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Peas and Barley Grown in the Strip-Till One Pass Technology as Row Intercropping Components in Sustainable Crop Production

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Abstract: Simplified, ploughless tillage and multi-species, multifunctional crop production are important components of sustainable agriculture. Technologies that combine these components can play an even greater pro-ecological role in modern agriculture. The claim is made that row intercropping of spring barley and peas, along with strip tillage, is an alternative to traditional methods of sowing cereals and legumes. This hypothesis was verified in a three-year field experiment in which row intercropping of barley and peas (alternating every row) was compared with traditional mixed-crop, within-row cropping (plants of each species in each row) and pure sowing of each species. Row intercropping of barley and peas using strip-till, one-pass technology, as compared with mixed-crop, within-row, improved the uniformity of plant emergence and plant density of peas before harvesting and reduced weed infestation. The productivity of barley and peas was higher than with pure sowing by 8.5% and 10.2%, respectively, and the productivity of peas was also higher by 38.9% than when sowing in mixed-crop, within-row. The yield of barley grain/seeds and peas under row-intercropping was 1.75 t ha^{-1} higher than the yield of pea seeds with pure sowing, and 0.79 t ha^{-1} lower than the yield of barley in pure sowing. On the other hand, the yield of grain/seed protein under this mixture was similar to the pea protein yield with pure sowing and 109 kg ha^{-1} higher than the barley protein yield with pure sowing. The positive results should inspire further research to obtain a better understanding of the conditions and effects of growing grains with legumes with strip-till one-pass technology.

Keywords: legume; peas; cereal; barley; intercropping; row intercropping; strip-till one-pass; yield; protein yield

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1. Introduction

Contemporary societies increasingly perceive the negative impact of industrial agriculture on their sustainable development [1]. Intensive agriculture is leading to, for example, the degradation of soil and water sources, and a reduction in biodiversity in the soil and in agricultural ecosystems [2]. Yields do not always justify the high social and environmental costs of agricultural production [3], especially the high energy inputs and greenhouse gas emissions [4]. Equally high yields can be obtained in sustainable agriculture, the main elements of which are no-till, crop rotations and a continuous soil cover [5].

Understanding of the need to green our agricultural production is rapidly increasing the proportion of conservational farming and sustainable plant growing practices. According to a study by Kassam et al. [6] and their estimated pace of growth in conservation agriculture, this currently accounts for 15% of the world's arable area. In Europe, according to ECAF [7], conservation agriculture covers about 3.0 million ha. The analysis of habitat factors (soil properties, water conditions, risk of erosion), economic factors (field size, degree of mechanisation, economic size of farms) and social factors indicates that Europe and many other parts of the world are particularly predestined for the development of conservation agriculture [8]. Its features, such as no-till methods and multifunctional crop production, are increasingly being introduced into other agricultural systems, thus positively influencing the environment and landscape [9–11].

Ploughless soil cultivation, including strip-till, increases the efficiency of water use, organic carbon content, biomass and activity of microorganisms, has a positive effect on the physical properties of the soil, and reduces erosion. These tillage methods also affect the soil weed seed bank and the weed infestation of the plant canopy [12,13] and lower plant production costs [14]. Strip-till one-pass is a particularly advantageous ploughless tillage method and simplified plant cultivation technology. One pass of a multi-functional machine loosens strips of soil, applies fertilisers and sows seeds [15,16]. The deep tillage of narrow strips of soil in which seeds are sown reduces the adverse effects of no-till that result from its hindering the growth of plant roots in unturned soil, but retains the benefits of no-till in inter-rows and the presence of plant residues as a surface mulch [17,18]. This method is increasingly used in the cultivation of plants in rows with both wide and narrow spacings [19,20]. However, there is no scientific information on the cultivation of mixed annual crops using strip-till one-pass. The authors of this study put forward the hypothesis that it is possible to grow cereals and legumes in alternating adjacent strips of tilled soil in accordance with the strip-till method, instead of simply mixing these crops within each row of the field.

In modern agriculture, crop mixtures provide very important nutritional, economic and ecological services [21,22]. Plants of different genotypes (cultivars, species) may exist in the same rows, in alternative rows or in strips. Depending on the spatial and temporal distribution of plants, they can differ in proximity, mutual influence and environmental impact [23]. According to Malézieux et al. [24], the benefits of mixed crops are: increasing and stabilising plant productivity, preserving and increasing biodiversity, protecting soil and water, sequestering carbon, and controlling harmful organisms. Growing mixtures allows for a better use of the production area (as measured by the Land Equivalent Ratio—LER). Bacchi et al. [25] indicate, based on fodder crop and protein yields, that LER is 16.0% and 11.5% higher, respectively. One feature of crop mixtures as compared to pure sowing is that they have higher yields [26,27] but, very importantly, greater yield stability under various environmental conditions, including stress conditions [28]. Creissen et al. [29] show, using the example of a mix of barley cultivars, that the greater yield stability results from the plants' reduced susceptibility to diseases and lodging. Boudreau [30], based on the results of over 200 studies, found that cultivating plants in mixtures reduced the occurrence of leaf diseases by over 70%. A diverse agricultural ecosystem hampers the spread not only of diseases and pests, but also of weeds [31,32]. Mixed crops are indicated by many authors as an effective non-chemical method for reducing the occurrence of organisms damaging the crops [33].

