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ORIGINAL PAPER

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THE EFFECTS OF SEEDING RATE, MINERAL FERTILIZATION AND A GROWTH REGULATOR ON THE ECONOMIC AND ENERGY EFFICIENCY OF DURUM WHEAT PRODUCTION

Kamila Sabina Bożek, Tomasz Winnicki✉, Krystyna Żuk-Gołaszewska

Department of Agrotechnology, Agricultural Production Management and Agribusiness, University of Warmia and Mazury in Olsztyn
Oczapowskiego 8, 10-718 Olsztyn, **Poland**

ABSTRACT

Background. The effects of agrotechnical factors have an influence on a major portion of total operational and non-operational energy inputs. The aim of this study was to analyze the effects of various agronomic factors on the economic and energy efficiency of *Triticum durum* L. production.
Material and methods. The analyzed factors in the production of durum wheat were mineral fertilization rates (0, 80 and 120 kg N·ha^{-1}), seeding rate (350, 450 and 550 kernels·m^{-2}) and the application of a growth regulator. Total energy consumption was calculated for the evaluated technologies of spring durum wheat production, including nitrogen fertilization, plant protection, agricultural machinery, transport and the associated operations.
Results. The value of wheat grain production was highest at 2227.86 USD·ha^{-1} in the production technology with a fertilizer application rate of 120 kg·ha^{-1} N and a seeding rate of 550 kernels·m^{-2}. This variant was also characterized by the highest production costs of 1017.17 USD·ha^{-1}. The economic efficiency (cost-benefit ratio) was highest (2.32) in the production technology with a fertilizer rate of 120 kg·ha^{-1} and a seeding rate of 350 kernels·m^{-2}. The energy efficiency ratio was highest in the unfertilized treatment with a seeding rate of 350 kernels·m^{-2}. This technology was characterized by the highest energy efficiency both when the energy value of grain (5.62) and the energy value of grain and straw (8.40) were taken into account.
Conclusion. The production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} generated the highest profits. Technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} had the highest energy inputs (22.60 GJ·ha^{-1}). The cost-benefit ratio was highest in the production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 350 kernels·m^{-2}. Energy gain was highest in the production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} at 82.88 (grain) and 137.03 (grain + straw) GJ·ha^{-1}.

Key words: economic and energy efficiency, *Triticum durum*

INTRODUCTION

The geographic distribution of durum wheat, a cereal species with high temperature requirements, has been expanded due to global warming, in particular in Europe where this crop can now be grown north of the Mediterranean region, including in Poland and the Czech Republic. Durum wheat is traditionally cultivated in regions with a sufficient supply of water, and water stress is one of the main production constraints in these areas (Moragues *et al*., 2006). In 2016/2017, the global production of durum wheat

✉ tomasz.winnicki@uwm.edu.pl, kamka.b@onet.eu , kzg@uwm.edu.pl

reached 40 million tons of grain, with Canada being the global leader (7.3 million tons). In Europe, the leading producers of durum wheat are Italy (5.3 million Mg), France (1.6 million Mg), Greece and Spain (1 million Mg each). Durum wheat grain is used mainly in the production of food in Europe (8 million Mg), seeds (0.5 million Mg), industrial goods (0.1 million Mg) and feed (0.8 million Mg). The common practice in Italy is to delay the harvesting date in response to changes in price to ensure the maximum profitability of production (Siad *et al*., 2017).

Effective energy use in agriculture, including in the production of durum wheat, is one of the key requirements for sustainable agricultural production. The application of integrated production methods is regarded as an effective strategy for reducing production costs and maximizing the efficiency of labor and other factors (Shahan *et al*., 2008). Conventional tillage, in particular chisel-plow tillage, is the most common practice in durum wheat cultivation. The chemical composition of grain and cereal products is influenced by genotype as well as agronomic factors such as nitrogen fertilization and stand density. However, high rates of nitrogen fertilizer contribute to lodging, which compromises grain quality. Anti-lodging agents are used in the production process to address this problem (Harasim and Wesołowski, 2013).

The concepts of economic and energy efficiency, which are defined as the generation of maximum profit and maximum output with minimum input, are very important in agriculture, including in the production of wheat (Canakci *et al*., 2005; Sartori *et al*., 2005; Meyer-Aurich *et al*., 2012; Heidari *et al*., 2015). Agricultural inputs determine the cost of durum wheat production. The main production costs are associated with the purchase of seeds, fertilizers, crop protection agents as well as irrigation (Bakhshoodeh and Thomson, 2001; Siad *et al*., 2017). In agriculture relevant knowledge contributes to an increase in productivity, food security and rural development. The aim of this study was to compare the economic and energy efficiency of durum wheat produced under different agronomic conditions.

