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ORIGINAL RESEARCH PAPER

Development and production response of edible and forage varieties of pea (*Pisum sativum* L.) to temporary soil drought under different levels of phosphorus application

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Abstract

The change in weather conditions in Central Europe has led to the need to review current standards for fertilization of pulse crops. Physiologists claim that phosphorus may play a significant role in raising tolerance to a temporary lack of water in the soil. The objective of the 2-year field study (2011–2012) was to assess the effect of phosphorus application on characteristics of the aerial and underground plant parts of different varieties of pea and elements of their yield structure. The study showed that a higher phosphorus application rate led to significant intensification of photosynthesis and thus to more rapid vegetative development in the plants, manifested as a greater number of leaves and greater leaf area. The higher rate of phosphorus application significantly influenced the flowering process of pea during soil drought. The number of flowering nodes increased significantly as phosphorus application increased. The plants fertilized with the higher level of phosphorus produced a greater weight of root nodules with more *Rhizobium* bacterial colonies. Increased phosphorus fertilization had a significant role during the year of permanent semi-drought, 2012, resulting in a significantly greater number and weight of pods as well as a greater number and weight of seeds per plant, and thus a larger final yield.

Keywords

growth stages; aridity index; soil drought; yield; phosphorus

Introduction

The growing global demand for pulses in recent years is believed to be the direct result of the growing trend towards healthy food. For this reason, 2016 has been declared the International Year of Pulses [1]. Pulses are a source of protein (<20%), fiber, vitamins, and minerals [2]. The global harvested area of pulses is 78 million ha [3]. The greatest production of pulse crops (70%) is in India, China, and Africa [3,4]. A factor severely limiting the production of pulse crops is water, as pointed out by Peterson et al. [5] and Namugwanya et al. [6]. A lack of stability of pulse yields is observed not only on dry continents, but in recent years also in the temperate climate conditions characteristic of Europe [7]. Zając et al. [8] and Dacko et al. [9] have shown that weather conditions in Poland are a significant predictor of the number of fruiting nodes and of seed weight per pod. Recent years have seen a continual rise in temperatures in Central Europe, which has necessitated new research on cultivation of pulse crops.

Adaptation of pulse plants to cope with drought has long been analyzed by many groups of researchers around the world. Levitt [10] distinguished morphological traits of pulse plants whose plasticity allows the plant to adapt in order to cope with drought. The author shows that adaptation of the aerial and underground morphological traits is the most fundamental element of the strategy. The root characteristics enumerated by the author include: (***i***) rooting depth, (***ii***) root length density, (***iii***) root hydraulic conductivity, and (***iv***) scope for genetic improvement, while the morphological traits of aerial parts are: (***i***) canopy structure, (***ii***) leaf movements, (***iii***) leaf surface characteristics, and (***iv***) stomatal and cuticular characteristics. Moreover, the author pointed out a significant role of physiology in adaptation to stress conditions. A more comprehensive approach was initiated by Subbarao et al. [11] who found that consideration of individual morphological characteristics or physiological processes is not able to improve yield in new varieties of pulse crops in soil drought conditions. Bargaz et al. [12] report that visible progress in adaptation of pulse plants to limited drought stress involves multigene-controlled traits. Due to the growing trend in Europe towards promotion of pulse crops in sustainable agriculture, different methods of raising the tolerance of plants to drought stress, not necessarily leading to genomic changes, are continually sought [13].

Selection response has an important role in adaptation of plants to stress conditions. An example of this trend is the change in the canopy structure of the pea plant, in which the leaves have become transformed into tendrils [14]. Agronomists and physiologists are promoting a different approach, arguing that phosphorus content in the soil plays a significant role in raising tolerance for a temporary lack of water in the soil [15]. Zheng et al. [16] demonstrated that an increase in the phosphorus application rate is the most efficient strategy for raising soybean yield in the conditions of permanent soil drought observed in northeastern China. However, the authors indicate that phosphorus application is determined regionally by the soil content of phosphorus, which is commonly understood around the world.

In terms of development and productivity, pulse crops have varying responses to fertilization with phosphorus. According to Chaves et al. [17], phosphorus uptake increases the development of the root system of bean at the seedling stage, which significantly improves resistance to dry soil conditions. Similar results were obtained by Garg et al. [18], Jones et al. [19], and Jin et al. [20], who showed that application of phosphorus to soybean (*Glycine max*) and barley increases root mass development and accelerates ripening of the plants. For this reason, an adequate level of applied phosphorus leads to earlier plant ripeness prior to the onset of soil drought.

The literature currently contains few studies on the effects of phosphorus on minimizing the impact of temporary semi-drought and drought during the flowering and ripening stages of pea. The aim of the study was to assess the effect of phosphorus fertilization on characteristics of aerial and underground plant parts and components of the seed yield structure.

