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Productivity, Energy and Economic Balance in the Production of Different Cultivars of Winter Oilseed Rape. A Case Study in North-Eastern Poland

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Abstract: In this study, the agricultural inputs, energy requirements and costs associated with the production of semi-dwarf (PR45 D03 and Avenir) and long-stem (Visby) cultivars of winter oilseed rape were optimized in an experiment with $3^{5\text{-}1}$ fractional factorial design. A field experiment was carried out in the Agricultural Experiment Station in Bałcyny (north-eastern Poland) in 2008–2011. The study investigated the responses of two morphotypes of hybrid cultivars of winter oilseed rape to key yield-forming factors (seeding date, seeding rate, nitrogen fertilization) and yield protection factors (fungal disease control). Agronomic inputs were tested at three levels. Our findings indicate that production technologies (characterized by a different intensity of agricultural inputs) should target the specific requirements of winter oilseed rape cultivars. Semi-dwarf cultivars of winter oilseed rape (PR45 D03 and Avenir) were characterized by higher yield potential at different input levels than the long-stem cultivar (Visby). Semi-dwarf cultivars required higher levels of agricultural inputs than the long-stem cultivar. Semi-dwarf cultivars grown in high-input technologies were characterized by the highest energy efficiency ratio. In contrast, the long-stem cultivar was characterized by the optimal energy input-energy output ratio in the low-input technology. Regardless of cultivar, high-input production technologies were more profitable because the resulting increase in seed yield significantly outweighed the rise in production costs.

Keywords: cultivar; agronomic inputs; seed yield; energy efficiency ratio; profitability

1. Introduction

Growing food and energy requirements around the world increase the demand for plant biomass. Global food security, in particular in quantitative terms (physical availability of food), is determined mainly by the production of cereals (wheat, rice and corn) and protein and oilseed crops (soybeans, rapeseed). In 1998–2017, grain production increased by 2% y^{-1}, and the corresponding rise in the production of oilseed crops was three-fold higher (5–6% y^{-1}) [1]. The global increase in cereal and rapeseed production was induced mainly by higher yields (2% and 3% y^{-1}, respectively) [1]. In contrast, the increase in soybean production resulted mainly from an increase in the area under soybean cultivation (4% y^{-1}) [1].

In the last three fiscal years (2015–2017), the European Union countries (30% of the global output), Canada (28%), China (19%) and India (10%) were the world's leading producers of rapeseed [1]. On the EU market, 46% of rapeseed is produced by Germany and France, of which the combined annual output is estimated at 9.7 Tg Mg^{-1} [1]. In 2008–2017, Germany and Great Britain were the only leading producers of winter oilseed rape in the EU that did not report a clear increase in rapeseed yield or area under rapeseed cultivation [1]. In the remaining EU countries, the area under rapeseed increased by 1500–4000 ha y^{-1} (France and Czechia) to 12,000 ha y^{-1} (Poland) [1]. In 2008–2017, the leading rapeseed producers in the EU increased their output by 6200 Mg y^{-1} (France) to 32,500–65,400 Mg y^{-1} (Czechia and Poland) [1].

According to Święcicki et al. [2], the increase in cultivated area is responsible for only a 20% rise in global crop biomass production, whereas the intensification of the production process, mainly through breeding progress, accounts for the remaining 80% increase in output. The morphological traits responsible for the agronomic performance of oilseed rape can be considerably modified by breeders. Intensive breeding efforts conducted in the 1960s have contributed to the economic significance of this species (low levels of erucic acid and glucosinolates) [3].

The introduction of rapeseed varieties with improved chemical composition induced only a minor increase in yield [4]. In the early 1990s, the yield of oilseed rape was considerably increased by breeding and improving the performance of hybrid cultivars. The popularity of single-cross hybrids continues to increase in all regions of rapeseed cultivation, including in Europe [5]. Rapeseed yield can also be increased by inducing phenotypic changes which: (i) speed up leaf development before inflorescence emergence and delay flowering to promote maximum light absorption during reproductive growth [6–11], and (ii) delay ripening to optimize light absorption during the growing season [12,13].

New varieties of oilseed rape that differ considerably in qualitative (fatty acid profile, fiber content), quantitative (yield) and phenotypic (growth rate) traits have been introduced to the market in the last two decades. Genotypic and phenotypic modifications of oilseed rape often induce changes in production technology. Production success is largely determined by the observance of a strict technological regime, and some morphotypes require a customized production process. If technological requirements are not adequately met, the increase in yield potential induced by breeding may not be noticeable. The agronomic requirements of rapeseed cultivars are often analyzed based solely on their nitrogen demand [14] or resistance to pathogens [15]. The requirements of new rapeseed cultivars are usually evaluated in field experiments with one, two and three experimental factors, often under different soil and weather conditions. In practice, the production process is determined by multiple factors. Standard field experiments generally have a small number of factors (1–3), and they do not support the development of comprehensive production technologies characterized by the desired productivity, energy efficiency and profitability. In the conventional approach, multiple production factors are analyzed in experiments with an s^k factorial design [16,17]. Fractional factorial designs have been introduced to experimental practice by Finney [18–20] and Kempthorne [21], and their popularity increased steadily, particularly in industrial experiments [22–27].

In agricultural practice, the applied technologies constitute a logical series of operations and treatments, which contribute to the achievement of the anticipated yields and profits [28]. The effectiveness of the applied technology is the key to financial success in crop production [29,30]. Inadequate agricultural practices generate high costs and compromise the quality of the final product, which undermines breeding progress, decreases productivity and, consequently, lowers the producer's competitive advantage. In the current stage of agricultural development, technological and financial problems carry equal weight [31,32].

Energy generation from agricultural biomass plays an increasingly important role in the face of the current challenges to global energy security [33–35]. Agricultural biomass is the key substrate in the production of first-generation biofuels [36]. Bioethanol produced from cereal grain and sugar cane is the most common type of first-generation biofuel [37–39]. The EU is the world's leading producer of biodiesel (approx. 60% of the global output) from rapeseed oil [40,41]. The production of oilseed rape for non-food uses leads to changes in agronomic goals and indicators for evaluating crop performance. The optimal production technology of oilseed rape for non-food uses should be selected primarily based on an energy efficiency analysis [36].

The objective of this study was to develop an effective technology for the production of heterozygous and morphologically distinct cultivars of winter oilseed rape (long-stem and semi-dwarf) in a field experiment with a $3^{5\text{-}1}$ fractional factorial design. The most productive technologies were selected and evaluated for profitability and energy efficiency.