MATERIAL AND METHODS

Field experiment

Spring durum wheat cv. SMH87 was evaluated in a field experiment conducted in 2015–2017 on grey-brown podsolic soil formed from light clay, underlain by class IVa heavy clay with very high suitability for rye production. The experimental soil was slightly acidic with a pH range of 5.0 to 6.1. The arable layer was characterized by high phosphorus content and a moderate content of potassium and magnesium.

The experiment was conducted in north-eastern Poland (53°40’ N; 19°50’ E) in the Agricultural Experiment Station in Bałcyny, which is owned by the University of Warmia and Mazury in Olsztyn. Winter oilseed rape was the preceding crop in two experimental years, and faba beans were the preceding crop in one year (oilseed rape was frost damaged).

The experimental factors were (treatment abbreviations are given in parentheses):

– nitrogen fertilization (N):
  - 0: control treatment without nitrogen fertilization – natural soil fertility (N0),
  - 1: 80 kg·ha^{-1} (50 kg·ha^{-1} pre-sowing and 30 kg·ha^{-1} in the stem elongation stage, Z33) (N1),
  - 2: 120 kg·ha^{-1} (50 kg·ha^{-1} pre-sowing, 30 kg·ha^{-1} in the stem elongation stage, Z33, and 40 kg·ha^{-1} at the beginning of heading, Z51), (N2) (Zadoks *et al*., 1974);

– seeding rate (SR):
  - 0: 350 kernels m^{-2} (SR0),
  - 1: 450 kernels m^{-2} (SR1),
  - 2: 550 kernels m^{-2} (SR2);

– application of the growth regulator (R):
  - 0: control treatment without the growth regulator (R0),
  - 1: application of the growth regulator in the heading stage (R1).

The experiment had a strip-split plot design in three blocks. Fertilization variants and seeding rates were randomly distributed in sub-blocks. Growth regulator variants were randomly distributed in perpendicular strips. The Medax Top 350 SC growth regulator (active ingredients: mepiquat chloride and calcium prohexadione) was applied in the stem elongation stage (Z37-39).

Mineral P and K fertilizers were applied before sowing. Phosphorus (46% triple superphosphate) was applied at 35 kg·ha^{-1}, and potassium (60% potash salt) was applied at 83 kg·ha^{-1}. Calcium (calcium carbonate) was applied once every 4 years. All treatments were conventionally tilled. The preceding crop was harvested and the soil was tilled with a disc harrow and a chisel-plow to incorporate post-harvest residues into the soil and to control weeds. In autumn the soil was deep plowed and laid into ridges. In spring the soil was harrowed twice and a cultivation aggregate was applied. Fertilizers were thoroughly mixed with the soil using a harrow. Durum wheat was sown on 25 March in 2015 and on 29 March in 2016 and 2017. Crop protection agents were applied in all treatments. Weeds were controlled with the Chwastox Extra 300 SL herbicide (active ingredient: 2-methyl-4-chlorophenoxyacetic acid – MPCA potassium salt, a phenoxy compound) at 3 dm^3·ha^{-1} in the tillering stage. Amistar 250 EC fungicide (active ingredient: azoxystrobin – a strobilurin compound) was applied during heading at 1 dm^3·ha^{-1}. Karate Zeon 050 CS insecticide (active ingredient: lambda-cyhalothrin – a pyrethroid compound) was applied in the early heading stage at 0.1 dm^3·ha^{-1} according to the recommendations of the Institute of Plant Protection to protect crops against the cereal leaf beetle (*Oulema melanopa* L.). The experiment was a small-scale field trial conducted in three replications in plots with an area of 8.75 m^2 each.

Economic efficiency analysis

The economic efficiency of durum wheat production was analyzed based on average grain yield. Total direct costs were analyzed in stages. The first stage involved the establishment of treatments, and the second stage was the production of durum wheat. Direct costs were associated with setting up and running the field experiment in each year of the study. The data acquired during the field experiment were used to calculate the direct cost of every agricultural operation per hectare. The inputs associated with labor and machine operation were determined based on the list of agricultural treatments and operations, in accordance with the adopted methodology. All values were expressed in terms of 2018 prices. The gross price of 1 kg of durum wheat seeds was USD 0.64, and the value of harvested grain was determined at 332.45 USD·ha^{-1}. Economic efficiency was evaluated with the use of the following indicators: Direct Margin (DM) as the difference between Production Value (PV) and Direct Costs (DC); Income (I) as the difference between DM and Indirect Costs (IC); and Total Costs (TC) (Goraj 2000; Augustyniak-Grzymek *et al.*, 2009). Other indicators of economic efficiency were also calculated (Juchniewicz, 1999): Gross Margin Ratio ((DM/PV) x 100%), Profit Rate ((I/PV) x 100%), Production Profitability Index (PV/TC) and Relative Cost Index (TC/PV).