Material and methods

Study conditions

A 2-year field experiment (2011–2012) was conducted on brown, good wheat complex soil. The soil characteristics were as follows: C-org 1.02 %, N-org 0.09 %, pH 5.2, content of P_2O_5 9.3 mg 100 g^{-1}, K_2O 12.8 mg 100 g^{-1}, Mg 9.7 mg 100 g^{-1}. A two-factor field experiment was set up as a randomized block design. The first factor was the level of phosphorus application (P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}) and the second factor was the variety. We compared six varieties of pea, including three forage varieties, i.e., 'Klif' (KLI), 'Milwa' (MIL), and 'Muza' (MUZ), and three multipurpose edible varieties – 'Batuta' (BAT), 'Bohun' (BOH), and 'Tarchalska' (TAR). The forecrop each year was maize. Field work was conducted according to agricultural standards. Before sowing, mineral fertilizers were applied and the soil was treated with a cultivator. N was applied at the starter rate of 30 kg ha^{-1} as well as 100 kg of potassium and two levels of phosphorus (P1 – 70 kg ha^{-1} and

P2 – 140 kg ha^{-1}). Sowing was carried out in the first 10 days of April with a seed drill, with 15 cm row spacing. Chemical protection was applied during the vegetative period. Weed control was carried out three times, using Fusilade forte 150 EC at 2.5 L ha^{-1} and Basagran 480 SL at 3 L ha^{-1}. Talstar 100 EC at 0.2 L ha^{-1} was applied against the pea aphid (*Acyrthosiphon pisum*).

Sowing was carried out in the first 10 days of April and harvest time depended on weather conditions. It was earlier in 2011 (5 August), and delayed in 2012 (10 August).

During the flowering stage, five plants were collected from each plot for measurement of biometric characteristics: fresh weight of the stem (g), number of leaves, leaf area (cm^{-2}), and number of flowering nodes. During this phase, the root mass was collected by the spade method from the topsoil (to a depth of 30 cm) to determine the dry weight of the roots (g) and the dry weight of the root nodules (g).

From each plant, four root nodules were collected at random and then washed under running water. The root nodules were sterilized for 2 min in sodium hypochlorite (NaOCl) and for 1 min in 70% ethanol and then washed four times with sterile distilled water. After sterilization, each root nodule was crushed with a sterile glass stick in 1 mL of saline solution (0.85% NaCl) and shaken in a Petri dish for 15 minutes. *Rhizobium* spp. colonies were isolated using YEM (yeast extract mannitol). The culture was grown at 28°C for 5 days. After the incubation period, the number of colony-forming units (CFU) per nodule was determined. The results were presented as the mean for the nodules.

During the fully ripe stage, five plants were collected from each plot for determination of yield structure characteristics. The number of pods, number of seeds per plant, seed weight, and seed yield were analyzed.

Statistical analysis

The results of the study were analyzed statistically by analysis of variance (STATISTICA 10.0 software, StatSoft Inc.). Homogeneous groups were determined by Tukey's test at a significance level of $\alpha = 0.05$.

Weather conditions

We used meteorological data from the IMGW (Institute of Meteorology and Water Management) station in Krakow-Balice from the years 2011 and 2012 and values for the mean monthly air temperature and precipitation sum from 1981–2010. The data were used to calculate the aridity index A [21].

The index is calculated by the following formula: $A = (T_i - T) / Sdt - (P_i - P) / Sdp$, where: T_i – mean monthly air temperature in successive years, P_i – monthly precipitation sum in successive years, T – mean long-term air temperature, P – mean long-term precipitation sum, Sdt – standard deviation of mean monthly air temperature, Sdp – standard deviation of monthly precipitation sum.

The A index has a positive value in dry periods. This is due to positive anomalies in air temperature and negative anomalies in monthly precipitation sums. Analogously, negative values for the index will be the consequence of a negative anomaly in the mean monthly temperature sum and a positive anomaly in the precipitation sums.

We considered a moderately dry period to be indicated by a value of A > 1, a dry period by A > 2, a very dry period by A > 3, a wet period by A < −2, and a very wet period by A < −3. A value between −1 and +1 can be considered to indicate conditions close to normal, while 0 indicates average values (temperature and precipitation not deviating from the 30-year norm).

Daily maximum and minimum temperatures, daily precipitation sums, and the dates of phenophases were used to characterize the course of temperature and rainfall conditions during the growing period of pea in the years 2011 and 2012 (Fig. 1).

