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The Energy Efficiency of the Production and Conversion of Spring Triticale Grain into Bioethanol

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Abstract: According to the assumptions of *Organisation for Economic Co-operation and Development* OECD, the share of biofuels in the global transport sector is estimated to reach 15–23% by 2050. The triticale can be used to produce bioethanol. The appropriate production process should generate as much renewable energy as possible per production unit. Plant production can be carried out in various tillage systems and using appropriate doses of nitrogen fertilization. The objective of this study is to compare the effect of traditional tillage system (TRD) and reduced (RED) tillage technology and nitrogen fertilizer (0, 40, 80, 120 kg N ha^{-1}) on grain and bioethanol yield of spring triticale. The field experiment was performed in the south east of Poland (50°42′ N, 23°15′ E) on medium dystrophic typical brown soil. Based on research and calculations, the TRD system and between 40 and 80 kg ha^{-1} of N fertilizer are recommended for use in the cultivation of triticale for bioethanol production purposes. Such a variant will ensure a sufficient yield of grain (5.190 and 5.803 t ha^{-1}), starch (3.462 and 3.871 t ha^{-1}) and bioethanol (2487.3 and 2780.7 L ha^{-1}) and good agronomic efficiency of N fertilizer (16.96 and 12.15 L of bioethanol per 1 kg of nitrogen (N) applied). The best ratio of energy efficiency of bioethanol production (EROI—Energy Return on (Energy) Investment or "net energy") was recorded for the TRD system (1.138:1) and for the N fertilizer at 40 kg N ha^{-1} (1.144:1).

Keywords: triticale; soil tillage; nitrogen; energy intensity of production; bioethanol; EROI

1. Introduction

In the last decade, the production and consumption of biofuels around the world have rapidly increased in connection with the need for reducing the emissions of greenhouse gases, diversifying transport fuels, promoting renewable energy, creating new jobs and retaining employees, in particular in rural areas and in developing countries [1]. The European Council determined two main targets under the climate and energy package, published in 2008: (1) at least a 20% reduction in greenhouse gas emissions by 2020, and (2) at least a 20% increase in the share of renewable energy sources in the national gross energy consumption [2]. Therefore, biofuels including ethanol are an attractive alternative to imported diesel oil and fuel oil and contribute to reducing CO_2 emissions that are the main cause of the greenhouse effect [3,4]. The concept of using bioethanol as fuel dates back to the origins of the automotive industry. As early as 1908 Henry Ford considered ethanol produced from plants as the fuel of the future. Ethanol exhaust fumes are less toxic and more environmentally friendly than previously used petroleum products [5].

Bioethanol is a renewable source of fuel which can be produced by fermentation of sugar from plants containing starch (first-generation feedstock) or lignocellulosic biomass (second generation feedstock) [1]. Bioethanol is a strategic resource widely used in the food, pharmaceutical, cosmetic and petrochemical industries. Currently, it is also mentioned among the most important biofuels used in transport [5]. Feedstock for the production of bioethanol contains sugar, starch and lignocelluloses [6,7]. The utilization of biofuels for transport purposes is a priority measure in many countries of the world, including the member states of the European Union [8]. According to the assumptions of OECD, the share of biofuels in the global transport sector is estimated at 15–23% by 2050 [9]. Scientists propose that its production should be based on a sustainable model [10]. Therefore, the main purpose of using the grains to produce bioethanol is generating the highest possible amount of renewable energy per production unit [11,12].

Plant production is connected with emissions of greenhouse gas (GHG). The emissions can be reduced by changing the plant production technology and allocating land for less intense crops adapted to lower mineral fertilization. Therefore, the dosage of nitrogen fertilizers can be reduced and crops with a lower nitrogen (N) requirement must be introduced [13]. Annual energy crops, due to short rotation, can, depending on the requirement, become a source of feedstock in a relatively short time. In Poland light soils are predominant and, due to the moderate European climate, triticale which does not need high-quality soil is the most suitable feedstock for the production of bioethanol [14–16]. Triticale is a synthetic hybrid of wheat and rye (*Triticosecale* Wittm. ex A. Camus or *Triticale* A. Müntzing) [17]. The first winter triticale crops were cultured in Hungary in 1968 and spring triticale was grown in Canada in 1970. Spring varieties are predominant in the world, while in Europe mainly winter ones are cultivated. Triticale is not very competitive to other species of grains, but the area of its crops is increasing mainly in Northern America, Central Australia, New Zealand, and in Europe: in Poland, France, Germany, Austria, Turkey, Sweden, Czech Republic, Ukraine and Russia. Industrial crops in 2017 in the EU-28 accounted for 7% of the total area of cropland and the share of triticale in the structure of grain crops was 4.6% only 2534.1 thousand ha [18].