2. Materials and Methods

2.1. Experimental Design and Crop Management

The experiment was carried out in 2008–2011 in the Agricultural Experiment Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, elevation—137 m above sea level) in north-eastern Poland. The station is operated by the University of Warmia and Mazury in Olsztyn. The experiment had a $3^{5\text{-}1}$ fractional factorial design with 2 replications, where 5 factors (A, B, C, D, E) were tested simultaneously at 3 levels (0, 1, and 2) (Table 1).

Table 1. Agronomic factors and levels in the experiment with a $3^{5\text{-}1}$ fractional factorial design.

Agronomic Factor	Symbol	Level		
		0	1	2
Hybrid cultivar	A	PR45 D03 (semi-dwarf)	Avenir (semi-dwarf)	Visby (long-stem)
Seeding date	B	early (−10 days)	optimal (22 August)	delayed (+10 days)
Seeding rate (pure live seeds m^{-2})	C	40	60	80
Spring N rate (kg ha^{-1})	D	120 (32 BBCH†)	120 + 60 (32 + 50 BBCH)	120 + 60 + 60 (32 + 50 + 57 BBCH)
Spring fungicide treatment	E	None	100 g ha^{-1} dimoxystrobin and 100 g ha^{-1} boscalid (65 BBCH)	150 g ha^{-1} flusilazole and 300 g ha^{-1} carbendazim (32 BBCH) 250 g ha^{-1} azoxystrobin (59 BBCH)

† BBCH identification key for growth stages [42].

Plot size was 15 m^2 (1.5 m × 10 m). Each year, the experiment was established on Haplic Luvisol originating from boulder clay [43]. Composite soil samples composed of 8 to 10 cores each were collected annually (before fertilization and planting) from each plot to a depth of 20 cm to determine the chemical properties of soil. In the experimental sites, soil pH ranged from 5.7 to 6.2, and soil nutrient levels were determined at: 1.5% to 1.8% for organic carbon (C_{org}), 45 to 82 mg P kg^{-1}, 125 to 168 mg K kg^{-1}, 80 to 120 mg Mg kg^{-1} and 23 to 28 mg SO_4^{2-} kg^{-1}. Soil C_{org} was determined using the modified Kurmies' method. Soil pH was measured using a digital pH meter with temperature compensation (20 °C) in deionized water with 1 mol potassium chloride at a 5:1 ratio. Plant-available P and K were extracted by the Egner-Riehm method [44] (using 3.5 mol ammonium lactate acetic acid buffered to pH = 3.75 as extracting solution). Phosphorus was determined by the vanadium molybdate yellow colorimetric method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan) and K was determined by atomic emission spectrometry (AES) (Flame Photometers, BWB Technologies Ltd., Newbury, UK). Magnesium was extracted with 0.01 mol calcium chloride and determined by atomic absorption spectrophotometry (AAS) (AAS1N, Carl Zeiss, Jena, Germany). Sulfate sulfur was determined by extracting a soil sample with acetate buffer according to the method proposed by Bardsley and Lancaster [45].

Agricultural inputs other than the experimental variables were applied in accordance with good agricultural practice. In each year of the study, the preceding crop was winter wheat (*Triticum vulgare* L.). The applied tillage treatments were skimming, pre-sowing plowing and soil loosening before sowing. Mineral fertilizers were applied before seeding at 30 kg ha^{-1} N (34% ammonium nitrate), 35 kg ha^{-1} P (40% enriched superphosphate) and 100 kg ha^{-1} K (60% potash salt). Immediately after seeding, metazachlor (2-[2,6-dimethyl-*N*-(pyrazol-1-ylmethyl)anilino]-2-oxoethanesulfonic acid) was applied at 999 g ha^{-1} and quinmerac (7-chloro-3-methylquinoline-8-carboxylic acid) was applied at 249 g ha^{-1}. Four insecticides, including a neonicotinoid insecticide (acetamiprid—N-[(6-chloropyridin-3-yl)methyl]-N′-cyano-N-methylethanimidamide) and three pyrethroid insecticides (tau-fluvalinate—[cyano-(3-phenoxyphenyl)methyl] (2R)-2-[2-chloro-4-(trifluoromethyl)anilino]-3-methylbutanoate, deltamethrin—[(S)-cyano-(3-phenoxyphenyl)methyl] (1R,3R)-3-(2,2-dibromoethenyl)-2,2-dimethyl-cyclopropane-1-carboxylate and alpha-cypermethrin—[cyano-(3-phenoxyphenyl)methyl] 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate), were applied during the spring growing season. In each year of the experiment, winter oilseed rape was harvested in the second half of July.

2.2. Energy Efficiency

Only the production process (technology) of seeds of different winter oilseed rape cultivars in the field was subjected to energy analysis (*loco* field). The analysis did not include the energy requirements of further seed processing operations associated with seed conversion to biofuels and/or bioproducts.

The energy requirements associated with the production of winter oilseed rape were determined based on direct measurements of diesel oil consumption, labor and the field capacity of farming machines and equipment in fields with an area of 50–100 ha, situated at a distance of 800–1200 m from the center of the farm (Table 2). Energy inputs were divided into categories based on farming operations (tillage, sowing, fertilization, etc.). The energy inputs associated with the operation of tractors and machines were calculated by multiplying the specific consumption of a machine unit by the energy equivalent of 125 MJ kg^{-1} of tractor mass and 110 MJ kg^{-1} machine mass [46]. Labor was estimated based on the energy equivalent of 80 MJ man-hours^{-1} [46]. The energy value of 1 kg of diesel oil was set at 48 MJ [47]. To estimate fuel consumption, each farming operation was started with a full fuel tank that was refilled at the end of the operation. The energy inputs associated with production materials were determined based on the energy indicators proposed by Wójcicki [47], i.e., seeds for sowing—12 MJ kg^{-1}, nitrogen fertilizers—77 MJ kg^{-1} N, phosphorus fertilizers—15 MJ kg^{-1} P_2O_5, potassium fertilizers—10 MJ kg^{-1} K_2O, and crop protection chemicals—300 MJ kg^{-1} of active ingredient, as well as the indicator proposed by Fore et al. [48], i.e., sulfur fertilizers—8.9 MJ kg^{-1} S.