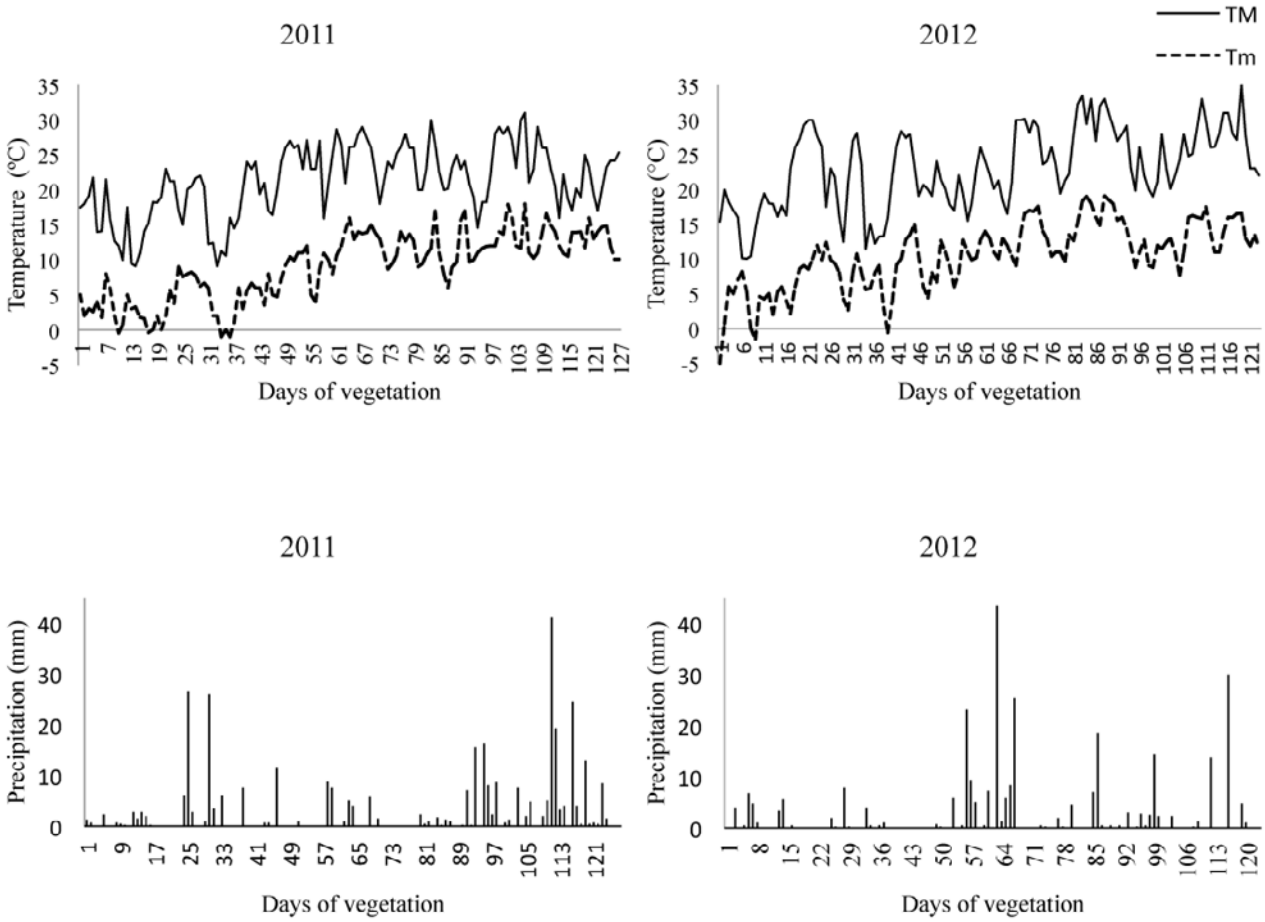

Fig. 1 Maximum (T_M) and minimum (T_m) temperatures and rainfall during pea growth in 2011 and 2012.

Results

On the basis of the mean monthly air temperature, precipitation sum and calculated A index, differences in meteorological conditions for pea growth can be seen for the 2 years (Tab. 1). June 2011 was very dry and warm (A = 2.5). In the second year (2012), due to light frost and precipitation, sowing was carried out later, on 10 April (Tab. 2). In May of that year, due to relatively high temperatures and low rainfall, severe soil drought was observed (A = 2.2, which means dry conditions). During the flowering stage, which began at the beginning of June, first there was rainfall (which probably delayed and prolonged this stage), but in the later period of the flowering stage it was sunny and warm.

The pod-forming period in the first year (2011) was longer than in the second year, because it was very rainy in July (A = –3.1). The temperature and rainfall conditions during pod-forming were much more beneficial in 2012, but less favorable conditions during the bud-forming period resulted in fewer flowers and thus fewer pods.

Tab. 1 The course of weather conditions during the years of the study.

Meteorological elements		April	May	June	July	August
Mean precipitation (mm)	1981–2010	46.0	81.0	87.0	88.0	77.0
	2011	77.0	49.0	32.0	192.0	65.0
	2012	49.0	17.5	143.8	70.6	54.6
Mean temperature (°C)	1981–2010	8.7	14.0	16.8	18.8	18.2
	2011	10.4	13.6	18.2	17.5	18.9
	2012	9.8	15.1	18.0	20.3	18.9
A index	2011	−0.1	0.4	2.5	−3.1	0.8
	2012	0.6	2.2	−0.5	1.3	1.1

Tab. 2 Phenological stages of pea during the growing seasons.

Growth stages	2011	2012
Emergence	20.04	28.04
Plant growth	up to 22.05	up to 20.05
Bud forming	27.05	25.05
Flowering	05.06 – 16.06	02.06 – 15.06
Fully ripe	10.08	30.07