An important role of crop mixtures in agroecosystems, especially those including leguminous species, is that of improving the exploitation and protection of abiotic environmental resources, including a beneficial influence on the physical [34–36] and chemical properties of soil [37,38]. Cultivating mixtures also increases the number, variety and activity of microorganisms [39,40]. This is because it causes complementary niches to be occupied in time and/or space, phenotypic plasticity, and differentiation in the structure and development of the roots of individual plant species within the mixture [41,42].

In view of the significant role of simplified, no-till cultivation and crop mixes in environmentally friendly agriculture, as well as the adopted research hypothesis relating to the strip-till method, the aim of the research was to determine, by experiment, the possibility of growing barley and peas by row intercropping using strip-till technology and comparing the results with mixed crops and pure sowing of these species.

2. Materials and Methods

2.1. Study Site

The research was carried out in the agricultural company Agro-Land Marek Różniak, Research & Development Centre Agro-Środki-Technika-Technologia in Śmielin (53°09′04.0″ N; 17°29′10.7″ E), Kuyavia-Pomerania Voivodeship, Poland in cooperation with the Department of Agronomy at the Bydgoszcz University of Technology.

Three-year field experiments were carried out on soil classified by the WRB [43] as Luvisol. The soil grain-size composition was: 50.6% sand (2–0.05 mm), 43.4% silt (0.05–0.002 mm), 6.0% clay (<0.002 mm). The soil in the 0–20 cm layer contained: organic carbon (g C kg^{-1} soil)—12.1; total nitrogen (g N kg^{-1} soil)—1.15; $P_{Egner\text{-}Riehm}$ (mg P kg^{-1} soil)—116.7; $K_{Egner\text{-}Riehm}$ (mg K kg^{-1} soil)—160.8; $Mg_{Schatschabel}$ (mg Mg kg^{-1} soil)—61.5; and the pH_{KCL} index was 6.14.

According to the Köppen–Geiger classification [44], the research area lies in a humid continental climate zone classified as Dfb (cold, without dry season, warm summer). Where field experiments were carried out, the average annual air temperature in recent decades was 8.1 °C, and the sum of precipitation was 485 mm. Meteorological conditions (monthly mean air temperatures and sums of precipitation) during the study period are presented in Table 1.

Table 1. Meteorological conditions during the field experiment period.

	Year							
Month	**2019**	**2020**	**2021**	**30-Year Mean**	**2019**	**2020**	**2021**	**30-Year Mean**
	Air Temperature (°C)				**Monthly Precipitation (mm)**			
January	-	2.6	−1.1	−1.8	-	37.7	28.3	26.8
February	-	3.6	−1.8	−0.9	-	36.0	0.8	20.7
March	5.4	3.9	3.7	2.5	28.8	26.1	21.7	31.9
April	9.3	8.2	6.2	7.9	1.5	0.7	30.7	27.0
May	12.1	11.2	12.2	13.3	89.2	34.2	75.2	49.3
June	21.9	17.9	20.1	16.1	17.7	142.0	30.1	52.8
July	18.6	18.3	20.9	18.6	22.4	67.2	61.7	69.8
August	19.7	19.9	17.4	17.9	37.7	114.4	38.1	62.6
September	13.5	15.1	-	13.1	98.5	66.7	-	46.0
October	9.8	10.5	-	8.2	35.9	72.9	-	31.5
November	5.5	6.0	-	2.9	69.6	12.4	-	32.4
December	2.7	1.8	-	-0.6	21.1	33.8	-	34.0

2.2. Field Experiments

In a three-year, single-factor field experiment, the possibility of cultivating spring barley (*Hordeum vulgare* L.) and peas (*Pisum sativum* L.) by mixed crops within-row and by row intercropping was investigated. Four treatments were compared:

- Spring barley, pure sowing, $B_{p.}$
- Pea, pure sowing, $P_{p.}$
- Mixed-crop within-row (BP_{mc}), barley (B_{mc}) + peas (P_{mc}).
- Row intercropping (BP_{ri}), barley (B_{ri}) + peas (P_{ri}).

Each method of sowing (growing) barley and peas was carried out on plots of 4 m × 100 m, randomly distributed in four blocks. Barley, peas and any kind of mixture of these plants were set up in four plots with an area of 400 m^2. Plants were harvested from the entire plot area. After harvesting, the mixture yield was separated into its components—barley grain and pea seeds.

All agrotechnical procedures (loosening soil strips, application of nitrogen–phosphorus fertiliser, sowing seeds) were performed with a single pass of a Mzuri-Pro Til 4T multifunctional machine. Potassium fertiliser only was applied across the entire experimental field before barley and peas were sown, using an Amazone ZG-TS 8200 spreader. Irrespective of the treatment, the mineral fertilisation was: nitrogen 27 kg N ha^{-1}, ammonium phosphate 69 kg P_2O_5 ha^{-1}, and potassium chloride 90 kg K_2O kg ha^{-1}. In pure sowing, spring barley was additionally fertilised in the BBCH 32 stage of 50 kg N ha^{-1}. Spring barley cv. KWS Vermont (pure sowing), pea cv. Batuta (pure sowing), and the two species together were sown on 27 March, 2 April and 12 April of the successive study years. Sowing density (seeds m^{-2}) was, depending on experiment: barley, pure sowing—280; peas, pure sowing—120; mixed crop within-row (barley + peas)—140 + 60; mixed crops by row intercropping—140 + 60. Strips of loosened soil, the same for each of the four treatments of the experiment, were about 12 cm wide, and untilled inter-rows were 24 cm wide. A 6-cm-wide strip of seeds was sown along the centre of the loosened soil strip to a depth of 20 cm. Barley grain was sown to a depth of 3 cm, and peas to a depth of 6 cm. The mixture of barley grain and pea seeds (BP_{mc} treatment) was sown to a depth of 4 cm in every row. In the first year, barley and peas were alternately sown (one row of barley/one row of peas)—BP_{ri} by one pass of a machine with a row spacing of 72 cm sowing peas and a second pass shifted across by 36 cm sowing barley. In the years 2020 and 2021, the same effect was obtained by both plant species sown with a single pass of the sower, with alternating rows of barley and peas and adjacent rows spaced 36 cm apart (Figure 1). For this, the Mzuri machine was modified and the sowing method was developed at the Research & Development Centre Agro-Środki-Technika-Technologia in Śmielin.