The unit energy value (higher heating value, HHV) of the seeds of winter oilseed rape was determined by adiabatic combustion in the IKA calorimeter C2000 (IKA-Werke GmbH, Staufen, Germany) with the use of a dynamic method. Moisture content and HHV were used to determine the lower heating value (LHV) of seeds (Equation (1)). The energy value of seeds (energy output) was calculated as the fresh matter yield (FMY) and LHV of harvested seeds (Equation (2)).

$$\mathrm{LHV} = \frac{\mathrm{HHV} \times (100 - \mathrm{W})}{100} - \mathrm{W} \times 0.0244 \tag{1}$$

where:

LHV—lower heating value of harvested fresh seeds (MJ kg^{-1});
HHV—higher heating value of dry seeds (MJ kg^{-1} DM);
W—seeds moisture content (%);
0.0244—correction factor for water vaporization enthalpy (MJ kg^{-1} per 1% moisture content);

$$\text{Energy output (GJ ha}^{-1}) = \text{LHV (GJ Mg}^{-1}) \times \text{FMY (Mg ha}^{-1}) \tag{2}$$

The energy efficiency of winter oilseed rape production was determined based on energy gain (Equation (3)) and the energy efficiency ratio (Equation (4)).

$$\text{Energy gain (GJ ha}^{-1}) = \text{Energy output (GJ ha}^{-1}) \text{ - Energy input (GJ ha}^{-1}) \tag{3}$$

$$\text{Energy efficiency ratio} = \frac{\text{Energy output (GJ ha}^{-1})}{\text{Energy input (GJ ha}^{-1})} \tag{4}$$

Table 2. Technical parameters of agricultural machines, machine performance and fuel consumption in the production of winter oilseed rape (across years, 2008–2011).

Farming Operations	Engine Power of Self-Propelled Machine (kW) [a]	Parameters of Accompanying Machine	Service Life				Weight (kg)		Performance of Self-Propelled Machine and Accompanying Machine (ha h^{-1}) [f]	Fuel Consumption (l h^{-1}) [f]
			Self-Propelled Machine		Accompanying Machine		Self-Propelled Machine	Accompanying Machine		
			Hours (h)	Years (y)	Hours (h)	Years (y)				
Tillage-cultivation unit (5–8 cm)	246	4 [b]	12,000	12	2000	7	13,003	2150	4.4	38.2
Pre-sowing plowing (18–20 cm)	169	7 [c]	12,000	12	2000	7	9420	3370	1.6	47.6
Seeding	246	6 [b]	12,000	12	1440	10	13,003	8900	3.3	24.7
Mineral fertilization	114	30 [b]	9000	10	1200	10	5635	300	8.8	8.2
Chemical crop protection	53	20 [b]	9000	10	1050	10	3550	1350	12.1	8.1
Seed harvest	220	6 [b]	3000	10	-	-	13,300	-	2.7–3.3 [g]	31.8
Seed transport	59	10 [d]	9000	10	6000	10	6100	3740	-	8.5
Loading	55	2500 [e]	4800	8	-		4922	-	-	8.0

[a] tractor/harvester/loader; [b] working width (m); [c] number of furrows; [d] carrying capacity (Mg); [e] load capacity (kg); [f] average of 3 years; [g] differences resulting from different yields.

2.3. Profitability

Production costs were calculated by aggregating direct and indirect costs. The reference period was the growing season. The direct costs were labor, seeds, fertilizers and crop protection chemicals, and the indirect costs were the costs associated with the operation of tractors and farming machines and fuel costs. Direct costs were estimated based on actual material consumption and prices in the fourth quarter of 2019. The costs associated with the operation of tractors and agricultural machines were estimated based on the current prices (fourth quarter of 2019), standard number of operating hours in the analyzed period, period of use, and machine performance (measured by the authors, Table 2). Labor costs were determined at €4.50 h^{-1} (Agricultural Experiment Station in Bałcyny). The value of winter oilseed rape production was calculated (Equation (5)) based on the experimental yields and average rapeseed prices in Poland (€385 Mg^{-1}) in the fourth quarter of 2019 (Agricultural Experiment Station in Bałcyny). The economic efficiency of winter oilseed rape was determined based on the following indicators: revenue per hectare (Equation (6)) and the profitability index (Equation (7)).

$$\text{Production value } (\text{€ ha}^{-1}) = \text{seed yield } (\text{Mg ha}^{-1}) \times \text{price } (\text{€ Mg}^{-1}) \tag{5}$$

$$\text{Revenue } (\text{€ ha}^{-1}) = \text{production value } (\text{€ ha}^{-1}) - \text{total production cost } (\text{€ ha}^{-1}) \tag{6}$$

$$\text{Profitability index } (\%) = \frac{\text{Production value } (\text{€ ha}^{-1})}{\text{Total production cost } (\text{€ ha}^{-1})} \tag{7}$$

The values in Polish zloty (PLN) were converted to Euro (€) based on the average exchange rate quoted by the National Bank of Poland in the fourth quarter of 2019 (€1 = PLN 4.2460) [49].

2.4. Statistical Analysis

The seed yields of the studied cultivars of winter oilseed rape grown in different production technologies were determined in a quartile analysis to select the highest and lowest yielding technologies. Production technologies characterized by seed yields below the lower quartile (<Q1) and above the upper quartile (>Q3) were identified. The lower and upper quartiles represent the 25th and 75th percentiles of the distribution, respectively. The 25th percentile is a value below which 25% of the observations (values of a variable) may be found. Similarly, the 75th percentile is a value below which 75% of the observations may be found. The quartiles were arranged in order based on minimum yield values. As a result, 25% of the lowest-input technologies (<Q1) and 25% of the highest-input technologies (>Q3) were selected from all experimental treatments. These technologies were approved for further analyses (profitability and energy efficiency) based on the yields observed in each year of the study. The above approach was applied separately to every cultivar, which indicates that the number of the approved variants could differ within groups of cultivars and treatment effects. Data were processed statistically in the Statistica 13.1 program [50].

3. Results

3.1. Productivity

In the group of production technologies above the upper quartile (>Q3), the seed yield of the semi-dwarf cultivar of winter oilseed rape (PR45 D03) ranged from 4.21 (2010/2011) to 5.94 Mg ha^{-1} (2009/2010). In low-input technologies, the seed yield of cv. PR45 D03 (<Q1) was determined in the range of 2.14 (2010/2011) to 4.25 Mg ha^{-1} (2009/2010). The difference in seed yield between the highest-input (A0B1C2D2E1) and the lowest-input (A0B2C0D0E1) production technologies was 1.65 Mg ha^{-1}. The semi-dwarf cv. PR45 D03 produced the highest yields (4.54–5.92 Mg ha^{-1}) when sown on the optimal seeding date at 80 seeds m^{-2}, supplied with 240 kg N ha^{-1} in spring and subjected to one fungicide treatment in stage BBCH 65 (A0B1C2D2E1). In the second high-input technology (A0B1C1D2E2; optimal seeding date, 60 seeds m^{-2}, 240 kg N ha^{-1}, two fungicide treatments), the seed

yield of cv. PR45 D03 was lower by 0.64 Mg ha^{-1} on average. In all low-input production technologies, this semi-dwarf cultivar of winter oilseed rape was sown with a delay (B2) in each year of the study. When sowing was delayed (B2), cv. PR45 D03 was characterized by the lowest yields (3.28–3.39 Mg ha^{-1}) when sown at 40 seeds m^{-2} (C0), supplied with low and moderate rates of nitrogen fertilizer (D0, D1), and supplied with no fungicide treatment (E0) or one fungicide treatment (E1). The seed yield of cv. PR45 D03 was equally low (3.45 Mg ha^{-1}) in treatments with a delayed seeding date, seeding rate of 60 seeds m^{-2}, the lowest rate of nitrogen fertilizer and no disease control (A0B2C1D0E0) (Table 3).