The costs associated with the operation of tractors and machines were determined based on the relevant indicators (Muzalewski, 2007). The economic efficiency of durum wheat was determined in view of different rates of nitrogen fertilization (0, 80 and 120 kg N·ha^{-1}), different seeding rates, and the presence or absence of the growth regulator (treatments R1 and R0). An analysis of economic and energy efficiency was not performed in the study due to the absence of significant differences between the treatments where the Medax Top 350 S.C growth regular was and was not applied. The analysis was based on the average price of wheat in Poland in 2018, i.e. USD 219 per ton. Prices and costs were expressed in USD based on the exchange rate quoted by the National Bank of Poland on 15 September 2018 (USD 1 = 3.79 PLN).

Energy output analysis

The energy value of biomass yield was calculated as the product of grain yield per ha and the lower heating value of durum wheat grain:

$$Y_{ev}= Y_b \cdot Q^r_i$$

where:

Y_{ev} – energy value of biomass yield (GJ·ha^{-1}),
Y_b – durum wheat grain yield (Mg·ha^{-1}),
Q^r_i – lower heating value of grain (GJ·Mg^{-1}).

Energy input analysis

The accumulated energy inputs associated with the production of durum wheat were determined with the use of the method proposed by Wójcicki (2002). The total (accumulated) energy inputs in the evaluated treatments were calculated based on the following formula:

$$E_{total} = \Sigma E_{materials} + \Sigma E_{fixed\ assets} + \Sigma E_{diesel} + \Sigma E_{labor}\ (MJ \cdot ha^{-1})$$

where:

E_{total} – total (accumulated) energy inputs production (MJ·ha^{-1}),
$\Sigma E_{materials}$ – accumulated energy inputs associated with raw materials (MJ·ha^{-1}),
$\Sigma E_{fixed\ assets}$ – accumulated energy inputs associated with machines and equipment (MJ·ha^{-1}),
ΣE_{diesel} – accumulated energy inputs associated with fuel consumption (MJ·ha^{-1}),
ΣE_{labor} – accumulated energy inputs associated with labor (MJ·ha^{-1}).

The energy inputs (*Ep*) associated with crop production are the total energy inputs associated with the operation of tractors, agricultural machines and means of transport. The following formula was used to calculate the energy inputs associated with the operation of a tractor with a machine implement:

$$\mathrm{E_{hp}} = E_{hc} + E_{hm} = \frac{(m_c \cdot e_c + m_{zc} \cdot e_{z)}}{T_{hc}} + \frac{(m_m \cdot e_m + m_{zm} \cdot e_{z)}}{T_{hm}} (\mathrm{MJ} \cdot \mathrm{h}^{-1})$$

where:

E_h – energy consumption during one hour of tractor (E_{hc}) and machine (E_{hm}) operation, (MJ·h^{-1}),
m – weight of tractors (m_c), machines and equipment (m_m), (kg),
m_z – weight of spare parts for repairing tractors (m_{zc}), machines and equipment, (kg),
e – energy equivalent coefficient associated with the production of tractors (e_c), machines and equipment (e_m), (MJ·kg^{-1}),
Th – operating time of tractors (T_{hc}), machines and equipment (T_{hm}), (h).

Fuel consumption per unit area (*Qib*) was determined based on hourly fuel consumption (*Gib*) and automotive kinetic energy of agricultural machines (*W*) with the use of the following formula:

$$Q_{ib} = \frac{G_{ib}}{W}\ (\mathrm{kg} \cdot \mathrm{ha}^{-1}).$$

RESULTS AND DISCUSSION

Economic efficiency analysis

The agricultural operations applied in the experiment and the associated costs are presented in Table 1. Total soil tillage costs reached 67.82 USD·ha^{-1}, and plowing was the most cost-intensive operation (32.02 USD·ha^{-1}) (Table 1).

The total cost of tractor and machine operation reached 204.53 USD·ha^{-1} and was 14.9% higher than the costs associated with the production of durum wheat in a study by Winnicki and Żuk-Gołaszewska (2017). Among the total cost the most cost-intensive operation was combine harvesting, which lasted 0.8 h. The cost of combine harvesting was determined at 80.69 USD·ha^{-1}, and it accounted for 43.83% of the total cost of agronomic operations (Table 1). The rate of Ca and PK fertilization was identical in all treatments. The direct costs associated with Ca and PK fertilization were determined at: Ca – 124.01 USD ha^{-1}, P – 114.11 USD·ha^{-1}, and K – 62.19 USD·ha^{-1}. Crop protection agents accounted for 11.95-14.78% of total costs. The applied crop protection strategies generated the following costs: Chwastox Extra 300 SL herbicide – 13.12 USD·ha^{-1}, Amistar 250 SC fungicide – 49.41 USD·ha^{-1}, and Karate Zeon 050 CS insecticide – 23.35 USD·ha^{-1}. Nitrogen fertilization and seed costs contributed to variations in production value. Nitrogen fertilizers generate significant costs in the production of cereals, including durum wheat. The yield of spring durum wheat cv. SMH87 ranged from 4.69 to 5.86 Mg grain·ha^{-1}, and from 2.09 to 3.01 Mg straw·ha^{-1}. The costs associated with nitrogen fertilization rates of 80 and 120 kg·ha^{-1} of N were determined at 62.40 and 93.62 USD·ha^{-1}, respectively (Table 2). Seed purchase costs ranged from 120.16 to 189.04 USD·ha^{-1}, subject to stand density, and accounted for 14.61-18.58% of total costs. In a study by Siad et al. (2017), seed purchase costs were 90.74 USD·ha^{-1}. The cost associated with the application of Medax Top 350 SC growth regulator, in accordance with the adopted methodology, was determined at 35.62 USD·ha^{-1}, and it did not contribute to significant differences in production costs. The total cost of durum wheat production was 809.44 USD·ha^{-1}, and the benefit-cost ratio was determined at 1.43 (Shahan *et al*., 2008). In a study by Canakci *et al*., the specific energy of wheat production was 5.24 MJ·kg^{-1}.