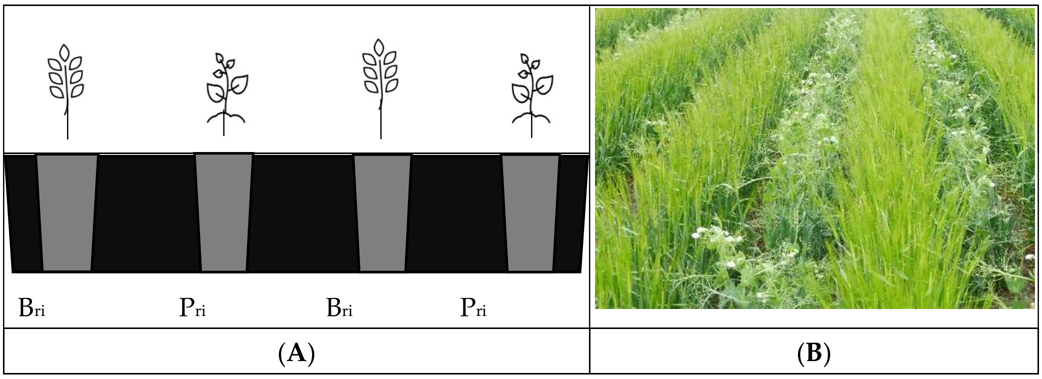

Figure 1. Scheme of plant distribution (**A**) and photo (**B**) of rows of barley and peas cultivated as row intercropping.

The occurrence of pests was chemically reduced with the minimum number of treatments and amount of active ingredients. The fungicide azoxystrobin was applied at 200 g ha^{-1} in the BBCH 39 stage in 2020 and 2021, and the insecticide deltamethrin was applied at 7.5 g ha^{-1} in the BBCH 21 stage in each study year, and in the BBCH 49 stage in 2019 and 2021. Crop protection products were applied in accordance with current recommendations and instructions.

The grain/seed yield was harvested by combine harvester from the entire plot in the BBCH 89 full maturity stage and expressed in t ha^{-1} with a water content of 15%.

2.3. Measurements and Assessments

After the emergence of the plants in the BBCH 12 stage, and before harvesting at BBCH 89, plant/ear density was determined on each plot at four places of 1 m^2. The density after emergence relative to assumed sowing density was used to calculate the field emergence capacity, while canopy density before harvest, after considering yield features, was used to determine weight of grain/seeds per area. In the BBCH 31–32 and 60–61 development stages, the physiological parameters of plants and the canopy were measured. Photosynthetically active radiation (PAR) and leaf area index (LAI) were determined. PAR and LAI measurements were made using an AccuPAR LP-80 m (METER Group, Inc., Pullman, WA, USA). The measuring probe was placed perpendicular to the crop rows. The evaluations of the PAR index above the crop canopy and near the soil surface beneath the canopy were used to calculate the intercepted photosynthetic active radiation index (IPAR%). At the same developmental stages, leaf stomatal conductance and relative chlorophyll content were evaluated. These measurements were taken on fully shaped upper leaves using a Leaf Porometer SC-1 (METER Group, Inc.) and a CM1000 chlorophyll meter (Spectrum Technologies, Inc.), respectively. Stomatal conductivity was expressed in mmol H_2O m^{-2} s^{-1}, and the content of chlorophyll as a unitless quantity in the range 0–999.

In the BBCH 60–61 and BBCH 89 stages, weed infestation was determined at two locations within each plot. Above-ground weed biomass was collected and dried for 72 h at 70 °C using a Solid Line FD-S 115 dryer (BINDER GmbH). The result is expressed in g d.m. m^{-2}.

Prior to harvest, biometric measurements were also performed on 20 representative barley and pea plants in each plot. Determinations were made of the following: stem/shoot length, number of grains per ear, weight of grain per ear, number of pods per plant, number of seeds per pod, and weight of seeds per plant. After harvesting, an assessment was made of the weight of a thousand grains/seeds, weight of a hectolitre of grain/seeds, and grain/seed protein content. The grain/seed parameters were assessed using a grain counter (Sadkiewicz Instruments) for the weight of a thousand grains/seeds, and an Infratec NOVA analyser (Foss Analytical). Protein yield was calculated based on grain/seed yield and protein content.

Intercropping efficiency was assessed using land equivalent ratio (LER). The LER index is commonly used in comparative studies of the effectiveness of mixed crops and pure sowing [22,25].

$$\mathrm{LER} = (\mathrm{LERa} + \mathrm{LERb});\ \mathrm{LERa} = \mathrm{Ya(b)}/\mathrm{Yaa},\ \mathrm{LERb} = \mathrm{Yb(a)}/\mathrm{Ybb} \quad (1)$$

where: Yaa and Ybb—yield of barley and peas in pure sowing, respectively; Ya(b)—yield of barley by mixed crops; Yb(a)—yield of peas by mixed crops.