Table 3. Seed yield of the semi-dwarf cultivar PR45 D03 of winter oilseed rape in production technologies comprising agronomic factors with the strongest and weakest yield-forming effects.

Yield Group	Production Technology	Agronomic Factor/Level					2008/2009		2009/2010		2010/2011		Across Years (2008–2011)	
		A	B	C	D	E	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
>Q3	I	0	1	2	2	1	5.05	0.09	5.94	0.17	4.54	0.73	5.18	0.71
	II	0	1	1	2	2	4.77	0.15	5.62	0.30	4.21	0.75	4.87	0.71
<Q1	III	0	2	1	0	0	3.46	0.17	4.25	0.26	2.63	0.52	3.45	0.81
	IV	0	2	0	1	0	3.86	0.35	4.16	0.43	2.14	0.10	3.39	1.09
	V	0	2	0	0	1	3.61	0.68	3.82	0.25	2.40	0.47	3.28	0.76

$\bar{x}$—mean; s—standard deviation. A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The seed yield of Avenir, a semi-dwarf cultivar of winter oilseed rape, above the upper quartile (>Q3) ranged from 4.50 to 6.53 Mg ha^{-1} (Table 4). An analysis of mean values noted during the entire experiment (2008–2011) revealed that the difference in the seed yield of cv. Avenir grouped in extreme quartiles reached 1.91 Mg ha^{-1} (Table 4). The semi-dwarf cultivar Avenir was characterized by the highest seed yield (4.76–6.53 Mg ha^{-1}) when sown in the last 10 days of August (B1) at 80 seeds m^{-2} (C2), supplied with the highest rate of nitrogen fertilizer (D2, 240 kg ha^{-1}) and subjected to one fungicide treatment (E1). When the seeding rate was decreased to 60 seeds m^{-2} (C1) without any changes in the intensity of the remaining agricultural inputs (production technology II), only a minor decrease (by 0.18 Mg ha^{-1}) in the seed yield of cv. Avenir was noted relative to the highest-input technology (I). Production technology III differed from technology I only in seeding date (10 days earlier) (Table 4). All low-input technologies were characterized by a low seeding rate (B2, 40 seeds m^{-2}) and delayed sowing (C0, early September) (Table 4).

The seed yields of the long-stem cultivar of winter oilseed rape (Visby) in the group above the upper quartile (>Q3) ranged from 4.11 to 6.20 Mg ha^{-1} (Table 5). The low yield group (<Q1) was characterized by lower average seed yield in the range of 1.33 (2010/2011) to 1.79 Mg ha^{-1} (2008/2009). The long-stem cultivar of winter oilseed rape produced the highest yields when sown on the optimal date (B1) at a higher seeding rate than recommended for heterozygous cultivars (C2, 80 seeds m^{-2}), supplied with a high rate of nitrogen fertilizer in spring (D2, 240 kg ha^{-1}) and subjected to two fungicide treatments (E2) (Table 5).

In each year of the study, low-input production technologies were characterized by a low seeding rate (C0, 40 m^{-2}), delayed seeding (B2), a low rate of nitrogen fertilizer (D0, 120 kg ha^{-1}) and two fungicide treatments (E2). In the long-stem cultivar, the difference in seed yield between the highest-input technology (A2B1C2D2E2) and the lowest-input technology (A2B2C0D0E2) was determined at 1.49 Mg ha^{-1} (Table 5). The difference between the extreme yield groups was significantly smaller in the long-stem cultivar than in the semi-dwarf cultivars of winter oilseed rape (Tables 3–5). These results indicate that the choice of a sub-optimal production technology can have far more adverse consequences in the semi-dwarf than in long-stem cultivars of winter oilseed rape.

Table 4. Seed yield of the semi-dwarf cultivar Avenir of winter oilseed rape in production technologies comprising agronomic factors with the strongest and weakest yield-forming effects.

Yield Group	Production Technology	Agronomic Factor/Level					2008/2009		2009/2010		2010/2011		Across Years (2008–2011)	
		A	B	C	D	E	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
>Q3	I	1	0	2	2	1	5.60	0.16	6.20	0.27	4.75	0.27	5.52	0.73
	II	1	1	2	2	0	4.96	0.13	6.53	0.17	4.76	0.62	5.42	0.97
	III	1	1	1	2	1	5.08	0.17	6.42	0.33	4.50	0.80	5.34	0.99
<Q1	IV	1	2	0	1	2	3.94	0.16	5.19	0.91	2.07	0.19	3.73	1.57
	V	1	2	0	0	0	3.25	0.26	5.01	0.46	1.60	0.47	3.29	1.71

$\bar{x}$—mean; s—standard deviation. A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

Table 5. Seed yield of the long-stem cultivar Visby of winter oilseed rape in production technologies comprising agronomic factors with the strongest and weakest yield-forming effects.

Yield Group	Production Technology	Agronomic Factor/Level					2008/2009		2009/2010		2010/2011		Across Years (2008–2011)	
		A	B	C	D	E	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
>Q3	I	2	1	2	2	2	5.40	0.35	6.20	0.00	4.11	0.19	5.24	1.05
<Q1	II	2	2	0	0	2	3.61	0.36	4.85	0.50	2.78	0.61	3.74	1.04

$\bar{x}$—mean; s—standard deviation. A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

3.2. Energy Efficiency

The cumulative energy inputs in high-input production technologies (I–II) of the semi-dwarf cultivar PR45 D03 were estimated at 28.4 GJ ha^{-1}. In low-input production technologies (III–V), the demand for energy was 27% lower on average. Mineral fertilizers accounted for 74%–81% of total energy inputs in all production technologies (I–V) (Table 6).