Table 1. Costs associated with tractor and machine operation in the analyzed production technologies of durum wheat

Field operations	Tractor operation USD·ha^{-1}	Machine operation USD·ha^{-1}	Tractor and machine operation USD·ha^{-1}	Operating hours h	Value in USD·ha^{-1}
Disking	44.0	4.4	48.4	0.20	9.69
Chiseling	24.1	6.4	30.5	0.30	9.15
Deep plowing	44.0	9.4	53.4	0.60	32.02
Cultivation aggregate	44.0	11.9	55.9	0.30	16.76
Harrowing ×3	24.1	0.9	25.0	0.30	7.50
N before sowing + Ca, P, K fertilization	24.1	6.5	30.6	0.15	4.59
Sowing	24.1	13.2	37.4	0.40	14.95
Chwastox Extra 300 SL	24.1	5.0	29.1	0.15	4.35
Amistar 250 SC	24.1	4.9	29.0	0.15	4.35
Karate Zeon 050 CS	24.1	4.9	29.0	0.15	4.35
Medax Top 350 SC	24.1	4.9	29.0	0.15	4.35
Harvest	0.0	100.9	100.9	0.80	80.69
Transport (5 km)	30.7	5.2	35.9	0.20	7.17
Total				4.0	199.92
N fertilization variant					
Fertilization (N1)	24.1	6.5	30.6	0.15	4.59
Fertilization (N2)	24.1	6.5	30.6	0.30	9.18

Production technology N2, SR2 (N fertilization rate – 120 N kg·ha^{-1}, seeding rate – 550 kernels·m^{-2}) was characterized by the highest direct costs (704.47 USD·ha^{-1}) which accounted for 69.26% of total costs. In production technology N0, SR0 (no N fertilization, seeding rate – 350 kernels m^{-2}), direct costs reached 541.97 USD·ha^{-1}. The highest production value was in technology SR2, N2 (2227.86 USD·ha^{-1}), where direct costs were 704.47 USD·ha^{-1}. Differences in indirect costs resulted from variations in tractor and machine operation and labor. Indirect costs were highest at 312.70 USD·ha^{-1} in treatments with the highest rate of N fertilization (120 kg·ha^{-1}). Total costs were highest in production technology N2, SR2 (1017.17 USD·ha^{-1}) and lowest in production technology N0, SR0 (822.20 USD·ha^{-1}). Economic efficiency was highest in treatments with the highest rate of N fertilization (120 N kg·ha^{-1}), and it was influenced by seeding rate (Table 3). In these production technologies, gross margin was highest at 1565.25 USD·ha^{-1} in treatments with seeding rate of 450 kernels·m^{-2}, where agricultural income reached 1032.54 USD·ha^{-1} (Table 3). The cost-benefit ratio was highest at 2.32 in the production technology with the highest N fertilization rate of 120 N kg·ha^{-1} and a seeding rate of 350 kernels·m^{-2}. In turn, the production technology without N fertilization and a seeding rate of 550 kernels·m^{-2} was characterized by the lowest cost-benefit ratio of 1.63 and the highest total cost per 1 ton of grain (251.72 USD). In a study by Winnicki *et al.* (2013), an increase in grain yield increased the cost-benefit ratio of spring barley. The cost-benefit ratio of wheat produced without irrigation was 2.56 (Ghorbani *et al.*, 2011).