The statistical analysis showed that the weather strongly influenced the morphological characteristics of the pea plants during the flowering stage (Tab. 3). The shoot weight, leaf number and total leaf area, and number of fruiting nodes were significantly greater in 2011. A greater stem weight, leaf number, and total leaf area were obtained by the edible varieties, while these values for the forage varieties were lower. Among the edible varieties of pea, 'Tarchalska' had a significantly higher number of leaves and 'Bohun' the lowest total leaf area. Among the forage varieties, 'Klif' had the greatest weight of shoot and leaves. Leaf area was significantly influenced by the interaction of years, fertilization, and variety (Fig. 2). The forage varieties responded to the higher rate of phosphorus application with an increased leaf area in the conditions of temporary soil drought and semi-drought (2012). The edible varieties responded differently during the 2 years of the study. The 'Bohun' exhibited a significant increase in leaf area following application of the higher level of phosphorus, while the 'Tarchalska' in the conditions of standard application of phosphorus. The number of fruiting nodes on the fruiting part of the stem was significantly different in the 2 years and was significantly increased by phosphorus application. Significantly more flowers were observed in 2011, despite the soil drought occurring during the flowering stage. The water shortage during the bud-forming stage in 2012 proved to be very significant, leading to a significant decrease in the number of fruiting nodes and a shortening of the flowering stage. The study showed that the increase in phosphorus application significantly increased the number of flowering nodes on the plant. The edible varieties had significantly more fruiting nodes. Despite the significant differentiation in the main effects, no significant interactions were found for the factors tested.

Tab. 3 Selected morphological characteristics of pea during the flowering stage.

Factor		Fresh weight of shoot (g)	Number of leaves (pc)	Leaf area (cm²)	Number of fruiting nodes (pc)
Year (Y)	2011	34.38 a	16.20 a	297.80 a	4.96 a
	2012	31.70 a	13.00 b	193.60 b	3.71 b
Variety (V)	BAT	35.30 ab	14.80 a	299.10 b	4.25 ab
	BOH	31.06 ab	13.40 a	196.20 a	4.85 a
	KLI	37.52 b	14.40 a	224.20 a	4.35 ab
	MIL	27.97 ab	12.90 a	199.60 a	4.30 ab
	MUZ	26.92 a	11.70 a	226.80 a	4.00 b
	TAR	34.87 ab	18.30 b	307.40 b	5.00 a
Phosphorus (P) application	P1 §	31.00 a	13.90 a	237.60 a	4.12 a
	P2	35.07 a	15.20 a	253.80 b	4.55 b
Y × V		0.09 ns	0.04*	0.000*	0.06 ns
Y × P		0.377 ns	0.32 ns	0.948 ns	0.60 ns
V × P		0.154 ns	0.17 ns	0.000*	0.39 ns
Y × V × P		0.169 ns	0.53 ns	0.000*	0.76 ns

* Significant at 0.05 probability level; ns – not significant. Mean values with different letters denote a significant probability at 5% according to Tukey's test. § P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}.

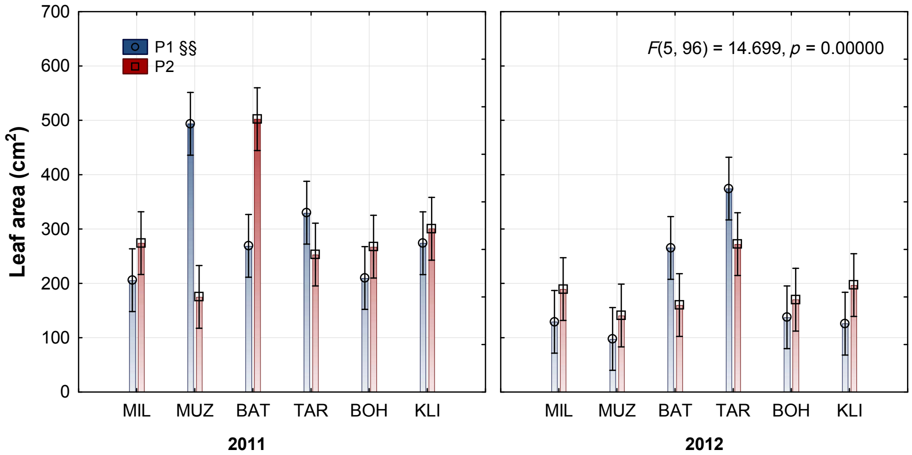

Fig. 2 The effect of the interaction of year, fertilization and variety on the leaf area of the pea plants. §§ P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}. Bars mean ±*SD* (ANOVA, Tukey's test at 0.05 level).

The dry weight of root nodules was significantly influenced only by the level of phosphorus application (Tab. 4). Increased phosphorus application significantly reduced the dry weight of root nodules. The study showed significantly larger variation between varieties in the number of *Rhizobium* colonies formed in the root nodules of the plants. Significantly more bacterial colonies were formed both by the forage ('Muza', 'Klif') varieties and edible ('Bohun', 'Batuta') pea varieties. The most colonies were formed by the forage variety 'Muza'. Moreover, the interaction of year and phosphorus application significantly affected the number of *Rhizobium* colony-forming

Tab. 4 Dry weight of root nodules, weight of roots, and mean number of colony-forming units per nodule.