The seeds of the semi-dwarf cultivar of winter oilseed rape PR45 D03 grown in high-input production technologies (I–II) accumulated around 123.7 to 131.6 GJ ha^{-1} of energy. In low-input production technologies (III–V), the energy output of the semi-dwarf cultivar PR45 D03 was 42.0 GJ ha^{-1} lower on average. Energy gain per hectare was around 53% higher in high-input (I–II) than in low-input (III–V) production technologies. The most productive combination of agronomic factors (I) was also characterized by the highest energy efficiency. The energy efficiency of the semi-dwarf cultivar PR45 D03 in production technology II was comparable to that determined in low-input technologies (III, V) where a low rate of nitrogen fertilizer was applied (120 kg ha^{-1}) (Table 7).

In high-input production technologies (I-III) of the semi-dwarf cultivar of winter oilseed rape Avenir, energy inputs were estimated at 28.3 GJ ha^{-1}. In low-input production technologies (IV-V), energy inputs were lower by 4.1 to 9.2 GJ ha^{-1}. Mineral fertilizers were also the most energy-intensive agronomic inputs in the production of the semi-dwarf cultivar Avenir, and they accounted for around 75%–82% of all energy inputs (Table 8).

Table 6. Energy inputs (MJ ha^{-1}) in the production of the semi-dwarf cultivar PR45 D03 of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			Low-Input	
	I A0B1C2D2E1	II A0B1C1D2E2	III A0B2C1D0E0	IV A0B2C0D1E0	V A0B2C0D0E1
Energy inputs (MJ ha^{-1}), including:	28,362	28,459	19,113	23,816	19,219
Tillage	2215	2215	2215	2215	2215
Seeding	5538	526	526	513	513
Mineral fertilizers	22,913	22,913	14,252	18,967	14,252
Weed control	502	502	502	502	502
Pest control	204	204	204	204	204
Disease control	118	327	0	0	118
Seed harvest and transport	1872	1772	1414	1414	1414

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

Table 7. Energy efficiency of the semi-dwarf cultivar PR45 D03 of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			Low-Input	
	I A0B1C2D2E1	II A0B1C1D2E2	III A0B2C1D0E0	IV A0B2C0D1E0	V A0B2C0D0E1
Energy output (GJ ha^{-1})	131.6	123.7	87.6	86.1	83.3
Energy gain (GJ ha^{-1})	103.2	95.2	68.5	62.3	64.1
Energy efficiency ratio	4.64	4.35	4.58	3.62	4.33

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

Table 8. Energy inputs (MJ ha^{-1}) in the production of the semi-dwarf cultivar Avenir of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
		High-Input		Low-Input	
	I A1B0C2D2E1	II A1B1C2D2E1	III A1B1C1D2E1	IV A1B2C0D1E2	V A1B2C0D0E0
Energy inputs (MJ ha^{-1}), including:	28,384	28,384	28,266	24,227	19,111
Tillage	2215	2215	2215	2215	2215
Seeding	560	560	560	524	524
Mineral fertilizers	22,913	22,913	22,913	18,967	14,252
Weed control	502	502	502	502	502
Pest control	204	204	204	204	204
Disease control	118	118	0	327	0
Seed harvest and transport	1872	1872	1872	1487	1414

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

In high-input production technologies (I-III), the seeds of the semi-dwarf cultivar Avenir accumulated around 135.4 to 140.2 GJ ha^{-1} of energy. In low-input production technologies

(IV-V), the energy output of cv. Avenir was lower by approximately 48.6 GJ ha^{-1} (35%) on average. The highest-input technology (A1B0C2D2E1) was also most energy efficient. The energy gain per hectare was highest (approx. 111.8 GJ ha^{-1}) when winter oilseed rape cv. Avenir was sown early at 80 seeds m^{-2}, supplied with the highest rate of nitrogen fertilizer (240 kg ha^{-1}) and one fungicide treatment. This combination of agronomic factors (A1B0C2D2E1) was also characterized by the highest energy efficiency ratio (4.94). The energy efficiency of the remaining production technologies was lower by 1–3% (II–III) to 11–21% (IV–V) (Table 9).

Table 9. Energy efficiency of the semi-dwarf cultivar Avenir of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			Low-Input	
	I A1B0C2D2E1	II A1B1C2D2E1	III A1B1C1D2E1	IV A1B2C0D1E2	V A1B2C0D0E0
Energy output (GJ ha^{-1})	140.2	135.4	137.7	94.7	83.6
Energy gain (GJ ha^{-1})	111.8	107.0	109.4	70.5	64.5
Energy efficiency ratio	4.94	4.77	4.87	3.91	4.37

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The energy requirements of the high-input production technology (A2B1C2D2E2) of the long-stem morphotype of winter oilseed rape cv. Visby were estimated at 28.6 GJ ha^{-1}. The energy demand of the low-input technology (A2B2C0D0E2) was lower by around 9.1 GJ ha^{-1}. The structure of energy inputs differed across the tested production technologies. In the high-input technology, mineral fertilizers accounted for around 80% of all energy inputs. In the low-input technology, the share of energy inputs associated with mineral fertilization was determined at 73% (Table 10).

Table 10. Energy inputs (MJ ha^{-1}) in the production of the long-stem cultivar Visby of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology	
	High-Input I—A2B1C2D2E2	Low-Input II—A2B2C0D0E2
Energy inputs (MJ ha^{-1}), including:	28,584	19,507
Tillage	2215	2215
Seeding	551	520
Mineral fertilizers	22,913	14,252
Weed control	502	502
Pest control	204	204
Disease control	327	327
Seed harvest and transport	1872	1487

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

In the high-input production technology, the energy output of winter oilseed rape cv. Visby was estimated at 133.1 GJ ha^{-1}, and it was approximately 40% higher than in the low-input technology. The highest energy gain per hectare (104.5 GJ) was noted when winter oilseed rape cv. Visby was cultivated in the most efficient production technology (A2B1C1D2E0, 60 seeds m^{-2}, optimal seeding date, spring nitrogen fertilizer rate of 240 kg ha^{-1}, no fungicide treatment). The highest ratio of energy inputs to energy outputs (1:4.87) was observed in the low-input technology (A2B2C0D0E2) where winter oilseed rape cv. Visby was late-sown at 40 seeds m^{-2}, supplied with 120 kg N ha^{-1} in spring and subjected to one fungicide treatment (Table 11).