Table 2. Production technology and production costs of durum wheat (USD·ha^{-1})

Item	Production technology								
	N0			N1			N2		
	SR0	SR1	SR2	SR0	SR1	SR2	SR0	SR1	SR2
Yield, Mg·ha^{-1}	3.51	3.70	3.54	4.69	4.89	5.13	5.78	5.22	5.86
Total production value	1446.59	1509.76	1456.57	1838.89	1905.38	1985.17	2200.84	2015.09	2227.86
Grain value	1166.91	1230.08	1176.89	1559.21	1625.7	1705.49	1921.16	1735.41	1948.18
Direct payments					279.68				
Direct costs, USD·ha^{-1}	541.97	576.23	610.85	604.37	638.63	673.25	635.59	669.85	704.47
Seed purchase, kg	120.16	154.42	189.04	120.16	154.42	189.04	120.16	154.42	189.04
Ca, P, K fertilization, kg·ha^{-1}					176.30				
Nitrogen fertilization, kg·ha^{-1}	–	–	–	62.40	62.40	62.40	93.62	93.62	93.62
Pesticide, R0/R1					121.58				
Indirect costs, USD·ha^{-1}		280.23			290.03			312.70	
Tractor operation		204.53			209.12			213.71	
Agricultural tax					31.39				
Labor		19.94			24.16			24.84	
Operating profit margin, 7.5%		24.37			25.36			42.77	
Total cost, USD·ha^{-1}	822.20	856.46	891.01	894.40	928.66	963.28	948.29	982.55	1017.17

Table 3. Indicators of economic efficiency in durum wheat production

Item	Production technology								
	N0			N1			N2		
	SR0	SR1	SR2	SR0	SR1	SR2	SR0	SR1	SR2
Standard gross margin	904.62	904.62	933.53	845.72	1234.52	1266.75	1311.92	1565.25	1345.24
Agricultural income	624.39	653.30	565.49	944.49	976.72	1021.89	1252.55	1032.54	1210.69
Gross margin ratio	62.53	59.92	64.09	45.99	64.79	63.81	59.61	77.68	60.38
Profit rate	43.16	43.27	38.82	51.36	51.26	51.48	56.91	51.24	54.34
Total cost per 1 ton of grain	234.25	231.48	251.72	190.70	189.91	187.77	164.06	188.23	173.58
Benefit-cost ratio	1.76	1.76	1.63	2.06	2.05	2.06	2.32	2.05	2.19
Agricultural income, USD·ha^{-1}	183.49	183.49	94.01	158.67	231.62	237.66	228.96	273.17	234.77

Energy efficiency analysis

Low-input agricultural systems are generally characterized by a higher efficiency of energy use and lower greenhouse gas emissions than high-input systems. The type and performance of tractors and farming machines significantly influence the energy efficiency of agricultural production (Bakhshoodeh and Thomson, 2001). The type and operating parameters of tractors and machines applied in this experiment, which determined energy inputs, are presented in Table 4.

Table 4. Data for field operations

Operations	Tractors			Machinery			Comments
	name	mass kg	power kW	name	mass kg	operating period $h\cdot ha^{-1}$	
Disking	JD 6220	5970	70	BDF-3	1500	3.5	1 treatment
Chiseling	URSUS C-385	3200	56	Euro-Masz Pre-sowing cultivator AU 42	1350	4.1	width – 3.6 m
Deep plowing	JD 6220	5970	70	Kverneland BB-100	1120	1.5	5-ridge plowing
Cultivation aggregate	JD 6220	5970	70	Kverneland KTC 6.0 m Exacta	1350	2.5	1 treatment
Chemical fertilizers Ca, P, K, N	URSUS C-385	3200	56	Amazone ZA-M 1501	350	4.5	depending on production technology
Harrowing	URSUS C-385	3200	56	Harrow, 6 m	650	5.5	3 treatments
Sowing	JD 5720	3700	59	AGROMASZ SR250 seed drill	580	2.3	–
Crop protection, R0/R1	JD 5720	3700	59	Krukowiak ORP/2500/18/PHN	2100	5.1	3-4 treatments
Harvest	–	–	–	Claas Lexion 460	15400	221	–
Transport	JD 6220	5970	70	PRONAR PT610 10 t trailer	2500	–	–

Energy efficiency was determined by the structure of energy inputs in the analyzed production technologies. Energy inputs were highest at 22 599.40 $MJ\cdot ha^{-1}$ in production technology N2, SR2 (120 N $kg\cdot ha^{-1}$ and 550 $kernels\cdot m^{-2}$) (Table 5), where fertilizers (52%) and diesel fuel (16.05%) were the most energy-intensive operations. In the production technology with the lowest energy inputs, seed purchases had the highest share of total energy inputs at nearly 31%. An increase in fertilization rate led to an increase in total energy inputs per hectare and a decrease in the percentage of energy inputs associated with seeds and fuel, which accounted for a substantial portion of energy inputs. In agriculture, production costs can be decreased and labor efficiency can be maximized with the use of the integrated method. In the present experiment, labor accounted for a small portion of total energy inputs at only 1.52–2.84% (Table 5).