Factor		Dry weight of root nodules (g)	Number of CFU/ nodule	Number of CFU	Weight of roots (g)
Year (Y)	2011	0.07 a	44.80 a	89.60 a	0.55 a
	2012	0.05 a	38.80 b	77.10 b	0.51 a
Variety (V)	BAT	0.06 a	33.20 d	66.60 d	0.44 b
	BOH	0.10 a	50.80 b	101.70 b	0.56 ab
	KLI	0.10 a	40.40 c	80.80 c	0.77 a
	MIL	0.04 a	29.60 e	59.80 e	0.49 b
	MUZ	0.02 a	74.00 a	145.20 a	0.46 b
	TAR	0.05 a	23.20 f	45.80 f	0.49 b
Phosphorus (P) application	P1 §	0.08 a	40.40 a	79.60 a	0.49 a
	P2	0.04 b	43.40 b	87.00 b	0.57 a
Y × V		0.99 ns	0.00**	0.00**	0.47 ns
Y × P		0.43 ns	0.00**	0.00**	0.54 ns
V × P		0.44 ns	0.00**	0.00**	0.67 ns
Y × V × P		0.99 ns	0.00**	0.00**	0.80 ns

** Significant at 0.01 probability level; ns – not significant. Mean values with different letters denote a significant probability at 5% according to Tukey's test. § P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}.

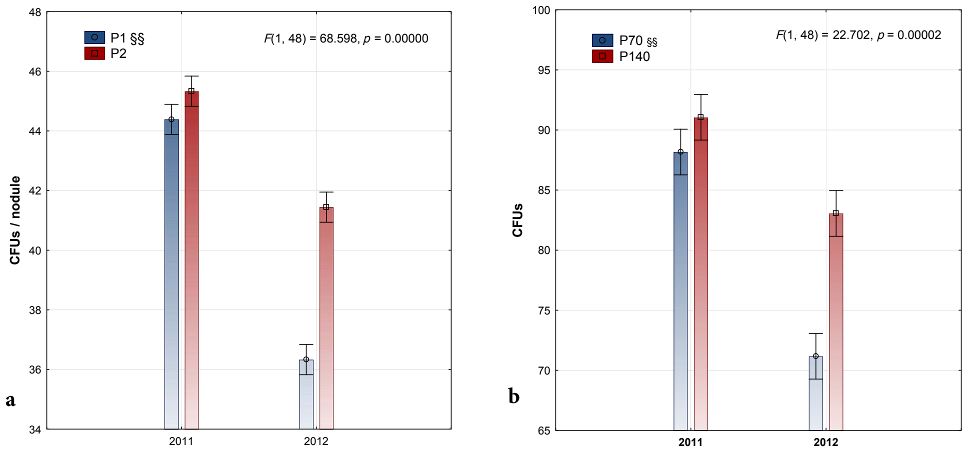

Fig. 3 Effect of interaction of year and phosphorus application on the number of CFU / root nodule (**a**) and number of CFU (**b**). §§ P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}. Bars mean ±*SD* (ANOVA, Tukey's test at 0.05 level).

units in the nodules. Significantly more bacterial colonies were formed by nodules in 2011 following phosphorus application at the higher rate (Fig. 3a,b). The dry weight of the roots was significantly differentiated by the variety. A significantly greater root weight was produced by the 'Klif' variety. However, no significant effect of phosphorus application was found on the dry weight of the pea roots.

The statistical analysis showed that all the factors analyzed had a significant effect on biometric parameters during the ripening stage (Tab. 5). The temporary soil drought in the years 2011–2012 significantly affected yield parameters. A more negative impact of the drought was observed in 2012. The study showed that increased

Tab. 5 Selected characteristics of elements of the seed yield structure of pea at the fully ripe stage.

Factor		Number of pods (pc)	Number of seeds per plant (pc)	Weight of seeds (g)	Yield (t ha^{-1})
Year (Y)	2011	7.50 a	33.80 a	9.25 a	3.43 a
	2012	5.71 b	28.80 b	6.81 b	2.55 b
Variety (V)	BAT	6.55 bc	34.10 abc	8.86 bc	3.42 b
	BOH	7.05 bc	36.10 bc	8.33 bc	3.32 b
	KLI	6.30 abc	30.30 ab	7.58 ab	2.71 bc
	MIL	4.95 a	26.10 a	6.19 a	2.11 c
	MUZ	5.95 ab	30.50 ab	7.41 ab	2.14 c
	TAR	7.50 b	41.50 c	9.79 c	4.23 a
Phosphorus (P) application	P1 §	5.95 a	29.68 a	8.16 a	2.72 a
	P2	6.81 b	33.00 b	7.89 a	3.26 b
Y × V		0.71 ns	0.158 ns	0.00*	0.53 ns
Y × P		0.02*	0.000*	0.015*	0.00*
V × P		0.32 ns	0.015*	0.00*	0.067 ns
Y × V × P		0.53 ns	0.302 ns	0.600 ns	0.51 ns

* Significant at 0.05 probability level; ns – not significant. Mean values with different letters denote a significant probability at 5% according to Tukey's test. § P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}.