Table 11. Energy efficiency of the long-stem cultivar Visby of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology	
	High-Input I—A2B1C2D2E2	Low-Input II—A2B2C0D0E2
Energy output (GJ ha^{-1})	133.1	95.0
Energy gain (GJ ha^{-1})	104.5	75.5
Energy efficiency ratio	4.66	4.87

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatment at 32 and 59 BBCH).

3.3. Profitability

The total costs associated with the production of the semi-dwarf morphotype of winter oilseed rape cv. PR45 D03 in high-input (I-II) technologies was estimated at €921–910 ha^{-1} on average (Table 12). In low-input technologies (III-IV), the associated costs were lower by around €181 ha^{-1}. Fertilization was the most expensive agronomic input in all production technologies of the semi-dwarf cultivar PR45 D03, and it accounted for 44%–50% of total costs. The costs associated with the remaining agronomic inputs were arranged in the following order: disease/pest/weed control (19%–24%), sowing (11%–15%), seed harvest and transport (11%–12%) and tillage (7%–9%) (Table 12).

Table 12. Total cost (€ ha^{-1}) associated with the production of the semi-dwarf cultivar PR45 D03 of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input		Low-Input		
	I A0B1C2D2E1	II A0B1C1D2E2	III A0B2C1D0E0	IV A0B2C0D1E0	V A0B2C0D0E1
Production costs, (€ ha^{-1}), including:	910	921	722	749	733
Tillage	66	66	66	66	66
Seeding	134	109	109	84	84
Mineral fertilizers	424	424	320	372	320
Weed control	96	96	96	96	96
Pest control	46	46	46	46	46
Disease control	36	77	0	0	36
Seed harvest and transport	108	103	85	85	85

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The average value of seeds of the semi-dwarf cultivar of winter oilseed rape PR45 D03 was estimated at €1935 ha^{-1} in high-input technologies (I-II), and it was approximately 33% lower in low-input technologies (III-V) (Table 13). The production of winter oilseed rape cv. PR45 D03 was more profitable in high-input technologies. Production costs per 1 ton of seeds were lowest (€176–189) when winter oilseed rape cv. PR45 D03 was sown at 80 seeds m^{-2} on the optimal seeding date, supplied with a high rate of nitrogen fertilizer (240 kg ha^{-1}) and subjected to one fungicide treatment (A0B1C2D2E1). This production technology was also characterized by the highest revenue (€953–1084 ha^{-1}) and the highest profitability (210%) (Table 13).

Table 13. Production profitability of the semi-dwarf cultivar PR45 D03 of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			Low-Input	
	I	II	III	IV	V
	A0B1C2D2E1	A0B1C1D2E2	A0B2C1D0E0	A0B2C0D1E0	A0B2C0D0E1
Production value (€ ha^{-1})	1994	1875	1328	1305	1263
Revenue (€ ha^{-1})	1084	954	606	556	530
Profitability ratio (%)	219	203	184	174	172

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The costs associated with the production of the semi-dwarf morphotype of winter oilseed rape cv. Avenir in high-input technologies (I-III) were estimated at €861–903 ha^{-1} (Table 14). The relevant costs were lower by €54–187 ha^{-1} in low-input technologies (IV-V). The structure of costs was similar in all production technologies. The highest production costs were associated with mineral fertilization (45%–49%), followed by chemical treatments (20%–27%), seed harvest and transport (10%–12%), sowing (10%–14%) and tillage (7%–10%) (Table 14).

Table 14. Total cost (€ ha^{-1}) associated with the production of the semi-dwarf cultivar Avenir of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			High-Input	
	I	II	III	IV	V
	A1B0C2D2E1	A1B1C2D2E1	A1B1C1D2E1	A1B2C0D1E2	A1B2C0D0E0
Production costs, (€ ha^{-1}), including:	903	880	861	827	694
Tillage	66	66	66	66	66
Seeding	127	104	104	80	80
Mineral fertilizers	424	424	424	372	321
Weed control	96	96	96	96	96
Pest control	46	46	46	46	46
Disease control	36	36	36	78	0
Seed harvest and transport	108	108	89	89	85

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

Despite higher costs, the production of cv. Avenir was more profitable in high-input (I-III) than low-input (IV-V) technologies (Table 15). Revenue per hectare was twice higher and production costs per 1 ton of seeds were 25% lower on average in high-input technologies. The highest profits were generated when winter oilseed rape cv. Avenir was sown early at 80 seeds m^{-2}, supplied with 240 kg N ha^{-1} and protected with one fungicide treatment. The profitability index increased when winter oilseed rape cv. Avenir was sown on the optimal date at only 60 seeds m^{-2} (III). A decrease in the rate of nitrogen fertilizer (technologies IV-V) significantly lowered the production profitability of the semi-dwarf cultivar Avenir (the decrease in seed yield far outweighed the decrease in cost associated with a reduction in nitrogen fertilizer rate) (Table 15).

Table 15. Production profitability of the semi-dwarf cultivar Avenir of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology				
	High-Input			Low-Input	
	I A1B0C2D2E1	II A1B1C2D2E1	III A1B1C1D2E1	IV A1B2C0D1E2	V A1B2C0D0E0
Production value (€ ha^{-1})	2125	2083	2052	1436	1267
Revenue (€ ha^{-1})	1222	1203	1191	609	573
Profitability ratio (%)	235	237	238	174	183

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The total costs associated with the production of the long-stem morphotype of winter oilseed rape cv. Visby in the high-input technology (A2B1C2D2E2) were determined at €956 ha^{-1} (Table 16). Production costs were lower by €176 ha^{-1} in the low-input technology (A2B2C0D0E2). Despite significant variations in total costs, the compared production technologies did not differ considerably in the cost structure. In both high-input and low-input technologies, mineral fertilization and disease/pest/weed control accounted for around 67%–69% of total costs. Seeding costs accounted for less than 14%, seed harvest and transport for 12%, and tillage for 9% of total production costs (Table 16).

Table 16. Total cost (€ ha^{-1}) associated with the production of the long-stem cultivar Visby of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology	
	High-Input I—A2B1C2D2E2	Low-Input II—A2B2C0D0E2
Production costs, (€ ha^{-1}), including:	956	780
Tillage	66	66
Seeding	138	85
Mineral fertilizers	424	320
Weed control	97	97
Pest control	46	46
Disease control	77	77
Seed harvest and transport	108	89

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

The production profitability of the long-stem cultivar of winter oilseed rape cv. Visby was also low in the low-input technology (II) where the decrease in costs did not compensate for the observed drop in seed yield. In the high-input technology (I) revenue per hectare was 61% higher than in the low-input production technology (Table 17).

Table 17. Production profitability of the long-stem cultivar Visby of winter oilseed rape (across years, 2008–2011).