2.4. Statistical Data Analysis

The dataset of measurements and evaluations of plant parameters was subjected to statistical analysis. The normality of distribution of results for each feature was checked using the Shapiro–Wilk test. The uniformity of barley and pea field emergence capacity by sowing method was determined using standard error, standard deviation, outliers and extreme results of plant emergence in 16 places in each experimental treatment (4 measurement places in a plot × 4 repetitions). The results are graphically presented in box-and-whisker charts. Due to the variability of the results in subsequent years, results are presented separately for each year. The column figure shows the mean values of the field emergence capacity of barley and peas, which allowed for conclusions to be generalized, regardless of the variability in the years. Such conclusions, the most valuable for science, were carried out on the basis of the mean value of plant features in the years of research presented in the tables and figures. This procedure was also justified by the fact that barley and peas were only found to have different responses to experimental treatments in the following years in terms of a few plant features, e.g., the ear/plant density before harvesting. However, no such reaction was found for the grain/seed and protein yield.

Normally distributed data were subjected to ANOVA. The statistical significance of the influence of experimental treatments on given plant features was evaluated with the *F* test. Tukey's post-hoc test (at $p < 0.05$) was used to assess the significance of differences between the mean values of each feature.

The results were statistically analysed in the Statistica.PL 12 computer software package [45].

3. Results

The field emergence capacity of spring barley intercropped with rows of pea (B_{ri}) was 85.8%; this did not differ from the emergence of barley in pure sowing (B_p) and was significantly higher than the emergence capacity of barley sown as mixed crops (B_{mc}) (Figure 2). Similarly, the emergence of peas in the mixed crop (P_{mc}) was smaller than that of pure-sown peas (P_p) or that of pea intercropped with barley (P_{ri}).

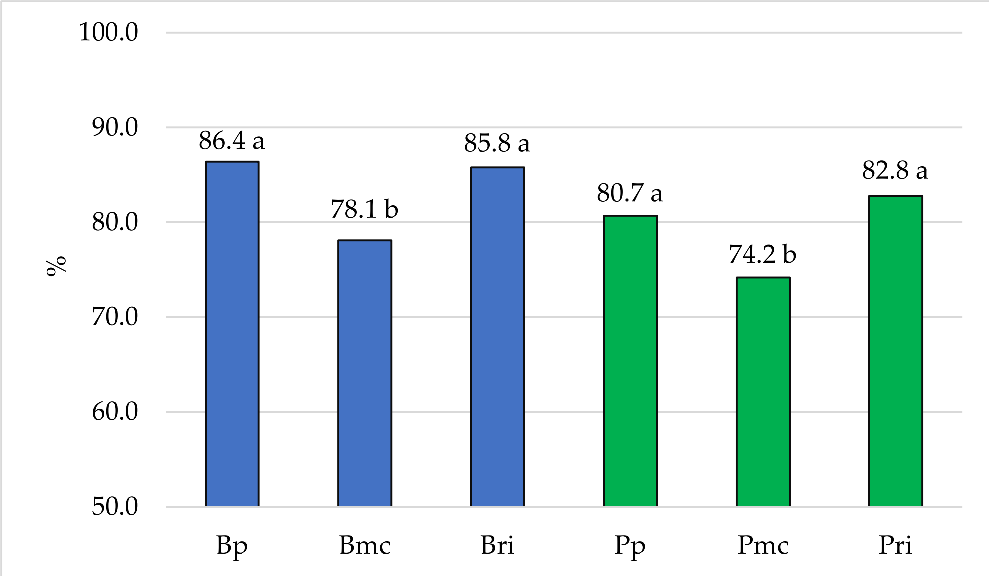

Figure 2. Field emergence capacity of spring barley and peas, depending on the growing method: B_p—spring barley, pure sowing; B_{mc}—spring barley, mixed crop within-row; B_{ri}—spring barley, row intercropping; P_p—pea, pure sowing; P_{mc}—pea, mixed crop within-row; P_{ri}—pea, row intercropping. a, b—letters indicate significant difference at $p < 0.05$.

In period of the research, despite the different value in each year, the lowest field emergence capacity was for barley sown in the B_{mc} mix. At the same time, its field emergence capacity was highly spatially variable. The standard deviation (as a measure of variability) was 4.08–5.70 depending on the year (Figure 3A). In 2019 and 2020, the differentiation of the emergence of B_p and B_{ri} barley within the experimental field was similar. In 2021, the field emergence capacity of B_{ri} was less variable than that of B_p. The standard deviations were 2.75 and 3.58, respectively.

The row intercropping of barley with peas (BP_{ri}) resulted in lower variability (i.e., greater uniformity) in the field emergence capacity of peas P_{ri} within the experimental field, especially as compared to P_{mc} (Figure 3B). In 2020 and 2021, the variability in field emergence capacity was also lower for P_{ri} than for P_p. This is indicated by lower standard deviations (shorter whiskers in the chart). In 2021, these were 1.92 and 2.84, respectively.

Plant species and sowing (growing) method significantly influenced the canopy's structure and the light conditions within it. In the initial stages of development, BBCH 31–32, the LAI and IPAR indices were highest in pure sowing (Pp) and the mixed crop of barley with pea (BP_{mc}). However, in the BBCH 60–61 stage, the LAI index was highest for P_p and BP_{ri}, and the IPAR index was highest for BP_{ri}. In the flowering stage, 87.5–100.3 g d.m. m^{-2} of weeds were found. Weed infestation was, nevertheless, not related to the growing method. Before harvesting, P_p and BP_{mc} were the most infested (Table 2).