In a study by Ghorbani *et al.* (2011), chemical fertilizers (37%) and diesel fuel (24.14%) were the largest energy inputs. The energy inputs associated with the production of winter wheat were determined at 35737.13 $MJ\cdot ha^{-1}$ by Yildiz (2016). In turn, field irrigation increased energy inputs from 9.74 $GJ\cdot ha^{-1}$ to 13.04 $GJ\cdot ha^{-1}$ (Kardoni *et. al*., 2015). In a study by Shahan *et al.* (2008), total energy inputs in wheat production reached 47.08 $GJ\cdot ha^{-1}$. Indirect inputs (seeds, fertilizers, manure, chemicals, machinery) accounted for 73.27%, and direct inputs (labor, diesel fuel) accounted for 26.73% of total energy inputs. Net energy and energy productivity value were estimated at 45.71 $GJ\cdot ha^{-1}$ and 0.096 $MJ\cdot ha^{-1}$, respectively (Shahan *et al*., 2008).

Table 5. Energy inputs in durum wheat production

Item	Production technology								
	N0			N1			N2		
	SR0	SR1	SR2	SR0	SR1	SR2	SR0	SR1	SR2
Seeds, MJ·ha^{-1}	3454.20	4379.40	5382.00	3454.20	4379.40	5382.00	3454.20	4379.40	5382.00
%	30.71	35.97	40.85	19.74	23.77	27.70	16.71	20.28	23.81
Chemical fertilizers CaNPK, MJ·ha^{-1}	2537.90	2537.90	2537.90	8697.90	8697.90	8697.90	11777.90	11777.90	11777.90
%	22.56	20.85	19.26	49.70	47.21	44.77	56.98	54.54	52.12
Plant protection, MJ·ha^{-1}	580.00	580.00	580.00	580.00	580.00	580.00	580.00	580.00	580.00
%	5.16	4.76	4.40	3.31	3.15	2.99	2.81	2.69	2.57
Labor, MJ·ha^{-1}	320.00	320.00	320.00	332.00	332.00	332.00	344.00	344.00	344.00
%	2.84	2.63	2.43	1.90	1.80	1.71	1.66	1.59	1.52
Machinery (tractor), MJ·ha^{-1}	831.08	831.08	831.08	860.09	860.09	860.09	889.10	889.10	889.10
%	7.39	6.83	6.31	4.91	4.67	4.43	4.30	4.12	3.93
Diesel fuel, MJ·ha^{-1}	3525.60	3525.60	3525.60	3576.00	3576.00	3576.00	3626.40	3626.40	3626.40
%	31.34	28.96	26.76	20.43	19.41	18.41	17.54	16.79	16.05
Total, MJ·ha^{-1}	11248.7	12173.9	13176.5	17500.1	18425.3	19427.9	20671.6	21596.8	22599.4

Energy efficiency indicators in the evaluated production technologies are presented in Table 6. In the analyzed production technologies, energy inputs per 1 t of durum wheat grain were lowest in the N0, SR0 treatment (3.21 GJ·Mg^{-1}) and highest in the N2, SR1 treatment (4.14 GJ·Mg^{-1}). The highest energy value of yield at 105.48 GJ·ha^{-1} was noted in production technology N2, SR2 (120 N kg·ha^{-1} and 550 kernels·m^{-2}). The energy value of straw increased by nearly 1 GJ·ha^{-1} with a rise in 350-450 seeding rate. The energy gain accumulated in grain was highest in the production technology with a fertilization rate of 120 N kg·ha^{-1} and a seeding rate of 350 kernels·m^{-2}. However, energy efficiency increased by 6.6% from 128.32 to 137.03 GJ·ha^{-1} when the seeding rate was increased from 350 to 550 kernels·m^{-2} and when the energy gain of straw was included in the calculations. The energy efficiency ratio was highest in the production technology without N fertilization and a seeding rate of 350 kernels·m^{-2} (N0, SR0). This parameter was highest when both the energy value of grain (5.62) and the energy value of grain and straw (8.40) were taken into account, which can be attributed to the relatively low energy inputs and high durum wheat yields. Similar results were reported by Ansari *et al.* (2018) where the energy efficiency ratio of wheat ranged from 6.54 to 7.48. In a study by Houshyar *et al.* (2010), total energy inputs in winter wheat production ranged from 38589.677 to 38817.823 MJ·ha^{-1} and were determined by the region of cultivation. In their work diesel fuel accounted for 44.61%, chemical fertilizers (mainly N fertilizers) – for 23.54%, seed purchases – for 10.11%, machinery – for 9.86%, crop protection agents – for 0.92%, and labor – for 0.38% of total energy inputs. Energy output was 84427.33 MJ·ha^{-1}. In the work of Shahan *et al.* (2008), the ratio of energy outputs to energy inputs was determined at only 1.97, which indicates that high inputs in wheat production are not always accompanied by an increase in outputs. The low energy efficiency ratio was attributed to higher energy inputs associated with mineral fertilization and manure application.

