output of triticale grain was calculated as the product of fresh matter yield (FMY) and LHV (Equation (3)) of grain.

$$\text{Energy output (GJ ha}^{-1}\text{) = FMY (Mg ha}^{-1}\text{)} \times \text{LHV (GJ Mg}^{-1}\text{)} \quad (3)$$

The energy efficiency of winter triticale grain was determined based on energy gain (Equation (4)) and the energy efficiency ratio (Equation (5)):

$$\text{Energy gain (GJ ha}^{-1}\text{) = Energy output (GJ ha}^{-1}\text{)} - \text{Energy inputs (GJ ha}^{-1}\text{)} \quad (4)$$

$$\text{Energy efficiency ratio} = \frac{\text{Energy output (GJ ha}^{-1}\text{)}}{\text{Energy inputs (GJ ha}^{-1}\text{)}} \quad (5)$$

The energy inputs in the production of winter triticale were determined in a process analysis by measuring diesel oil consumption, labor and the field performance of tractors and agricultural machines during standard agronomic operations in a large farm (own measurements, Table 3). Energy inputs were divided into two categories: (i) based on energy fluxes (labor, energy carriers, machines, agricultural tools, materials—seeds, fertilizers and pesticides) and (ii) agronomic operations (tillage, sowing, mineral fertilization, weed control, growth regulation, disease control, grain harvest).

Table 3. Technical parameters, performance and fuel consumption of agricultural machines in the production of winter triticale (2008–2011).

Farming Operation	Parameters of Self-Propelled Machine	Parameters of Accompanying Machine	Service Life (h)		Weight (kg)		Performance of Self-Propelled Machine and Accompanying Machine (ha h^{-1})	Fuel Consumption (dm^3 h^{-1})
			Self-Propelled Machine	Accompanying Machine	Self-Propelled Machine	Accompanying Machine		
Disc harrowing (5–8 cm)	130 kW	4.25 m (working width)	10,000	1500	7105	5100	3.0	18.0
Fall plowing (18–22 cm)	130 kW	5 (number of furrows)	10,000	1400	7105	2370	1.5	26.0
Tillage cultivation unit (5–8 cm)	130 kW	4 m (working width)	10,000	1800	7105	1880	3.5	17.2
Sowing	184 kW	4 m (working width)	10,000	1800	10,980	5600	4.0	29.5
Mineral fertilization	130 kW	24 m (working width)	10,000	2000	7105	685	13.5	8.7
Chemical control	94 kW	24 m (working width)	10,000	3000	5166	5600	10.0	7.6
Harvest	370 kW/10.5 m (working width)	-	2800	-	20,000	-	4.1	45.0
Biomass transport	130 kW	10 Mg (carrying capacity)	10,000	1400	7105	2600	-	8.0
Loading	55 kW/2500 kg (load capacity)	-	10,000	-	4922	-	-	3.0

3. Results and Discussion

The majority of conventional farming systems rely on high-input production technologies involving energy-intensive materials (fertilizers, pesticides) [89]. In crop production, energy inputs are determined mainly by crop species and the number of agronomic operations, i.e., by the intensity of the applied production technology [48,49,58,90,91]. In the present study, the average energy inputs associated with the 3-year production cycle of a semi-dwarf genotype of winter triticale ranged from 14.5–14.7 GJ ha^{-1} (low inputs A and B) to 17.1–19.3 GJ ha^{-1} (high inputs C and D) (Table 4). Similar energy inputs in the production of triticale grain were reported by Bielski et al. [49] (16.7–21.9 GJ ha^{-1}) and Raczkowski [92] (12.1–22.2 GJ ha^{-1}). In the work of Vigovskis et al. [93], the energy inputs associated with winter triticale production were much higher at 35 GJ ha^{-1}. In a study by Czarnocki et al. [94], the analyzed parameter ranged from 12.6 to 13.6 GJ ha^{-1}, depending on the applied tillage method.

Table 4. Structure of energy inputs in the production of a semi-dwarf genotype of winter triticale per farming operation (2008–2011).