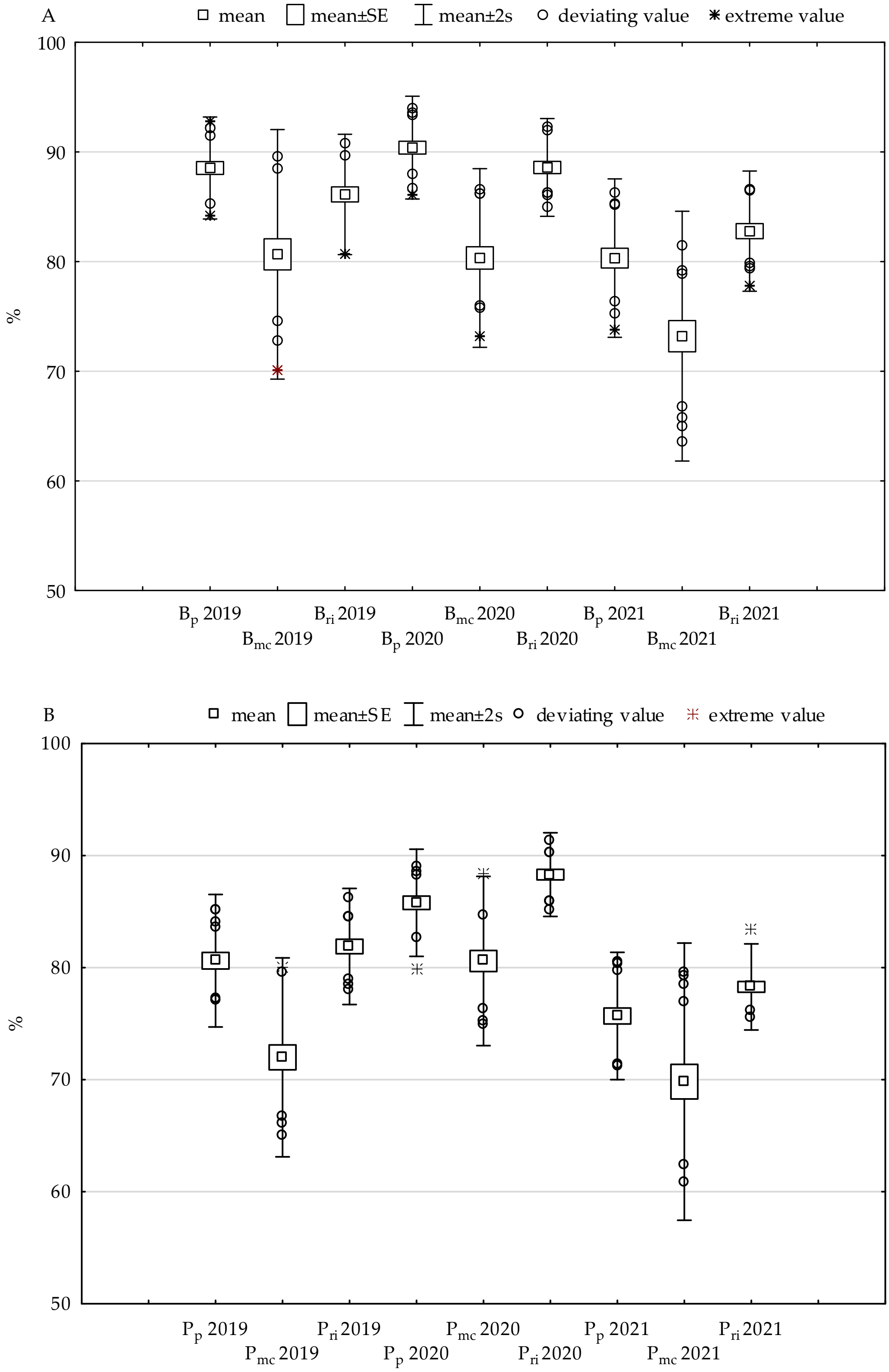

Figure 3. Uniformity of field emergence capacity of spring barley—(**A**) and peas—(**B**) depending on the growing method in 2019-2021: B_p—spring barley, pure sowing; B_{mc}—spring barley, mixed-crop within-row; B_{ri}—spring barley, row intercropping; P_p—pea, pure sowing; P_{mc}—pea, mixed-crop within-row; P_{ri}—pea, row intercropping.

Table 2. The value of the LAI, IPAR indices of barley and peas canopies, and weed biomass depending on the growing method: B_p—spring barley, pure sowing; P_p—pea, pure sowing; BP_{mc}—mixed crop within-row, barley + peas; BP_{ri}—row intercropping, barley + peas.

Growing Method	Growth Stage, BBCH					
	31–32		60–61			89
	LAI	IPAR (%)	LAI	IPAR (%)	Weeds (g d.m. m^{-2})	Weeds (g d.m. m^{-2})
B_p	1.38 b	74.3 a	3.24 c	83.9 b	94.6 a	116.5 b
P_p	1.51 a	72.7 b	4.16 a	85.4 ab	87.5 a	160.7 a
BP_{mc}	1.50 a	72.5 b	3.65 b		100.3 a	145.5 a
BP_{ri}	1.43 b	75.0 a	4.31 a	82.6 b 88.3 a	95.7 a	108.4 b

a, b—letters in columns indicate significant difference at $p < 0.05$.