The capacity of bioethanol per unit area depends on the yield of grain that is determined by the variety [16], and tillage conditions and nitrogen fertilizer dosage [12,19–21]. The soil tillage provides plants with optimal conditions for growth and development. Generally, the higher yield of spring triticale is obtained in the traditional system than in the simplified system (cultivating instead of plowing) [17]. However, the need to reduce energy expenditures incurred on the cultivation of plants and the need to protect the soil from degradation contributed to the search for untraditional solutions in farming systems. Not all of these solutions are optimal, because every tillage system must be adapted to the specific conditions of individual farms [17]. Nitrogen fertilization is the agronomic factor that most distinctly modifies the quality traits of grain. An appropriate dose and application schedule can facilitate the production of a good quality plant product and are very important for effective use of nitrogen [11,17,22]. Rosenberger [15] recounts that in adapting the dose of nitrogen for the purposes of producing crops intended as feedstock for the production of bioethanol, the accumulated starch content can be controlled instead of synthesizing protein. Thus, the efficiency and quality of alcohol fermentation can be controlled. At the same time, it is the most valuable grain for the production of industrial starch because it contains a lot of starch (65–68%) with a smaller percentage of protein, i.e., 12.5% [23]. Starch is the main reserve material stored in caryopses. According to Wojtkowiak et al. [24], the variety, nitrogen fertilization, location and years of research as well as the internal interaction between these factors, have a considerable determining effect on the starch level in triticale grain. Studies by Smith et al. [25] showed that 3.38 tonnes of triticale grains are needed to produce 1 tonne of bioethanol. Whereas Burczyk (2011) received the following bioethanol yields: 1533 L with 4.60 t of triticale, 1880 L with 5.64 t of winter wheat and 3123 L with 9.37 t of maize [26].

In Poland, the use of cereal grains for energy generation purposes is not widespread. In addition, a mental barrier exists due the fact that Polish producers highly respect cereal grains. However, grains of lower quality, not suitable for consumption or animal feed production, can be used for energy purposes. In addition, grains affected by fungal diseases can be used for energy generation purposes [27].

The scientific objective of this paper is to compare the effect of differentiated tillage technology (traditional TRD and reduced RED) and dosage of nitrogen fertilizer (0, 40, 80, 120 kg N ha^{-1}) on grain yield of spring Triticale and the energy efficiency of the production and conversion of spring Triticale grain for the production of bioethanol.

2. Materials and Methods

2.1. Field Experiment

The field experiment was performed in 2012–2014 in a randomized split-plot design (with four replications) in south east of Poland (50°42′ N, 23°15′ E) on medium dystrophic typical brown soil (BDt) (sand 68%, silt 31%, clay 1%). The soil reaction was slightly acidic (pH = 5.7). The content of assimilable phosphorus (P) in soil was high (53.5 mg kg^{-1}), that of potassium (K) was medium (85.2 mg kg^{-1}), and that of magnesium (Mg) was low (33.7 mg kg^{-1}). On the basis of rainfall and air temperature during the vegetation period (March–August), the Selyaninov hydrothermal coefficient was calculated (Table 1). According to the calculations, the 2012 growing season was defined as rather dry in the borderline to the optimal one (1.3), while the 2013 vegetation seasons were determined as optimal to the rather wet (1.6) and the 2014 growing season was defined as wet (2.3).

Table 1. The meteorological conditions (Meteorological Station in Zamość).

Years	Months (k)						Sum—Mean (III-VIII)		
	III	IV	V	VI	VII	VIII	† *k*	*p*	*t*
2012	1.0	0.7	1.1	1.2	0.9	1.8	1.3	330.2	2923
2013	1.1	1.2	1.8	2.3	0.9	0.5	1.6	395.6	2638
2014	2.3	1.1	5.2	1.7	2.2	1.4	2.3	619.7	2440
1981–2005	5.1	1.8	1.5	1.6	1.7	1.0	1.6	367.7	2353

† *k*—the Selyaninov hydrothermal coefficient † $k = [(p \times 10)/\sum t]$, *p*—precipitation (mm), *t*—temperature (°C).

The research facility of the experiment was spring triticale (*Triticosecale* Witt.) of the Milewo variety grown under 2 tillage systems with 4 doses of nitrogen and in 4 replications ($n = 32$).

(I) Tillage systems: TRD—traditional (i.e., traditional: harrowing (5 cm), deep pre-winter ploughing (20 cm). In spring: harrowing (5 cm), grubbing (15 cm), harrowing (5 cm); RED—reduced tillage: harrowing (5 cm), grubbing (15 cm). In spring: grubbing (15 cm), harrowing (5 cm).