Table 6. Energy efficiency indicators in durum wheat production

Item		Production technology								
		N0			N1			N2		
		SR0	SR1	SR2	SR0	SR1	SR2	SR0	SR1	SR2
Total (accumulated) energy inputs, GJ·ha^{-1}		11.25	12.17	13.18	17.50	18.43	19.43	20.67	21.60	22.60
Yield grain, Mg·ha^{-1}		3.51	3.70	3.54	4.69	4.89	5.13	5.78	5.22	5.86
Energy inputs of yield, GJ·ha^{-1}		3.21	3.29	3.72	3.73	3.77	3.79	3.58	4.14	3.86
Energy value of yield, GJ·ha^{-1}	A	63.18	66.60	63.72	84.42	88.02	92.34	104.04	93.96	105.48
	B	94.48	99.80	96.77	124.12	128.12	133.99	148.99	135.76	159.63
Energy gain, GJ·ha^{-1}	A	51.93	54.43	50.54	66.92	69.59	72.91	83.37	72.36	82.88
	B	83.23	87.63	83.59	106.62	109.69	114.56	128.32	114.16	137.03
Energy efficiency ratio	A	5.62	5.47	4.83	4.82	4.78	4.75	5.03	4.35	4.67
	B	8.40	8.20	7.34	7.09	6.95	6.90	7.21	6.29	7.06

A – grain, B – grain + straw

The differences in energy efficiency indicators in the evaluated production technologies relative to technology N0 are presented in Table 7. The highest increase in energy inputs (83.73%) was noted in technology N2, SR0, whereas the lowest increase was observed in technology N1, SR2. Nitrogen fertilization was responsible for the greatest changes in energy value in technology N2, SR2 (64.96%). Fertilization also increased energy gain, and the highest increase in this parameter (nearly 64%) was noted in technology N2, SR2. The energy gain accumulated in grain was determined at 63.99%, which indicates that technology N2, SR2 was characterized by the highest energy efficiency relative to technology N0, SR2. The least desirable changes in the values of energy efficiency indicators were observed in production technology N1, SR2.

Table 7. Changes in energy efficiency indicators in durum wheat production relative to technology N0 (%)

Item	Production technology					
	N1			N2		
	SR0	SR1	SR2	SR0	SR1	SR2
	N0,SR0=100%	N0,SR1=100%	N0,SR2=100%	N0,SR0=100%	N0,SR1=100%	N0,SR2=100%
Energy value of grain	33.62	32.16	44.92	64.67	41.08	65.54
Energy value of straw	26.84	20.78	26.02	43.61	25.90	63.84
Energy value of grain + straw	31.37	28.38	38.46	57.69	36.03	64.96
Total energy inputs	55.56	51.44	47.42	83.73	77.49	71.47
Energy gain – grain	28.87	27.85	44.26	60.54	32.94	63.99
Energy gain – grain + straw	28.10	25.17	37.05	54.18	30.28	63.93

Changes in energy value and the energy efficiency ratio in the evaluated production technologies are presented in Fig. 1. The energy value of grain and straw was highest at 160 GJ·ha^{-1} in technology N2, SR2, and it was more than 65 GJ·ha^{-1} higher in comparison with the lowest value of this parameter in technology N0, SR0. Despite the highest energy inputs (22.6 GJ·ha^{-1}), technology N2, SR2 was characterized by the highest energy efficiency ratio of 6.67, calculated as the ratio of the increase in the energy value of grain and straw to the increase in energy inputs.