Farming Operation	Levels of Agricultural Inputs							
	Low Input				High Input			
	A		B		C		D	
	MJ ha^{-1}	%	MJ ha^{-1}	%	MJ ha^{-1}	%	MJ ha^{-1}	%
Tillage	1621	11.2	1621	11.0	1621	9.5	1621	8.4
Sowing	2107	14.5	2107	14.4	2107	12.3	2107	10.9
Mineral fertilization, including	9165	63.2	9205	62.7	11,515	67.2	13,825	71.5
-N fertilization	7115	49.1	7196	49.0	9506	55.5	11,816	61.1
Chemical control, including	845	5.8	985	6.7	1131	6.6	1023	5.3
-disease control	11	0.1	140	1.0	286	1.7	178	0.9
Grain harvest and transport	756	5.2	756	5.2	756	4.4	756	3.9
Total	14,494	100.0	14,674	100.0	17,130	100.0	19,332	100.0

Technology D was the most energy-intensive due to the highest nitrogen fertilizer rates (90 and 60 kg ha^{-1} applied in stages BBCH 27 and 32, respectively) and a single fungicide treatment in stage BBCH 31. Energy consumption in the remaining production variants was lower by 11% (C), 24% (B) and 25% (A) (Table 4).

Regardless of the level of agricultural inputs, mineral fertilization had the highest share of energy inputs (62.7–71.5%; 9.2–13.8 GJ ha^{-1} in absolute values). Nitrogen fertilization alone was responsible for 49.0–61.1% of total energy inputs. Other energy-intensive operations included sowing (10.9–14.5% of total energy inputs), tillage (8.4–11.2%), chemical control of weeds, pathogens and lodging (5.3–6.7%), grain harvest and transport (3.9–5.2%) (Table 4). The structure of energy inputs in the production of triticale grain was similar in the experiments conducted by Czarnocki et al. [94], Raczkowski [92] and Bielski et al. [49]. It should be noted that energy inputs associated with various agronomic operations are fairly similar in the production of triticale and other cereals [95–97]. The structure of energy inputs was similar in the production of winter rapeseed [98,99], spring rapeseed, white mustard (*Sinapis alba* L.), Indian mustard (*Brassica juncea* (L.) Czern.) [100], maize (*Zea mays* L.), sweet sorghum (*Sorghum bicolor* (L.) Moench)) [70,71] and giant miscanthus (*Miscanthus* × *giganteus* Greef and Deuter) [56]. The structure of energy inputs in the production of different groups of crops (annual vs. perennial; monocots. vs. dicots) is comparable because mineral fertilization has the highest share of total energy inputs in most production technologies [56,70,71,98–100].

In the current study, the use of chemical control agents made only a minor contribution to total energy inputs (±6%) in the production of winter triticale grain (Table 4). According to Bielski [81] and Bielski et al. [49], fungicides account for 1.2–1.9% of total energy inputs in the production of winter triticale, subject to the intensity of the production technology. In a study by Deike et al. [84], fungicides were also responsible for a low percentage of energy inputs in the production of various crops, which could be attributed to the low fungicide dose per unit area [82]. Nonetheless, the use of pesticides should be minimized in agricultural production to prevent the contamination of soil, water and food, and to protect beneficial microorganisms. However, the application of pesticides can be reduced only when the pressure from weeds, pests and pathogens is low, but in the long-term perspective, this strategy can have adverse effects by considerably decreasing crop yields [101].

The analysis of energy fluxes (Table 5) revealed that agricultural materials (seeds, fertilizers, pesticides, growth regulator) accounted for 78.0–83.3% of total energy inputs associated with the evaluated levels of agricultural inputs. The above can be attributed mainly to considerable amounts of energy accumulated in mineral fertilizers (61.2–70.4% of total energy inputs) and seeds (8.7–11.5%). Other studies of winter triticale [49] and spring triticale [92] also demonstrated that agricultural materials had the largest share of total energy inputs in crop production (74–84%). In the work of Bielski [81], fertilizers and pesticides were responsible for 66% of total energy inputs (61% and 5%, respectively) in various winter triticale production systems. Agricultural materials also accumulated significant amounts of energy (77–89% of total energy inputs) in a study analyzing energy consumption in various production technologies of winter barley [90]. In other studies, agricultural materials had a somewhat smaller share of total energy inputs in the production of winter triticale (64%) [91] and spring triticale (58%) [55]. The relative proportions of mineral nitrogen fertilizers and pesticides in total energy inputs were determined to be 28% and 5%, respectively, by Deike et al. [84]. The relatively small share of fertilizers in the structure of energy inputs resulted from low rates of nitrogen application (98 kg ha^{-1} on average).

Table 5. Structure of energy inputs in the production of a semi-dwarf genotype of winter triticale by energy fluxes (2008–2011).