(II) Nitrogen dosage (kg ha^{-1}): 0, 40, 80 and 120, where: 1/2 dose was used before sowing (the last third of March), 1/2 dose at the tillering stage (BBCH 30–31).

The area of experimental plots was 30 m^2 (5 m × 6 m) (in a randomized split-plot design). Before sowing phosphorus fertilizers (triple superphosphate at the dose of 39.6 kg P ha^{-1}) and potassium fertilizers (potassium salt at the dose of 83 kg K ha^{-1}) were introduced. Spring triticale was sown in the last third of March or first third of April with a density of 550 grains m^{-2}. The harvest time was the middle or last third of August. Caryopses were subject to treatment before sowing and the plantation was protected against agrophages (see Supplement Table S2).

The grains were harvested at full maturity (BBCH 89–92). The yield of grain from each experimental field was weighed (in kg) and the yield was converted into t ha^{-1}. Grain samples were collected in order to determine the content of starch.

2.2. Energy Intensity of Spring Triticale Production

The energy intensity (E_t) of spring triticale production was determined by accumulating the material and energy expenditure (energy sum of direct energy carries + raw materials and materials + investments + human labor) on the resulting production and the total energy expenditure on successive tillage and maintenance procedures for respective production technologies. The energy intensity of spring triticale production was calculated on the basis of energy intensity indexes expressed in MJ ha^{-1} [17].

$$E_t = E_{TR} + E_M + E_T + E_E + E_D + E_{FR} + E_P \left(\text{MJ ha}^{-1}\right) \quad (1)$$

where, energy expenditure on the use of:

E_{TR}—tractors; E_M—machines; E_T—transport vehicles; E_E—employees; E_D—fuel; E_{FR}—fertilizers; E_P—pesticides

The expenditure of means of production, labor and traction power on the tillage, sowing, protection and harvest of plants was converted into MJ, where energy intensity indicators are: human labor, tractor driver—80 MJ hours^{-1}, an auxiliary employee—50 MJ hours^{-1}; resources and materials (MJ kg^{-1}): fertilizers—N 77, P_2O_5 14, K_2O 10, spring triticale seed 7.5, pesticides (in S.A.) 300, diesel oil—52, use of tractors and farming machinery 112, spare parts 80, materials for repairs 30, lubricants 22 [17].

For calculations of the energy consumption, aggregates were taken, composed of the Ursus C-360 tractor (produced by URSUS SA with its registered office in Lublin, Poland) with a rated power of 44.1 kW (60 hp) and appropriately selected machines in terms of weight and working width. Parameters of these machines were taken from a study printed by Institute of Technology and Life Sciences (ITP) in Falenty, in Poland [17].

The ratio of energy intensity was calculated based on the relation between the energy value of the grain yield of spring Triticale and the energy expenditure to produce the yield, from the formula:

$$Ee = \frac{Pe}{Ne} \quad (2)$$

where *Pe*—energy value of grain yield per 1 ha (MJ), one kg of air-dry weight of the main yield is equivalent to 18.36 MJ [17]; *Ne*—amount of energy expenditure on producing yield per 1 ha (MJ) (energy sum of direct energy carries + raw materials and materials + investments + human labor).

2.3. Analysis of The Content of Starch and Ethanol Efficiency

The content of starch was determined in 24 average grain samples collected under the presented experiment by polarimetric methods at the Central Agroecological Laboratory of the University of Life Sciences in Lublin (CLA/PLC/30) (A detailed description of the determination of starch in triticale grain is given in the Supplementary Information. See Supplement, part I). The efficiency of conversion of bioethanol from starch and the agronomic efficiency of nitrogen (N) were estimated based on a predictive equation [5,20].

The efficiency of conversion of bioethanol from starch (L/t) was calculated from the formula:

$$Eet = \left(\frac{\text{C} \times 1.11 \times 2 \times 46}{180.16}\right) / (0.789 \times 1000) \quad (3)$$

where *Eet* means the efficiency of ethanol, L t^{-1}; 1.11 is the starch to glucose conversion factor; 2 stands for the analytical multiplier for summing up the equation of the glucose to ethanol reaction; 46 g mol^{-1} is the molar mass of ethanol; 180.16 g mol^{-1} is the molar mass of glucose, C is the weighed portion of starch in g; 0.789 is the density of ethanol in g ml^{-1}.

Bioethanol yield (L ha^{-1}) will be calculated based on the formula:

$$BP = Eet \times GY \quad (4)$$

where *Eet* means the efficiency of ethanol in L t^{-1}, *GY*—is the grain yield in t ha^{-1}. The amount of energy needed to produce 1 L of bioethanol calculated as 100% spirit will be 12.74 MJ, and the calorific value of bioethanol is 20.4 MJ L^{-1} or 25.8 MJ kg^{-1} [5].