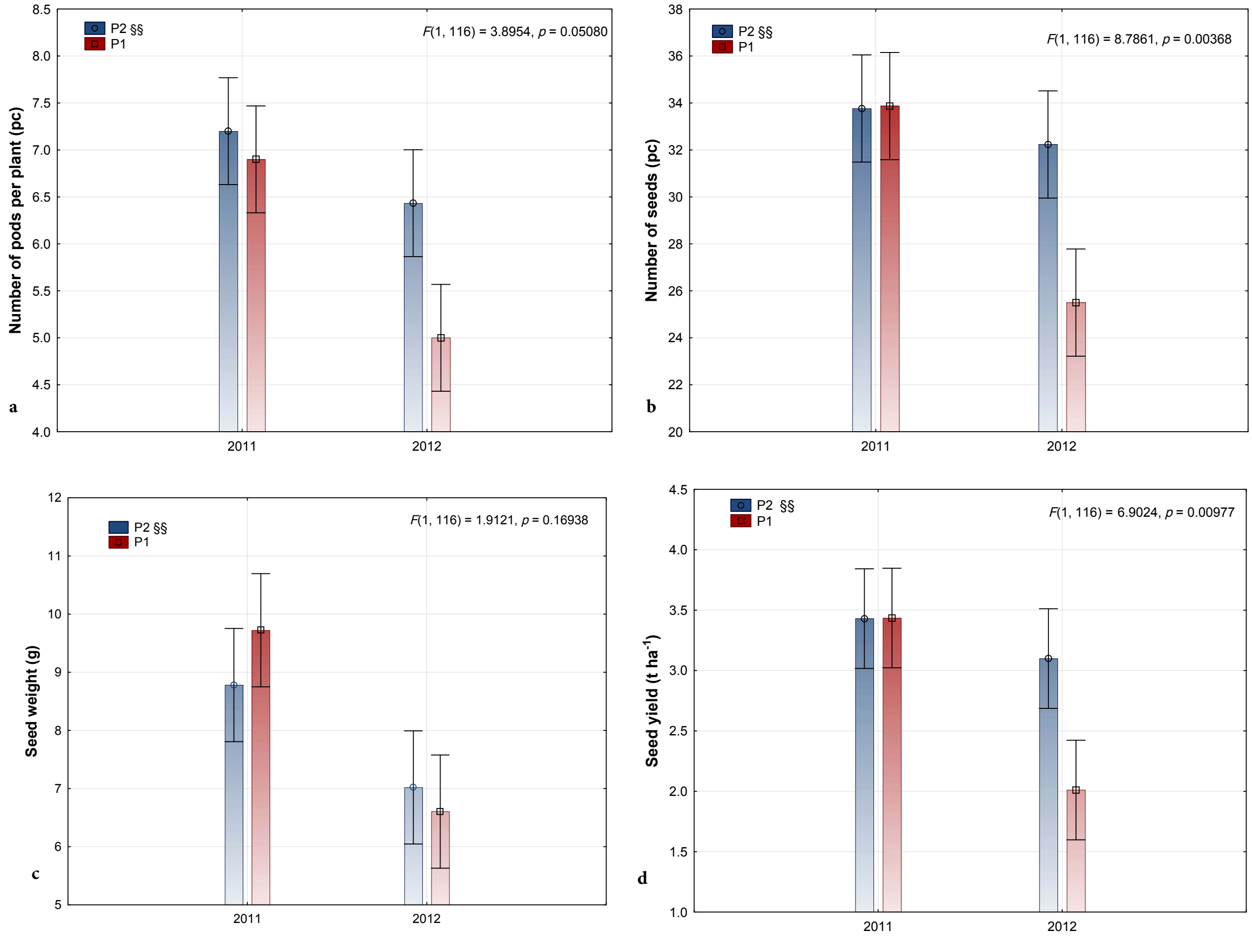

Fig. 4 Effect of interaction of year and fertilization on the number of pods (**a**), number of seeds (**b**), seed weight (**c**), and seed yield (**d**). §§ P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}. Bars mean ±*SD* (ANOVA, Tukey's test at 0.05 level).

application of phosphorus had a significant effect on pea yield parameters. The higher level of applied phosphorus significantly increased the number of pods per plant, the number of seeds per plant, and the seed yield. The greatest number of pods was formed by the edible 'Trachalska' variety, while among the forage varieties by 'Klif'.

In 2012 more pods were obtained following application of the higher level of phosphorus (Fig. 4a). Similar changes were noted for the number of seeds per plant (Fig. 4b). Significantly more seeds were obtained in 2011, regardless of applied phosphorus. The number of seeds produced by the edible varieties significantly increased with increased phosphorus, while the forage varieties 'Milva' and 'Muza' responded with an increased number of seeds under lower phosphorus application (Fig. 5a). The seed weight varied between the 2 years. A significantly greater seed weight was obtained in 2011 (Tab. 5). A significantly greater seed weight was observed in the edible varieties. Significantly greater seed weights were obtained with the lower levels of phosphorus. A significant interaction between years and fertilization on seed weight was observed (Fig. 4c). In 2011 a greater seed weight was obtained with the lower level of phosphorus, while in 2012 the increased application rate significantly increased the seed weight. The seed weight of the edible varieties significantly increased with the level of phosphorus applied (Fig. 5).

Pea yield significantly and strongly varied between the 2 years (Tab. 5). Pea yield was significantly higher in 2011. In 2011, with moderate temperature distribution and temporary drought during the flowering stage, no variation in pea yield was observed. In contrast, in 2012, when soil drought was observed during the bud-forming stage and semi-drought in the subsequent developmental stages, a significant increase in yield was obtained following application of the higher level of phosphorus (Fig. 4d).