Energy Flux	Levels of Agricultural Inputs							
	Low Input				High Input			
	A		B		C		D	
	MJ ha^{-1}	%	MJ ha^{-1}	%	MJ ha^{-1}	%	MJ ha^{-1}	%
Labor	208	1.4	222	1.5	230	1.3	222	1.1
Tractors and machines	839	5.8	874	6.0	901	5.3	874	4.5
Energy carriers	2078	14.3	2134	14.5	2164	12.6	2134	11.0
Materials, including:	11,369	78.4	11,444	78.0	13,835	80.8	16,102	83.3
-seeds	1674	11.5	1674	11.4	1674	9.8	1674	8.7
-mineral fertilizers	8980	62.0	8980	61.2	11,290	65.9	13,600	70.4
-nitrogen	6930	47.8	6930	47.2	9240	53.9	11,550	59.7
-pesticides	715	4.9	790	5.4	871	5.1	828	4.3
-fungicides	11	0.1	75	0.5	156	0.9	113	0.6
Total	14,494	100.0	14,674	100.0	17,130	100.0	19,332	100.0

In the present study, energy carriers, the operation of machines and tractors and labor accounted for 11.0–14.5%, 4.5–6.0% and 1.1–1.5% of total energy inputs, respectively (Table 5). Higher levels of agricultural inputs in winter triticale cultivation led to an absolute increase in all energy fluxes without inducing significant changes in their structure (Table 5). Raczkowski [92], Bielski et al. [49] and Gozubuyuk et al. [91] estimated the percentage of energy carriers in total energy inputs to be 8.8–14.5%, 17.2–21.5% and 27.9%, respectively, in winter triticale production. The cited authors also found that labor accounted for only 0.3–3.5% of total energy inputs. Similar results were reported by Szempliński [96], Dubis [97] and Gozubuyuk et al. [91] in studies investigating the main energy fluxes in the production of other cereal species (spring barley, spring wheat, winter wheat).

Research shows that intensive crop farming increases GHG emissions per unit yield, and N fertilizers and energy carriers are the main contributors [102,103]. The effect of plant protection products on GHG emissions remains relatively small because the applied doses are nearly 10-fold lower than the rates of N fertilizers [102]. In a study by Wójcik-Gront and Bloch-Michalik [102], GHG emissions in winter triticale production were higher (0.304 kg CO_2 eq. kg^{-1}) at higher levels of agricultural inputs and a mean N fertilizer rate of 124.65 kg ha^{-1}, and lower (0.277 kg CO_2 eq. kg^{-1}) at lower levels of agricultural inputs and a mean N fertilizer rate of 88.62 kg N ha^{-1}. Higher GHG emissions at a higher intensity of agricultural inputs and higher N fertilizer rates were also noted in wheat, rye, spring triticale, barley, oat and maize [102]. Hughes et al. [104] demonstrated that GHG emissions were higher in winter barley production (0.335 kg CO_2 eq. kg^{-1}) than in spring barley production (0.300 kg CO_2 eq. kg^{-1}), mostly due to higher N fertilizer rates. Van

Stappen et al. [105] reported GHG emissions of 0.349 kg CO_2 eq. kg^{-1} in wheat grain production in Belgium, whereas Charles et al. [106] noted an increase in GHG emissions to 0.381 kg CO_2 eq. kg^{-1} when winter wheat was fertilized with 140 kg N ha^{-1} in Switzerland. Other authors [107,108] found that GHG emissions can be reduced through agricultural intensification by increasing crop yield per unit area.

The energy potential of crop production technologies is determined based on energy gain and the energy efficiency ratio [49,70,71]. In the current experiment, semi-dwarf winter triticale cv. Alekto had a positive energy balance regardless of the levels of agricultural inputs, i.e., the energy output in terms of grain yield exceeded the energy inputs associated with grain production (Table 6). The energy output of grain was highest (163.3 GJ ha^{-1}) in treatment C with a nitrogen fertilization rate of 120 kg ha^{-1} and two fungicide treatments. The energy output of grain produced in the remaining treatments was lower by 3% (high inputs D), 6% (low inputs B) and 13% (low inputs A). Energy gain was also highest in treatment C (high inputs) at 146.2 GJ ha^{-1}. In the remaining treatments (A, B and D), the energy gain of winter triticale grain was lower by 7.0 to 18.9 GJ ha^{-1} relative to treatment C. Energy output (141.8 GJ ha^{-1}) and energy gain (127.3 GJ ha^{-1}) were lowest in the low-input treatment A where nitrogen was applied at 90 kg ha^{-1} and disease control was limited to seed dressing only. Other authors also found that the energy potential of winter and spring triticale is determined mainly by agricultural intensification, mostly the nitrogen rate [48,49,55,81]. In a study by Bielski et al. [49], the energy output of winter triticale grain supplied with nitrogen at 150 kg ha^{-1} increased by 19% and 39% relative to treatments where nitrogen was applied at 120 and 30 kg ha^{-1}, respectively. Agricultural intensification also enhances energy gain by increasing biomass yields [49,51,109]. The net energy output of crops can be improved through the application of cultivation and protective treatments which minimize yield losses caused by pests, weeds and pathogens [110] and increase nitrogen use efficiency [84].