The agronomic effectiveness of nitrogen (N) fertilizer was calculated from the formula:

$$EFA_N = \frac{PB_N - PB_0}{N} \quad (5)$$

where PB_N—bioethanol yield with N fertilizer, PB_0—bioethanol yield without N fertilizer, N—nitrogen (N) fertilizer dose.

The results of the studies and our own calculations will make it possible to determine the energy efficiency of the production of spring triticale grain expressed as EROI (*Energy Return on (Energy) Investment or "net energy"*) [5]. It is the ratio of energy contained in the bioethanol to the energy needed to produce the bioethanol:

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

where R_E is the (bare) ratio of efficiency, E_{OUT} output energy contained in the bioethanol, and E_{IN} input energy from sources needed to produce the bioethanol.

2.4. Statistical Analysis

To perform a statistical analysis on the obtained results, the ANOVA was used with the use of the Snedecor F test. The significance of differences was calculated using the Tukey test (p = 0.05). A comparison of the mean results with post-hoc analysis was then made. The calculations were carried out using statistical programs Statistica 10 (StatSoft Inc.: Tulsa, OK, USA, 2010; StatSoft Polska, Kraków 2010) and Excel 7.0 (2007 Microsoft Office System), (See Supplementary Information, Tables S4 and S9).

3. Results and Discussion

Different tillage systems and doses of nitrogen (N) fertilizers used in the experiment had a significant impact on the yield of grain, starch and bioethanol and on the agronomic effectiveness of N fertilizer. The content of starch in grain (mean 66.82%) and bioethanol efficiency (mean 480.0 L t^{-1}) in the presented study were not significantly dependent on the factors involved (Table 2, see Supplement Tables S3 and S4). The content of the starch of triticale according to other authors was 67.8–65.3% [18] and 62.3–65.8% [19]. Starch content and yield of grain crops per ha are important as a feedstock for bioethanol production [20]. The modern varieties of triticale are a very attractive and competitive raw material for the conversion of bioethanol [6,25,27]. The tested three varieties of spring triticale were characterized according to their starch yield, which ranged from 2.49 to 2.97 t ha^{-1}, and the yield of bioethanol ranged from 1571 to 1851 L ha^{-1} [28]. Similar results were obtained in the present experiment. Therefore, it can be stated that the high production potential of ethanol and the stability of ethanol yields prove that the seeds of spring triticale are a good raw material for its production [5,28].

The use of a traditional tillage system (TRD), in comparison to reduced tillage (RED), increased the yield of spring triticale grain by 16.5%, starch yield by 16.4% and bioethanol yield by 16.4%. It also increased the agronomic effectiveness of N fertilizer by 6.08 L of bioethanol per 1 kg of N applied (44.6%). The best yield of grain, starch and bioethanol was obtained after using 80 and 120 kg N ha^{-1}. A dose of 40 kg of N fertilizer per one hectare did not yield satisfactory results. Also, Knapowski et al. [29] had the highest N content in the grain of Triticale after application the highest N dose, i.e., 120 kg ha^{-1} and this was higher compared to the object fertilized with 80 kg N ha^{-1} by 1.1 g N kg^{-1} DM. The best agronomic effectiveness of N fertilizer was observed after using 40 and 80 kg N ha^{-1}. This phenomenon should be explained *by the law of decreasing increments (Mitscherlich law)*. Hirel et al. [30] conclude that utilization of N from fertilizers is increased when the level of plant production is lower and N fertilizer is used in small amounts.

Table 2. Grain yield and bioethanol yield of spring triticale as affected by N fertilization.