In the initial stage of barley growth, BBCH 31–32, the coexistence of pea plants, regardless of the sowing method (B_{mc}, B_{ri}), did not significantly affect the leaf stomatal conductance or leaf chlorophyll content (Table 3). Later, at BBCH 60–61, B_p stomatal conductance was the same as in the presence of pea (B_{ri}). Leaf chlorophyll content in B_p was similar to B_{ri}, but 42 units lower than in B_{mc}. Peas intercropped with barley (P_{ri}) only had a significant increase in leaf stomatal conductance relative to P_p in the BBCH 31–32 stage, and, when sown as P_{mc} and P_{ri}, had a greater stomatal conductance than P_p in the BBCH 60–61 stage.

Table 3. Stomatal conductance and chlorophyll content in leaf barley and peas depending on the growing method: B_p—spring barley, pure sowing; B_{mc}—spring barley, mixed-crop within-row; B_{ri}—spring barley, row intercropping; P_p—pea, pure sowing; P_{mc}—pea, mixed-crop within-row; P_{ri}—pea, row intercropping.

Growing Method	Growth Stage, BBCH			
	31–32		60–61	
	Stomatal Conductance (mmol H_2O m^{-2} s^{-1})	Chlorophyll (Relative Unit)	Stomatal Conductance (mmol H_2O m^{-2} s^{-1})	Chlorophyll (Relative Unit)
	Spring barley			
B_p	276 a	582 a	327 a	526 b
B_{mc}	265 a	560 a	275 b	568 a
B_{ri}	277 a	580 a	314 a	545 ab
	Pea			
P_p	357 b	488 a	411 c	526 a
P_{mc}	372 ab	493 a	430 b	521 a
P_{ri}	383 a	485 a	454 a	539 a

a, b, c—letters in columns indicate significant difference at $p < 0.05$.

The B_{mc} spring barley had longer stems than the B_p, a greater ear density and greater grain mass per area. However, the same comparison of peas shows the mixed crop to have shorter shoots, lower plant density at harvest, fewer pods, and lower seed weight per plant and per area. The weights per thousand seeds and seed protein content were also lower (Table 4). The biometric features of row-intercropped barley (B_{ri}) did not differ from those of B_p, except for a greater number of ears and per area grain weight. P_{ri} pea plants produced more pods with more seeds than did P_p, as well as greater seed weight per plant and per area. However, the protein content in the seeds from these plants was lower.

Intercropped BP_{ri} plants benefitted from increases in some yield features as compared to BP_{mc}, i.e., in the weight of grain per ear for B_{ri}, and in plant density at harvest, number of pods per plant, number of seeds per pod and weight of seeds per plant for P_{ri}. These plant features differed by 0.04 g; 8.8 pcs m^{-2}; 0.60 pcs; 0.27 pcs, 0.88 g, respectively.

Table 4. Features of plants and canopies of barley and peas depending on the growing method: B_p—spring barley, pure sowing; B_{mc}—spring barley, mixed-crop within-row; B_{ri}—spring barley, row intercropping; P_p—pea, pure sowing; P_{mc}—pea, mixed-crop within-row; P_{ri}—pea, row intercropping.

Feature	**Unit**	**Spring Barley**		
		B_p	**B_{mc}**	**B_{ri}**
Stem length	cm	65.2 b	70.1 a	65.8 b
Ear density	pcs m^{-2}	614 b	663 a	654 a
Grains per ear	pcs	23.0 a	22.7 a	23.2 a
Weight of grain per ear	g	1.05 ab	1.04 b	1.08 a
Weight of grain per area	g m^{-2}	645 b	690 a	700 a
Weight of a thousand grains	g	44.9 a	45.5 a	45.7 a
Weight of a hectolitre of grains	kg hl^{-1}	678 a	685 a	681 a
Grain protein content	g kg^{-1}	114.6 a	117.1 a	116.3 a
Feature	**Unit**	**Pea**		
		P_p	**P_{mc}**	**P_{ri}**
Shoot length	cm	92.6 a	84.7 b	93.5 a
Plant density	pcs m^{-2}	62.6 a	58.4 b	60.5 ab
Pods per plant	pcs	5.02 b	4.71 c	5.31 a
Seeds per pod	pcs	3.09 b	2.96 b	3.23 a
Weight of seeds per plant	g	3.92 b	3.40 c	4.28 a
Weight of seeds per area	g m^{-2}	363 b	288 c	400 a
Weight of a thousand seeds	g	251 a	240 b	247 ab
Weight of a hectolitre of seeds	kg hl^{-1}	816 a	804 a	809 a
Seed protein content	g kg^{-1}	223.4 a	214.6 b	208.9 b

a, b, c—letters in rows indicate significant difference at $p < 0.05$.

The sowing method significantly differentiated the yields of spring barley and pea. The yield of B_p barley was 2.54 t ha^{-1} higher than the yield of P_p pea. Conversely, however, the yield of barley when row-intercropped with peas (BP_{ri}) was 0.46 t ha^{-1} higher than for BP_{mc} (Figure 4A). The LER values of the mixed crop within-row and row intercropping were 0.93 and 1.13, respectively. This indicates that a more efficient use of growth resources was only obtained by the row intercropping of barley + peas, compared to pure sowing of these species.

The protein yield of BP_{ri} plants did not significantly differ for pea when compared to the yield of P_p protein, but, for barley, this was higher than the yield of barley protein in pure-sown B_p or barley sown mixed with peas (BP_{mc}) (Figure 4B). The differences were 0.109 t ha^{-1} and 0.080 t ha^{-1}, respectively.