Table 6. Energy indicators in the production of a semi-dwarf genotype of winter triticale (2008–2011).

Energy Indicators	Levels of Agricultural Inputs			
	Low Input		High Input	
	A	B	C	D
Energy output (GJ ha^{-1})	141.8	153.5	163.3	158.6
Energy gain (GJ ha^{-1})	127.3	138.8	146.2	139.2
Energy efficiency ratio	9.8	10.5	9.5	8.2

An analysis of energy indicators (Table 6) revealed that the energy efficiency ratio was highest (9.8–10.5) in low-input treatments A and B. Higher energy inputs associated with an increase in agricultural inputs decreased the energy efficiency of the production process by 3–10% (C) and 16–22% (D).

Bielski [81] and Gozubuyuk et al. [91] reported equally high energy efficiency ratios in the production of winter triticale grain of 7.4–9.9 and 10.5, respectively. In the work of Klikocka et al. [55], the energy efficiency ratio of spring triticale reached 6.8. In contrast, the energy efficiency ratios calculated by Vigovskis et al. [93] in other cereal species (spring barley, spring wheat, triticale) were significantly lower, in the range of 1.5–1.8. The energy efficiency ratio is a useful metric for determining the optimal allocation of agricultural inputs in crop production [62]. In a study by Bielski et al. [49], the energy efficiency ratio of semi-dwarf winter triticale cv. Twingo peaked at 8.2 with low-input production technology. The analyzed parameter decreased by 24–27% when agricultural inputs were intensified. Lewandowski and Schmidt [51], Bielski [81], Bielski et al. [48] and Bielski et al. [49] also reported a considerable decrease in the energy efficiency ratio of winter triticale production in response to a high nitrogen rate that was not compensated by a corresponding increase in the energy output in terms of grain yield. Agricultural intensification also decreased the energy efficiency ratio in the production of winter wheat and sugar beet [109], maize and sorghum [111], sweet sorghum [71], winter rapeseed [98] and fodder galega [112].

4. Conclusions

Energy inputs should be reduced in modern crop production technologies to optimize energy use and minimize the adverse environmental impacts of agriculture. For this reason, the importance of energy-efficient solutions is increasingly emphasized in the farming sector. In the present study, the energy inputs in the production of semi-dwarf genotype winter triticale cv. Alekto ranged from 14.5 to 19.3 GJ ha^{-1}, subject to the levels of agricultural inputs. Fertilizers had the largest share of total energy inputs (61.2–70.4%), and mineral fertilization was the most energy-intensive farming operation (62.7–71.5%). Energy output and energy gain peaked in response to two fungicide treatments, seed dressing and a fertilizer rate of 120 kg ha^{-1} applied in a split ratio of 50:50 (BBCH 27/32). The energy efficiency ratio was highest when winter triticale was fertilized with 90 kg ha^{-1} (60 and 30 kg ha^{-1} in BBCH stages 27 and 32, respectively), seeds were dressed and a single fungicide treatment was applied (BBCH 39). Regardless of the obtained results, the energy efficiency ratio of winter triticale grain was very high (8.2–10.5) at all levels of agricultural inputs. However, in order to minimize greenhouse gas emissions from agriculture, the energy efficiency of grain production should be improved by reducing agricultural inputs.

Author Contributions: Conceptualization, W.S. and B.D.; methodology, W.S. and K.J.J.; software, K.J.J.; validation, W.S., B.D. and K.J.J.; formal analysis, W.S.; investigation, B.D.; resources, B.D.; data curation, K.J.J.; writing—original draft preparation, B.D.; writing—review and editing, W.S., B.D., K.M.L. and K.J.J.; visualization, B.D.; supervision, B.D.; project administration, W.S. and B.D.; funding acquisition, B.D. and K.J.J. All authors have read and agreed to the published version of the manuscript.

Funding: The results presented in this paper were obtained as part of a comprehensive study of the University of Warmia and Mazury in Olsztyn (grant No. 30.610.013-110). The project was financially supported by the Minister of Science and Higher Education in the scope of the program entitled "Regional Initiative of Excellence" for the years 2019–2022, project No. 010/RID/2018/19, amount of funding PLN 12,000,000.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The research was conducted within the project 30.610.013-110.

Acknowledgments: We would like to thank the staff of the Agricultural Experiment Station in Bałcyny for technical support during the experiment.

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

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