Tillage Systems	**Nitrogen Dosage**	**Grain Yield** (t ha^{-1})	**Starch Content** (%)	**Starch Yield** (t ha^{-1})	**Efficiency of Ethanol** (L t^{-1})	**Bioethanol Yield** (L ha^{-1})	**Agronomic Effectiveness of N Fertilizer** (L 1 kg N^{-1} Applied)
TRD	0	3.777 a	66.67 a	2.518 a	478.9 a	1808.9 a	-
	40	5.190 a	66.70 a	3.462 a	479.2 a	2487.3 a	16.96 a
	80	5.803 a	66.70 a	3.871 a	479.2 a	2780.7 a	12.15 bc
	120	5.967 a	66.90 a	3.992 a	480.6 a	2667.9 a	8.82 c
	Mean	5.184 A	66.74 A	3.461 A	479.5 A	2486.2 A	13.64 A
RED	0	3.413 a	67.03 a	2.287 a	481.6 a	1643.4 a	-
	40	4.103 a	66.97 a	2.747 a	481.1 a	1973.5 a	8.25 c
	80	4.777 a	66.70 a	3.184 a	479.2 a	2287.7 a	8.05 c
	120	5.020 a	66.87 a	3.355 a	480.4 a	2410.2 a	6.39 c
	Mean	4.328 B	66.89 A	2.893 B	480.6 A	2078.7 B	7.56 B
Nitrogen dosage	0	3.395 C	66.85 A	2.403 C	480.3 A	1726.1 C	-
	40	4.647 B	66.83 A	3.105 B	480.1 A	2230.4 B	12.61 A
	80	5.290 AB	66.70 A	3.528 AB	479.2 A	2534.3 AB	10.10 B
	120	5.493 A	66.88 A	3.673 A	480.5 A	2639.1 A	7.61 C
Year	2012	4.748 B	66.59 B	3.160 B	478.4 C	2270.3 B	8.21B C
	2013	5.108 A	66.81 AB	3.413 A	480.0 AB	2452.0 A	12.35 A
	2014	4.414 C	67.05 A	2.958 C	481.7 A	2125.1 B	9.75 B
Mean		4.756	66.82	3.177	480.0	2282.5	10.10 AB

Explanations: TRD—traditional tillage system; RED—reduced tillage system. Values marked with different letters (A, B, C, D and a, b, c) in the column differ significantly ($p < 0.05$).

Weather conditions during the vegetation of spring triticale had a significant influence on the discussed features. The best meteorological conditions occurred in 2013 when the weather was described as "optimal to rather wet" (Sielianinov coefficient 1.6). In that year, the highest yields of grain, starch and bioethanol were recorded along with the highest agronomic effectiveness of N per the amount of bioethanol obtained. The worst weather situation was noted down in the 2014 growing season that was defined as 'wet' (Sielianinov coefficient 2.3). Janušauskaitė [27] stated that grain yield and quality of triticale depend not only on the nutrition regime but also on the weather conditions, and the weather conditions of the growing season can be responsible for 44–55% of the yield variation. Triticale is most sensitive to rainless conditions during the grain filling when drought stress causes 7–50% of the grain yield variation. Klikocka et al. [17] found significant correlations between grain yield and yield components of spring barley and selected elements of weather conditions as well.

In the structure of energy expenditure on the production of spring triticale, a large share of raw materials and materials was noted down (7828 MJ ha^{-1}, on average 58%). N fertilizers had a particularly large contribution (Tables 3–5; see Information Supplementary Information, Tables S5–S7). Energy expenditure was relatively higher when TRD tillage was involved (13,097 MJ ha^{-1}), which was approximately 4.3% in relation to RED tillage. On the other hand, RED tillage contributed to a decrease in the use of direct carriers of energy, in particular fuel and human labor. The largest share in energy expenditure on the cultivation of spring triticale was that of tillage and harvest (Table 3, Tables S5 and S6). Klikocka and Sachajko [17] obtained similar results in other studies concerning spring triticale. Czarnocki et al. [31], investigating the energy efficiency of various production technologies of winter triticale, found the largest consumption of fuel of all technologies for traditional tillage systems including shallow ploughing and pre-sow ploughing. Many studies showed that irrespective of experimental factors the highest share in energy expenditure was that of raw materials and materials (more than 60%), including energy from mineral fertilizers. On the other hand, the percentage of expenditure on soil cultivation and treatment ranged from 14.2% for traditional tillage to 7.4% for no-plough tillage [17,31,32].

Table 3. Energy inputs and their structure in spring Triticale production.

Tillage Systems	Nitrogen Dosage	Direct Energy Carries		Raw Materials and Materials		Investments		Human Labor		Total
		(MJ ha^{-1})	(%)	(MJ ha^{-1})	(%)	(MJ ha^{-1})	(%)	(MJ ha^{-1})	(%)	(MJ ha^{-1})
TRD	0	2564	31.0	3208	38.8	1743	21.1	760	9.2	8275
	40	2564	22.6	6288	55.4	1743	15.4	760	6.7	11355
	80	2807	19.1	9368	63.6	1743	11.8	816	5.5	14734
	120	2994	16.6	12448	69.1	1743	9.7	840	4.7	18026
	Mean	2733	22.3	7828	56.7	1743	14.5	794	6.5	13097
RED	0	2138	27.7	3208	41.6	1747	22.7	616	8.0	7710
	40	2138	19.8	6288	58.3	1747	16.2	616	5.7	10790
	80	2381	16.8	9368	66.1	1747	12.3	672	4.7	14169
	120	2567	14.7	12448	71.3	1747	10.0	696	4.0	17460
	Mean	2306	19.8	7828	59.3	1747	15.3	650	5.6	12532
Nitrogen dosage	0	2351	29.4	3208	40.2	1745	21.9	688	8.6	7993
	40	2351	21.2	6288	56.8	1745	15.8	688	6.2	11073
	80	2594	17.9	9368	64.8	1745	12.1	744	5.1	14452
	120	2781	15.7	12448	70.2	1745	9.8	768	4.3	17743
Mean		2519	21.1	7828	58.0	1745	14.9	722	6.1	12815