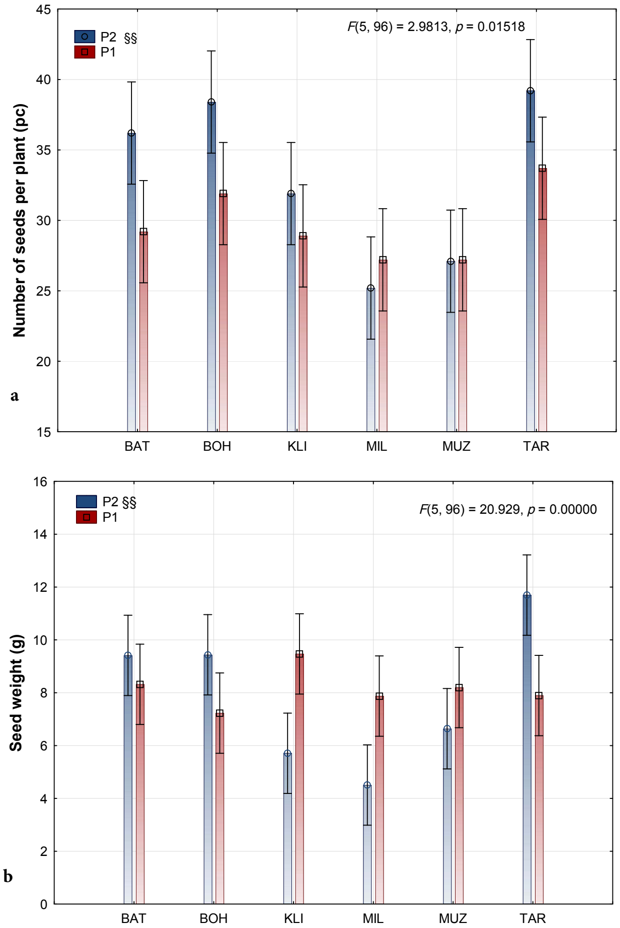

Fig. 5 Effect of interaction of varieties and phosphorus application on the number of seeds (**a**) and seed weight (**b**). §§ P1 – the optimum application rate for pea 70 kg ha^{-1} and P2 – 140 kg ha^{-1}. Bars mean ±*SD* (ANOVA, Tukey's test at 0.05 level).

Discussion

Differentiation in morphological and developmental characteristics between varieties was affected by weather conditions, phosphorus application, and genetic determinants of the varieties, representing edible or forage types.

Analysis of the development of the vegetative parts of the plants revealed a positive effect of increased phosphorus application on biometric parameters. This factor had a particularly beneficial effect on the number of leaves and their area. The plants fertilized with the higher level of phosphorus (140 kg P ha^{-1}) attained a much greater number of leaves, which they maintained until the end of the growing period. The plants with a lower supply of phosphorus in the soil developed less dynamically and produced less abundant leaves, despite having a better habit, particularly in the initial stages of development. This is confirmed in a study on lentil plants by Sarker and Karmoker [22], who found that phosphorus deficiency decreases accumulation of reducing sugars in the leaves and stems. Grzebisz [23] pointed out that good phosphorus supply to plants is manifested as increased content of structural constituents – mainly lignin – in the plant stems. The author reported that plants fertilized with higher levels of phosphorus developed a more efficient assimilation apparatus, with more leaves and greater leaf mass on single stems. Many authors [24–26] suggest that the intensity of photosynthesis is reduced by phosphorus deficiency. Podsiadło [27] demonstrated an increase in the photosynthesis rate as a result of application of a high level of phosphorus. Olszewski [28] showed that reducing the application of phosphorus by half led to a reduction in absorption of CO_2 from about 3 μmol CO_2 m^{-2} s^{-1} to about 2 μmol CO_2 m^{-2} s^{-1}. Grzebisz [23] states that phosphorus deficiency causes older leaves to dry out more quickly and in consequence to fall prematurely. In our experiment, considerably fewer leaves were observed on the pea plants fertilized with the lower level of phosphorus (70 kg P ha^{-1}).

Dacko et al. [9] showed that weather conditions strongly influence the number of fruiting nodes formed by a single pea plant. Our study confirmed that temporary soil drought during the bud-forming stage has a significant effect on the number of fruiting nodes per stem. The drought had a significant impact in the bud-forming stage, significantly reducing the number of flowers formed. Daryanto et al. [29] found that soil drought has a more negative impact on the yield of pulse crops during the period of inflorescence emergence and flowering than during leaf development or ripening of fruit and seeds. Farooq et al. [30] showed that drought during the period when the first true leaves are formed is better tolerated even if it leads to shortening of cells and tissues. Daryanto et al. [29] found that soil drought occurring during the flowering period is more harmful than drought in the later period of development. Drought during the flowering stage limits the quantity of assimilates flowing to the forming seeds. Moreover, Farooq et al. [30] showed that during the grain-filling period the occurrence of drought significantly limits the quantity of assimilates needed for synthesis of starch, which leads to small seed size.

Chaves et al. [17] demonstrated that resistance of common bean to soil drought was determined by the availability of phosphorus in the soil. Greater phosphorus uptake (140 kg P ha^{-1}) in the juvenile stage of plant development increased the development of roots and improved the fitness for the subsequent water shortage in soil. In our own study we observed a significant increase in the dry weight of roots following the higher level of phosphorus application. Substantial variation was observed between varieties, as the forage variety 'Klif' and the edible variety 'Bohun' produced a significantly greater root weight. The substantial root weight observed in the 'Klif' forage variety led to a significantly larger number of pods, number of seeds and seed weight than in the other forage varieties. The 'Bohun' variety, despite producing the greatest root weight among the edible varieties, did not display a significant increase in the elements of the yield structure.