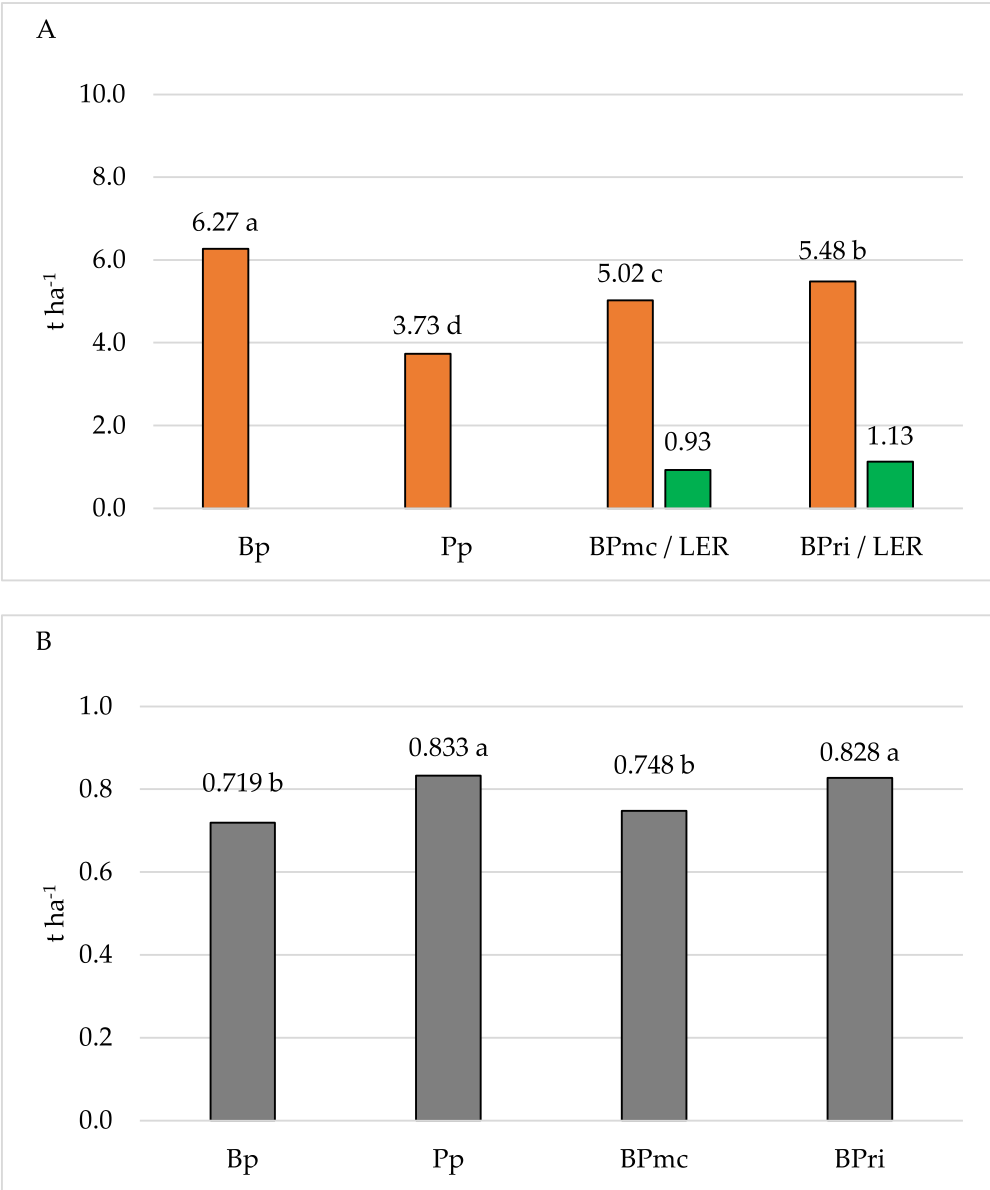

Figure 4. Grain/seeds yield and the LER value for mixed crops—(**A**) and protein yield—(**B**) of barley and peas depending on the growing method: B_p—spring barley, pure sowing; P_p—pea, pure sowing; BP_{mc}—mixed crop within-row, barley + peas; BP_{ri}—row intercropping, barley + peas. a, b, c, d—letters indicate significant difference at $p < 0.05$.

4. Discussion

The solutions proposed in the presented research are in line with the short-term and long-term assumptions of intercropping improvement presented in the synthetic paper by Brooker et al. [42]. The machine is designed for the simultaneous cultivation of plants of different genotypes and various agrotechnical practices (sowing density, sowing depth, fertilisation) and allows for the creation of different ecological niches for plant species in the adjacent rows. This distribution of plants enables a better use of the resources of the habitat and is an example of the currently promoted "sustainable intensification" of agriculture.