Explanations: TRD—traditional tillage system; RED—reduced tillage system.

Table 4. Structure of the energy inputs in the raw materials and materials in the production of spring-Triticale.

Tillage Systems	Nitrogen Dosage	Unit	Fertilizers			Pesticides	Seeds	Total
			N	P	K			
TRD and RED ‡	0	MJ ha^{-1}	0	1260	1000	448	500	3208
		% †	0.00	39.28	31.17	13.97	15.59	100.00
	40	MJ ha^{-1}	3080	1260	1000	448	500	6288
		%	48.98	20.04	15.90	7.12	7.95	100.00
	80	MJ ha^{-1}	6160	1260	1000	448	500	9368
		%	65.76	13.45	10.67	4.78	5.34	100.00
	120	MJ ha^{-1}	9240	1260	1000	448	500	12448
		%	74.23	10.12	8.03	3.60	4.02	100.00
	Mean	MJ ha^{-1}	4620	1260	1000	448	500	7828
		%	59.02	16.10	12.77	5.72	6.39	100.00

Explanations: TRD—traditional tillage system; RED—reduced tillage system; ‡ in both tillage systems means they had the same energy inputs for raw materials and materials; † percentage share in relation to the share of sum in raw materials and materials.

Table 5. Structure of the energy inputs in the cultivation of spring-Triticale.

Tillage Systems	Nitrogen Dosage	Unit	Soil Tillage	Fertilization	Care and Protection	Sowing	Harvest and Transport	Total
TRD	0	MJ ha^{-}	1377	354	365	407	1803	4307
		% †	31.97	9.46	8.23	8.48	41.87	100.00
	40	MJ ha^{-1}	1377	354	365	407	1803	4307
		%	31.97	9.46	8.23	8.48	41.87	100.00
	80	MJ ha^{-1}	1377	354	365	407	2046	4550
		%	30.26	8.95	8.02	8.02	44.97	100.00
	120	MJ ha^{-1}	1377	354	365	407	2234	4737
		%	29.07	8.60	7.71	7.71	47.15	100.00
	Mean	MJ ha^{-1}	1377	354	365	407	1972	4476
		%	30.76	7.91	8.15	9.09	44.06	100.00
RED	0	MJ ha^{-1}	955	354	365	407	1803	3886
		%	24.59	10.49	9.39	9.39	46.41	100.00
	40	MJ ha^{-1}	955	354	365	407	1803	3886
		%	24.59	10.49	9.39	9.39	46.41	100.00
	80	MJ ha^{-1}	955	354	365	407	2046	4129
		%	23.14	9.87	8.84	8.84	49.57	100.00
	120	MJ ha^{-1}	955	354	365	407	2234	4316
		%	22.14	9.44	8.46	8.46	51.75	100.00
	Mean	MJ ha^{-1}	955	354	365	407	1972	4056
		%	23.55	8.73	9.00	10.03	48.62	100.00
Nitrogen dosage	0	MJ ha^{-1}	1166	354	365	407	1803	4095
		%	28.47	8.64	8.91	9.94	44.03	100.00
	40	MJ ha^{-1}	1166	354	365	407	1803	4095
		%	28.47	8.64	5.91	9.94	44.03	100.00
	80	MJ ha^{-1}	1166	354	365	407	2046	4338
		%	26.88	8.16	8.41	9.38	47.16	100.00
	120	MJ ha^{-1}	1166	354	365	407	2234	4526
		%	25.76	7.82	8.06	8.99	49.36	100.00
Mean		MJ ha^{-1}	1166	354	365	407	1972	4264
		%	27.35	8.30	8.56	9.55	46.25	100.00

Explanations: TRD—traditional tillage system; RED—reduced tillage system; †percentage share in relation to the share of sum in treatments.