Garg et al. [18], Jones et al. [19], and Jin et al. [20] demonstrated that phosphorus increased the weight of the root system of barley and soybean in the seedling stage, which resulted in acceleration of full ripeness in the plants ahead of the onset of the summer soil drought. Our study showed no differentiation in root weight in the 2 years of the study, but the ripening period was shorter in the dry year – 2012.

Analysis of the development of the generative parts of the plant showed that increasing the application of phosphorus significantly affected yield structure parameters.

Grzebisz [23] points out that the yield-increasing functions of phosphorus are multifaceted and involve contributing to intensive vegetative and generative development in plants, manifested as a greater number of seeds formed. In particular, 19% more seeds were obtained from plants intensively fertilized with phosphorus. The author draws attention to the complexity of physiological processes determining the positive effect of phosphorus on yield. According to Mimura [31], uptake of phosphorus by the roots is crucial to the growth and yield of crop plants.

Leoport et al. [32] and Fang et al. [33] demonstrated that soil drought during the flowering period or the grain-filling period has a significant negative effect on the final seed yield. In our study, drought during the bud-forming period had a negative impact on parameters of the yield structure. A decrease was observed in the number of pods, number of seeds, and seed weight, resulting in reduced yield. Dacko et al. [9] showed that in optimal weather conditions pod length and seed weight are stabilized. Our study showed that phosphorus significantly minimized the consequences of the temporary soil drought and semi-drought for the yield structure. A significant interaction of year and fertilization was observed. In the year with moderate amounts of precipitation, but with drought during the flowering period, a greater seed weight was obtained with the lower level of phosphorus, while in the year with temporary soil drought and semi-drought (2012), increasing phosphorus application significantly increased the seed weight. The seed weight of the edible varieties significantly increased with the increased phosphorus application.

Studying the effect of soil content of available forms of macroelements on pea yield, Jaskulska et al. [34] showed that fertilization had a substantial effect on soil properties and thus on seed yield. The authors of this study found considerable variation in the number of pods per plant and seed weight per plant as a result of different soil properties. In their opinion, this phenomenon is explained mainly by changes in soil properties due to long-term fertilization. Therefore, it is likely that the change in weather conditions in Central Europe will lead to a revision of current fertilization standards, particularly for pulse crops.

Conclusions

The differences in the dynamics of plant development observed between varieties were largely the effect of genetic determinants. The varieties responded very differently to increased application of phosphorus. The edible varieties responded with a significant increase in seed weight as phosphorus application increased, while the forage varieties had a reverse reaction. The study showed that the higher phosphorus application rate led to more rapid vegetative development in the plants, manifested primarily as an increase in the number of leaves and their area. Drought during the bud-forming stage in 2012 had a significantly more negative effect on the number of flowers formed in comparison with drought during the flowering stage (2011). The higher level of phosphorus (140 kg) significantly reduced the negative effects of the temporary soil drought by significantly increasing the number of flowering nodes. The plants fertilized with a higher level of phosphorus produced a greater weight of root nodules with a greater number of *Rhizobium* bacterial colonies. Higher phosphorus application significantly affected yield structure parameters in the year with permanent semidrought (2012). Increased phosphorus application led to a significant increase in the number and weight of pods, and also increased the number and weight of seeds per plant and thus the final yield.

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Reakcja rozwojowa i produkcyjna odmian jadalnych i pastewnych grochu (*Pisum sativum* L.) na okresowy stres suszy w warunkach zróżnicowanego nawożenia fosforem

Streszczenie

Obserwowana zmiana warunków pogodowych w Centralnej Europie przyczynia się do potrzeby zweryfikowania obecnie przyjętych standardów nawożenia roślin strączkowych.

Fizjolodzy twierdzą, że fosfor może odgrywać istotną rolę w podnoszeniu tolerancji na okresowy brak wody w glebie. Celem dwuletnich badań polowych (2011–2012) była ocena wpływu nawożenia fosforem na kształtowanie się cech nad- i podziemnej części roślin oraz elementów struktury plonu różnych odmian grochu. W badaniach wykazano, że większa dawka fosforu istotnie wpłynęła na szybszy i intensywniejszy rozwój wegetatywny roślin, przejawiający się większą liczbą liści i ich powierzchnią. Większa dawka fosforu miała istotny wpływ na proces kwitnienia grochu siewnego w fazie suszy. Wraz ze wzrostem nawożenia fosforem istotnie zwiększyła się ilość kwitnących pięter. Rośliny nawożone wyższymi dawkami fosforu wykształcały, większą masę brodawek o większej liczbie kolonii bakterii *Rhizobium*. Intensyfikacja nawożenia fosforem miała istotne znaczenie w roku permanentnej suszy – 2012. Wyższe dawki fosforu wpływały na istotnie większą liczbę i masą strąków oraz wzrost liczby i masy nasion uzyskanych z poszczególnych roślin, wpływając istotnie na wzrost plonu.