Specification	Production Technology	
	High-Input I—A2B1C2D2E2	Low-Input II—A2B2C0D0E2
Production value (€ ha^{-1})	2025	1444
Revenue (€ ha^{-1})	1069	664
Profitability ratio (%)	212	185

A—Hybrid cultivars (level 0—semi-dwarf cv. 'PR45 D03', level 1—semi-dwarf cv. 'Avenir', level 2—long-stem cv. 'Visby'); B—Sowing date (level 0—sown 10 days earlier, level 1—optimal sowing date, level 2—sowing delayed by 10 days); C—Seeding rate (level 0—40 pure live seeds m^{-2}, level 1—60 pure live seeds m^{-2}, level 2—80 pure live seeds m^{-2}); D—Spring N rate (level 0—120 kg N ha^{-1}, level 1—180 kg N ha^{-1}, level 2—240 kg N ha^{-1}); E—Spring fungicide treatment (level 0—no fungicide treatment, level 1—1 fungicide treatment at 65 BBCH, level 2—2 fungicide treatments at 32 and 59 BBCH).

4. Discussion

4.1. Productivity

The growing demand for agricultural crops has to be reconciled with sustainability requirements, including limited use of artificial fertilizers, fuels and crop protection products. To meet those goals, agronomic knowledge has to be expanded, and decision-making support systems and modern crop production technologies have to be introduced in agricultural practice [51–53]. Święcicki et al. [2] have drawn far-reaching conclusions claiming that further progress in crop production is more likely to be influenced by modern technology than traditional means of production (land, capital and labor). Crop production, including rapeseed production, can be modernized by harnessing the progress in biological sciences (new cultivars), chemical sciences (new and improved fertilizers and crop protection agents) and technical sciences (machines, equipment, automation) [54]. According to Bartkowiak-Broda et al. [55], the yield and quality of winter rapeseed are significantly influenced by the intensity of agronomic inputs, in particular fertilizers, crop protection products, mechanization and effective management and organization of production processes. The results of this study indicate that production technologies that cater to the specific needs of different cultivars (morphotypes) of winter oilseed rape deliver tangible benefits. In all years, the semi-dwarf cultivar PR45 D03 delivered the highest yields (4.54–5.92 Mg ha^{-1}) in production technologies A0B1C2D2E1 (optimal seeding date—22 August, 80 seeds m^{-2}, spring nitrogen fertilizer rate of 240 kg ha^{-1} and one fungicide treatment) and A0B1C1D2E2 (optimal seeding date—22 August, 60 seeds m^{-2}, spring nitrogen fertilizer rate of 240 kg ha^{-1} and two fungicide treatments). The semi-dwarf cultivar Avenir was characterized by the highest yields when sown on the optimal date at 80 seeds m^{-2}, supplied with 240 kg N ha^{-1} and subjected to one fungicide treatment (A1B1C2D2E1). The long-stem cultivar Visby generated the highest yields when sown on the optimal date at a higher seeding rate than recommended for heterozygous cultivars (80 seeds m^{-2}), supplied with 240 kg N ha^{-1} in spring and subjected to two fungicide treatments (A2B1C2D2E2). When winter oilseed rape is sown at a date that is optimal for a given region, the parameters of rosette leaves (number of leaves, root collar diameter, epicotyl length, taproot length, dry matter content) guarantee the highest resistance to low temperatures during winter dormancy, high vigor in spring, effective competition against weeds, and the formation of a high number of buds, which contribute to high yields [56]. In north-eastern Europe (Lithuania, Latvia), the optimal sowing date for winter oilseed rape is 5–10 August [57] to 10–20 August [58]. In Poland (central-eastern Europe), winter oilseed rape should be sown between 10–15 August (north-eastern Poland) to 20–25 August (southern and south-western Poland) [56]. In western Europe, as compared with eastern and northern Europe, sowing date is a less important parameter in the production of winter oilseed rape due to a lower risk of freezing. In France, winter oilseed rape should be sown between the last days of August (northern France) and early September (southern France) [59], whereas in southern Germany, winter oilseed rape should not be sown later than in mid-September [60]. The difference in the seed yield of semi-dwarf cultivars PR45 D03 and Avenir between the highest-input and the lowest-input technologies reached 1.65–1.91 Mg ha^{-1} (33%–35%). The seed yield of the long-stem cultivar Visby was around 1.49 Mg ha^{-1} (28%) lower in low-input technologies. Intensive production induced a smaller decrease in the seed yield of cv. Visby, which suggests that long-stem cultivars are better suited for cultivation in low-input technologies than semi-dwarf cultivars. Cook et al. [61] and Budzyński et al. [62] also demonstrated that the seed yields of winter oilseed rape were 15%–20% and 30%–40% lower in medium-input and low-input production technologies, respectively, than in high-input technologies.

In winter oilseed rape, low yields do not always result from gross errors in production technology or the failure to observe process requirements, but they may be associated with production technologies that do not cater to the specific needs of a given cultivar [63]. In the current study, different combinations of agronomic factors decreased the seed yields of the analyzed cultivars of winter oilseed rape. The semi-dwarf cultivar of winter oilseed rape cv. PR45 D03 was sown late in each year of the study in all low-input production technologies (A0B2C1D0E0, A0B2C0D1E0, A0B2C0D0E1). The seed yields of cv. Avenir were low in low-input production technologies characterized by a low seeding rate (40 seeds m^{-2}) and delayed sowing (early September) (A1B2C0D1E2 and A1B2C0D0E0). In low-input technologies, the seed yields of cv. Visby decreased in response to a low seeding rate (40 seeds m^{-2}), delayed sowing (September), a low nitrogen fertilizer rate (120 kg ha^{-1}) and two fungicide treatments (A2B2C0D0E2).

4.2. Energy Efficiency

The energy inputs associated with the production of 1 ha of winter oilseed rape in Europe range from 13 to 35 GJ, depending on the intensity of agricultural inputs [64] and seed yields [65]. In Europe, the demand for energy is nearly twice higher in high-input than in low-input production technologies of oilseed rape [36]. In a study by Budzyński et al. [36], energy demand reached 29 GJ ha^{-1} in the high-input technology (seed yield—4.17 Mg ha^{-1}). The demand for energy in medium-input (seed yield—3.85 Mg ha^{-1}) and low-input (seed yield—3.48 Mg ha^{-1}) production technologies was determined at 24 and 19 GJ ha^{-1}, respectively. According to De Mastro et al. [66], the energy demand of oilseed rape grown organically in the Mediterranean Region reached 14–15 GJ ha^{-1}, and it was equivalent to approximately 38%–42% of energy consumption in conventional high-input production technologies. In the present study, the semi-dwarf and long-stem cultivars of winter oilseed rape had similar energy requirements in high-input production technologies, which ranged from 28.3 to 28.6 GJ ha^{-1}. In low-input technologies, the cultivation of winter oilseed rape required 6.7–7.7 GJ ha^{-1} (semi-dwarf cultivars) to 9.1 GJ ha^{-1} (long-stem cultivar) less energy.