According to the analysis of study results, the best energy efficiency ratio was recorded for TRD tillage (Table 6; see Supplementary Information, Tables S8 and S9). The RED tillage system, despite the fact that it was characterized by lower energy expenditure in the technological process, decreased grain yield. As a consequence of this relationship, the energy efficient ratio was significantly lower than that measured for the TRD system. The use of any incremental dose of N contributed to a significant decrease in the energy efficient ratio. The best ratio was calculated for the control site (nitrogen-free). This means that energy expenditure associated with the fertilizer was not compensated by the increase in energy associated with the grain yield. For this reason, we show for the first time, based on the presented studies, the use of 40 and 80 kg N ha^{-1} can be recommended as a good variant for fertilizing spring triticale from the perspective of production energy efficiency. The energy value of the yield of spring triticale grain was dependent on season variability (years of study), which is understandable, since this feature is closely linked to grain yield and its behavior complied with the distribution of yield (Tables 2 and 6; see Supplementary Information, Tables S3, S4, S8, S9).

Klikocka and Sachajko [17] recount that in average management conditions, approximately four energy units in the basic product (yield) should be generated per one unit of energy expenditure in plant production. In the presented studies, the average energy efficiency was 6.814, which means that the yield of grain obtained thanks to correctly selected technologies of spring triticale production was satisfactory (Figure 1). Czarnocki et al. [31] obtained the highest energy efficiency ratio on the winter triticale site where shallow ploughing was performed immediately after the harvest time. On the other hand, when such ploughing was abandoned, the energy efficiency ratio was significantly lower. According to Dobka [31], the use of a soil cultivator or rotary tiller instead of a plough for the preparation of soil for triticale cultivation led to reduced energy expenditure. Klikocka and Sachajko [17], studying spring triticale cultivation, found the highest energy efficiency ratio for plough-based tillage, whereas a reduced tillage system decreased the energy efficiency of mechanical treatments and human labor. However, as far as the TRD system is concerned, a higher share of direct energy carriers (fuel), capital expenditures and human labor were noted down in the structure of the expenditure.

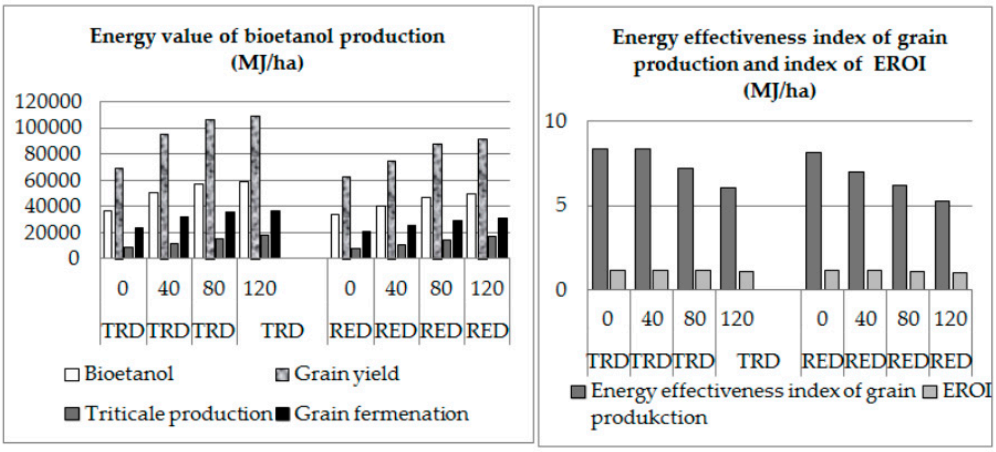

Figure 1. Energy value of bioethanol production and the energy effectiveness index (TRD—traditional tillage system; RED—reduced tillage system).

Table 6. Energy intensity in the production of spring Triticale and bioethanol.

Tillage Systems	Nitrogen Dosage	Energy Value of Grain Yield	Energy Expenditure on Producing Yield	Energy Intensity	Energy Value of Bioethanol	Energy Value of Inputs on Grain Fermentation	EROI
		MJ ha^{-1}			MJ ha^{-1}		
TRD	0	69340 a	8275 a	8.379 a	36901 c	23045 c	1.174 a
	40	95288 a	11355 a	8.392 a	50741 b	31688 b	1.176 a
	80	106549 a	14734 a	7.232 a	56730 a	35428 a	1.130 a
	120	109548 a	18026 a	6.077 a	58505 a	36537 a	1.071 a
	Mean	95181 A	13097 A	7.267 A	50719 A	31675 A	1.138 A
RED	0	62667 a	7710 a	8.128 a	33525 d	20936 c	1.162 a
	40	75337 a	10790 a	6.982 a	40259 c	25142 c	1.111 a
	80	87700 a	14169 a	6.190 a	46668 b	29145 b	1.070 a
	120	92167 a	17460 a	5.279 a	49169 b	30706 b	1.014 a
	Mean	79468 B	12532 B	6.341 B	42405 B	26482 B	1.089 B
Nitrogen dosage	0	66004 D	7993 D	8.258 A	35213 C	21991 C	1.168 A
	40	85312 C	11073 C	7.705 B	45500 B	28415 B	1.144 B
	80	97124 B	14452 B	6.720 C	51699 A	32287 A	1.100 C
	120	100858 A	17743 A	5.684 D	53837 A	33622 A	1.043 D
Year	2012	87164 B	12815 A	6.802 B	46314 B	28923 B	1.113 B
	2013	93773 A	12815 A	7.317 A	50022 A	31239 A	1.139 A
	2014	81036 C	12815 A	6.323 C	43351 C	27073 C	1.088 C
Mean		87325	12815	6.814	46562	29079	1.114