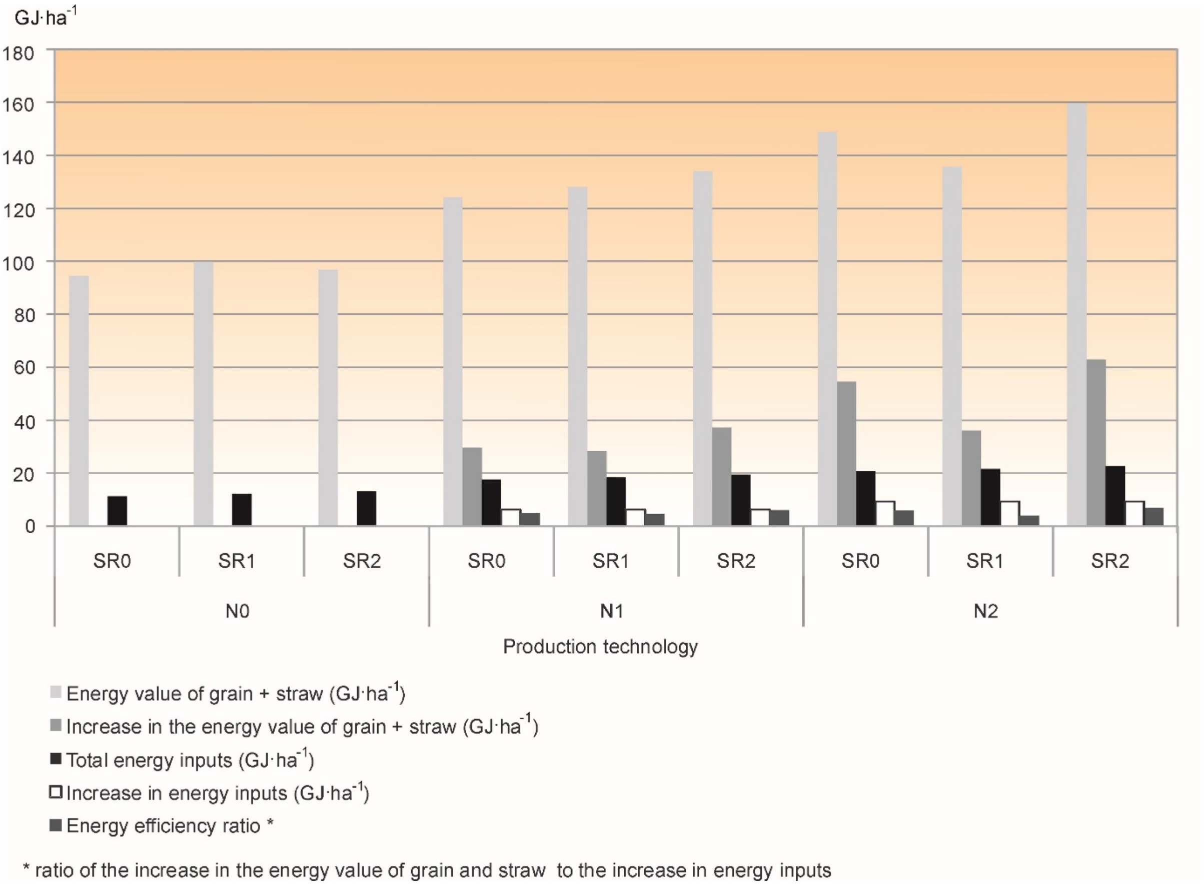

Fig. 1. The energy value of durum wheat in the evaluated production technologies relative to technology N0 (GJ·ha^{-1})

CONCLUSIONS

The results of this study indicate that agronomic factors (nitrogen fertilization, seeding rate, growth regulator), seed preparation and seeding regime affected a major portion of total operational and non-operational energy inputs. The production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} generated the highest profits. The value of *T. durum* production ranged from 1446.59 to 2227.86 USD·ha^{-1}, and the energy value of yield ranged from 63.18 to 105.48 GJ·ha^{-1}. The cost-benefit ratio was highest in the production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 350 kernels·m^{-2}. The production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} was characterized by the highest energy inputs (22.60 GJ·ha^{-1}). Energy gain was highest in the production technology with a fertilization rate of 120 kg·ha^{-1} and a seeding rate of 550 kernels·m^{-2} at 82.88 (grain) and 137.03 (grain + straw) GJ·ha^{-1}.

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WPŁYW GĘSTOŚCI SIEWU, MINERALNEGO NAWOŻENIA I REGULATORA WZROSTU NA EKONOMICZNĄ I ENERGETYCZNĄ WYDAJNOŚĆ PSZENICY TWARDEJ

Streszczenie

Pszenica twarda jest zbożem konsumpcyjnym, które swoimi właściwościami wkomponowuje się w obecne trendy żywnościowe. Celem badań była analiza efektywności ekonomicznej i energetycznej produkcji *Triticum durum* L. Czynnikami badań roślin pszenicy durum były: poziom nawożenia mineralnego 0, 80 i 120 kg N·ha^{-1}, gęstość siewu (350, 450 i 550 ziarniaków·m^{-2}) i regulator wzrostu. Całkowite zużycie energii dla systemów produkcji formy jarej pszenicy durum obliczono na podstawie nawożenia azotem, ochrony roślin i maszyn, transportu oraz wszystkich wykonanych zabiegów. Najwyższą wartość ziarna – 2227.86 USD·ha^{-1} – uzyskano w technologii o poziomie nawożenia 120 kg·ha^{-1} N i obsadzie 550 ziarniaków·m^{-2}. Poziom poniesionych w tym wariancie kosztów był również najwyższy – 1017.17 USD·ha^{-1}. Najkorzystniejsza relacja uzyskanych wyników ekonomicznych i poniesionych kosztów (2,32) wystąpiła w przypadku nawożenia azotem na poziomie 120 kg·ha^{-1} oraz obsadzie 350 ziarniaków·m^{-2}. Najkorzystniejszy wskaźnik relacji energii uzyskanej do włożonej w produkcję uzyskano w technologii bez nawożenia azotem i w przypadku siewu o gęstości 350 ziarniaków·m^{2} (N0, SD0). Wskaźnik ten był najwyższy zarówno w przypadku uwzględnienia wartości energetycznej ziarna (5,62), jak ziarna i słomy (8,40).

Słowa kluczowe: ekonomiczna i energetyczna wydajność, *Triticum durum*