Most agronomic and energy efficiency analyses in the process of solid biomass production do not go beyond the field (farm) [67–80]. It should be stressed, however, that the use of oilseed crops for biofuel production is economically justified when the energy efficiency of yield seeds ≥3 (i.e., the energy value of yield seeds should be at least three times higher than the relevant energy inputs) [81]. In Europe, the energy efficiency ratio of oilseed rape is relatively high in Germany, Poland, Lithuania, Latvia, France and Italy [82]. The production technologies of oilseed rape are modified by agroecological conditions [83,84], which influence productivity [82]. Energy efficiency analyses support the selection of biomass production technologies that deliver optimal results under local conditions [82] at different levels of agricultural inputs [85]. Research into the energy efficiency of various production technologies of oilseed rape indicates that a decrease in agricultural inputs (lower production intensity) is justified because it increases the energy efficiency ratio [36,66]. In a study by Budzyński [36] the energy efficiency ratio of winter oilseed rape was 12%–22% higher in a low-input production technology. In the work of De Mastro et al. [66], the energy efficiency ratio of oilseed rape reached 4.8 in conventional production technologies (seed yield—2.9 Mg ha^{-1}) and 13.4 in organic technologies (seed yield—2.5 Mg ha^{-1}). In the current study, the energy efficiency of the evaluated production technologies varied across the analyzed cultivars and morphotypes of winter oilseed rape. The technologies where the semi-dwarf cultivars (PR45 D03 and Avenir) produced the highest yields were also characterized by the highest energy efficiency ratio (4.64 and 4.94, respectively). The energy efficiency of low-input production technologies was 10% (PR45 D03) to 16% lower (Avenir). The long-stem morphotype of winter oilseed rape cv. Visby was characterized by the highest energy efficiency ratio (4.87) in the low-input technology. The intensification of production technology of cv. Visby decreased the energy efficiency ratio by 4% on average.

4.3. Profitability

From the economic point of view, the production of winter oilseed rape generates direct profits from the sale of seeds and indirect profits by increasing the yield of successive crops, in particular, cereals [86]. Oilseed rape is an attractive preceding crop for cereals because field residues are rapidly decomposed (narrow C:N ratio), they are abundant in macronutrients and micronutrients, and act as biofumigation agents [87–89]. The seed yield of winter wheat increased by 0.8 to 1.5 Mg ha^{-1} when grown after winter oilseed rape than when cultivated in a continuous monoculture [90,91].

According to Homolka and Mydlář [86], the production of winter oilseed rape is profitable when average seed yields reach a minimum of 3.0–3.5 Mg ha^{-1}. For this reason, the selection of the optimal technology characterized by high productivity and low production costs plays a very important role in the cultivation of oilseed rape [86]. In Europe, the costs associated with high-input production technologies of winter oilseed rape can be as high as €1000 ha^{-1}. Production costs are 12% and 40% lower in integrated and low-input technologies, respectively [92,93]. Winter oilseed rape has high agricultural requirements, and seed yields are frequently correlated with agricultural inputs [66,83]. According to Homolka and Mydlář [86], intensive production of winter oilseed rape is profitable because the cost of producing 1 Mg of seeds decreases with a rise in agricultural inputs and seed yields. In the present study, total production costs in high-input technologies ranged from €861–910 ha^{-1} (semi-dwarf cultivars) to €956 ha^{-1} (long-stem cultivar). The costs associated with the cultivation of semi-dwarf and long-stem cultivars of winter oilseed rape were €181–187 ha^{-1} and €176 ha^{-1} lower, respectively, in low-input technologies. Regardless of cultivar, fertilization was the most expensive agricultural input, which accounted for 41%–50% of total production costs. Despite the above, the most expensive production technologies with the highest rate of nitrogen fertilizer (high-input technology) were most profitable. Low-input technologies were not economically justified (regardless of cultivar) because the decrease in seed yield considerably outweighed the reduction in production costs. It should also be noted that the most profitable combinations of agronomic factors differed across the studied cultivars of winter oilseed rape. Production costs per 1 ton of seeds of the semi-dwarf cultivar PR45 D03 were lowest (€176–189) in technology A0B1C2D2E1 where winter oilseed rape was sown on the optimal date at 80 seeds m^{-2}, supplied with the highest rate of nitrogen fertilizer (240 kg ha^{-1}) and protected with one fungicide treatment. This production technology was also characterized by the highest revenue per hectare and the highest profitability ratio. The production of the semi-dwarf cultivar Avenir was most profitable in technology A1B0C2D2E1 (where winter oilseed rape cv. Avenir was sown 10 days earlier than cv. PR45 D03). The production of the long-stem cultivar Visby was most profitable (highest revenue per hectare and highest profitability ratio) in technology A2B1C2D2E2 where winter oilseed rape was sown on the optimal date at 80 seeds m^{-2}, supplied with the highest rate of nitrogen fertilizer (240 kg ha^{-1}) and protected with two fungicide treatments.

5. Conclusions

Experiments with a fractional factorial design facilitate evaluations of the agronomic requirements of new crop cultivars and support the development of production technologies characterized by the highest output, energy efficiency and profitability. In north-eastern Poland, the semi-dwarf cultivars of winter oilseed rape (PR45 D03, Avenir) responded differently to various levels of agricultural inputs than the long-stem cultivar (Visby). The production technologies where the seed yields of both morphotypes of winter oilseed rape were lowest also differed in the intensity of agricultural inputs. These findings indicate that new crop cultivars should be grown in production technologies that effectively target their agronomic requirements. Energy efficiency and profitability analyses also revealed differences in productivity between the analyzed cultivars and morphotypes of winter oilseed rape. In the production of semi-dwarf cultivars, the high-input technology was most energy efficient. In contrast, in the production of the long-stem cultivar, energy efficiency was highest in the low-input technology. None of the analyzed morphotypes of winter oilseed rape produced satisfactory yields in low-input technologies despite the fact that production costs were €176–187 ha^{-1} lower than in high-input technologies. The observed decrease in seed yield considerably outweighed the benefits associated with a reduction in production costs.

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