Explanations: TRD—traditional tillage system; RED—reduced tillage system; EROI—Energy Return on (Energy) Investment or “net energy”. Values marked with different letters (A, B, C, D and a, b, c) in the column differ significantly ($p < 0.05$).

The energy expenditure incurred to produce a grain yield of triticale represented an average of 27.5% in the energy value of bioethanol (Table 6). Research and analyses showed that in the production of bioethanol from triticale grain (grain fermentation), the energy expenditure on raw material processing was very high and it accounted for about 62% of the energy value of bioethanol. However, more energy was recovered in the form of biofuel than was expended on its production (agricultural engineering and fermentation). This is indicated by the ratio of energy efficiency of bioethanol production (EROI > 1) (Table 6, Figure 1). The best value of the above-mentioned ratio (1.138:1) was recorded for the TRD system and for the lowest dose of N fertilizer, i.e., 40 kg N/ha (1.144:1). RED systems and high doses of N fertilizers decreased the EROI. Bielski et al. [5] and Lewandowski and Kauter [12] claim that a need for rational utilization of N exists because in the process of raw material production the highest energy expenditure is incurred on fertilization using this macroelement. The optimization of N fertilization of energy crops must offset the conflict between efficiency and energy utilization aspects. The resulting EROI is unsatisfactory. According to some authors, minimal the value of the EROI indicator should be at least 3, guaranteeing the economic profitability of biofuel production [5]. Dobek et al. [33] also found that the ratio was poor, amounting to 0.68–0.92. On the other hand, Bielski et al. [5] came up with an average EROI for triticale grain at the level of 1.22. Therefore, triticale is particularly worth noting with regard to the fact that the species is characterized by a high yield of energy at a relatively low expenditure of energy on grain production [5,20,34].

4. Conclusions

On the basis of conducted field tests on dystrophic medium brown soil in the south east of Poland it was found that the best agronomic efficiency of N fertilizer was achieved after using the TRD system (13.64) and N fertilizer at a dose of 40 and 80 kg N ha^{-1} (respectively 12.61 and 10.10 L of bioethanol per 1 kg of N fertilizer). This means that using the RED system and excessive doses of N fertilizer are unjustified with regard to the utilization of N by spring triticale. This phenomenon confirms that the energy expenditure on the production of grain is least favorable when the highest dose of N, 120 kg ha^{-1}, is used. On the other hand, the reduction of fuel and labor consumption in RED systems is not compensated by the grain yield.

Generally, based on research and calculations, the TRD system and between 40 and 80 kg ha^{-1} of N fertilizer are demonstrated and recommended to be used in the cultivation of spring triticale in the described soil and climatic conditions of Poland for bioethanol production purposes.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/8/423/s1, Part I: Information about starch analysis, Table S1: Numerical values for various types of starch, Part II: Table S2: Chemicals used in the protection of spring wheat against pests, Table S3: Basic data for the preparation of the Table 2: Grain yield and bioethanol yield of spring triticale as affected by N fertilization, Table S4: Results of statistical calculations for the studied technological features of spring triticale grains and bioethanol—for the preparation of the Table S3. Table S5: Basic data for the human labor consumptions (hours ha^{-1}) of cultivation technology of spring Triticale (preparation of the Table 3: Energy inputs and their structure in spring Triticale production), Table S6: Basic data for energy inputs (MJ ha^{-1}) of the treatments in cultivation technology of spring Triticale, Table S7: Basic data for energy inputs (MJ ha^{-1}) of the raw materials and materials in cultivation technology of spring Triticale (preparation of the Table 5: Structure of the energy inputs in the raw materials and materials in production of spring-Triticale), Table S8: Basic data for the preparation of the Table 6: Energy intensity of production of spring Triticale and bioethanol, Table S9: Results of statistical calculations for the studied energy features of spring triticale grains and bioethanol—for the preparation of the Table S8.

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