The collective and simultaneous cultivation of several crop species or varieties at in a field is one of the more important ways of increasing biodiversity and gross energy production in agroecosystems [46,47]. The hope that is being placed in these agricultural practices is reflected by the creation of special cultivation programmes for mixed crops [48]. The environmental impact of mixed crops depends, inter alia, on the genetic composition of plant mixtures and the method of sowing/cultivation [49–51]. Spring barley, as an important fodder plant, is one component in mixtures grown in various parts of the world. It features in mixes with other cereals, e.g., oats [52], wheat [53] and triticale [54]. It often constitutes fields of fodder plants along with peas [55,56] and other species of legumes [57], including vetch, field beans and lentils [58–60]. However, studies show that barley is an aggressive species that often dominates in multi-species canopy of plants [61]. The high competitive power of barley is evidenced by the results of research on plant competition in multi-species fields in which it is included. Treder et al. [62] showed that barley had a stronger negative effect on wheat than vice versa, as shown in smaller increases in the dry weight of plants from tillering to heading. The competitive advantage of barley results from, inter alia, its uptake of nutrients such as nitrogen [63] or phosphorus [64], which is better and more efficient than that of co-occurring plants. Tosti et al. [65] confirmed the aggressiveness and dominance of barley including in mixture with legumes, especially under conditions of high nitrogen content in the soil. However, the effects of competitive interaction between barley and peas can depend on soil conditions. Michalska et al. [66] found that, on light soil, barley outperformed pea in the initial development stages, while, on heavy soil, barley also had a competitive advantage in the heading stage. In the presented research, having barley in their immediate vicinity within the same row significantly limited growth for peas—the plants were shorter and had fewer pods. The weight of seeds from the pea plant mixed with barley was 13.3% lower than that of pure-sown plants.

In-field interactions between plants, including competition, also depend on their mutual spatial distribution, which results from sowing density, row spacing and other agricultural operations [67–69]. Furthermore, plants in multi-species fields may facilitate as well as limit the mutual growth and increase productivity and yield. Zhang and Li [70] provide an example of mixed crops of wheat with maize and wheat with soybean, in which wheat yield exceeded that of pure-sown wheat. However, plants were sown in rows or strips of several rows separated according to species. This layout of plants in the field enables an edge effect to occur, as well as below-ground and above-ground interactions between plants. The yield (grain weight) of wheat in rows immediately adjacent to maize or soybean was higher than in inner rows within the sowing strip. The increase in wheat yield in the row adjacent to maize was 74%, with 47% being due to above-ground interspecies interactions and 27% to below-ground interactions. Accordingly, a 53% increase in wheat yield in rows bordering soybean was 30% due to above-ground interaction and 23% to below-ground interaction. However, the interaction between plants cultivated as strip (row) intercropping and the effects of this cultivation depend on the species reactions of plants and their spatial distribution, and are not always positive [71]. These conclusions result from, for example, the study by Li et al. [72] into sowing maize and soybeans according to a 2/2 and 3/6 pattern (maize rows/soybean rows). Therefore, in the present research, it was assumed that separating barley from co-occurring peas by planting it in adjacent rows might, but does not necessarily, reduce the adverse effect on the legume, or even stimulate pea growth as compared to the within-row mixing of barley and peas. To maximise the interaction of plants between rows, the pattern of one row of barley/one row of peas was used. Since row intercropping and, especially, mixed intercropping within-row are common methods for growing annuals together [73], but have not been tested in combination with strip-tillage, these methods were adapted to cultivate spring barley and peas in our experiments. It was assumed that if the results were positive, this field crop cultivation technique, and row intercropping with strip-till one pass in particular, might constitute an important aspect of sustainable agriculture.

The row-intercropping of peas helped avoid the aggressive competition of barley seen in within-row mixed cropping. There were more pods on the pea plants and more seeds in the pods. The increases in the weight of seeds per plant as compared to pure sowing and to within-row mixing with barley were 9.2% and 25.9%, respectively. At the same time, the similarity between plant density and pure sowing (which results from the optimal placement of the seeds in the soil and the lack of aggressive barley in the direct vicinity) explains why the yields and protein yields of this combination were higher than those for mixed intercropping within-row.

The high LAI index maintained in the late developmental stages after flowering, and the observed lack of lodging affecting the light conditions in the canopy (especially for peas in row intercropping), were probably the main reasons that the weight of weeds before harvest in this mixture was lower than the more lodging pure-sown peas and the peas grown as a mixed crop within-row. Corre-Hellou et al. [74], after analyzing the results of studies from many countries, indicate that the weight of weeds in pure-sown peas was three times greater than in peas mixed with barley, which has a high potential to suppress weeds in the canopy.

5. Conclusions

The conducted field experiments show that strip-till one-pass technology allows for the row intercropping of multiple plant species as an alternative to traditional mixed sowing. Mzuri Pro-Til machines allow for individual agrotechnical practices to be adjusted, e.g., selection of plant type and different sowing depths in adjacent strips of cultivated soil. This method of sowing spring barley and peas resulted in more uniform emergence of both plant species in different field habitat conditions than mixed crop within-row. The productivity of barley and peas was higher than that obtained with pure sowing. The LER value of more than 1.0 for this method of growing barley with peas indicates a better use of growth resources compared to pure sowing of these species. The total yield of grains/seeds barley and peas cultivated under row intercropping, according to a 1/1 pattern, was 1.75 t ha^{-1} greater than the yield of pea seeds under pure sowing and only 0.79 t ha^{-1} lower than the yield of barley under pure sowing. At the same time, the grain/seed protein yield of these plants was similar to the pure-sown pea protein yield and more than 100 kg ha^{-1} higher than the pure-sown barley protein yield.

The production of a high amount of fodder (grain/seeds), protein yield similar to pea protein yield, as well as reduced weed infestation before harvesting despite the lack of application of herbicides, makes the row intercropping of cereals and legumes a suitable practice in sustainable crop production.

However, the positive results of this three-year series of field experiments do not negate the need for further research to optimize the technology for various habitat and agrotechnical conditions.

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