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ORIGINAL RESEARCH PAPER

The value of different vegetative indices (NDVI, GAI) for the assessment of yield potential of pea (*Pisum sativum* L.) at different growth stages and under varying management practices

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Abstract

This research evaluated the NDVI (normalized difference vegetation index) and GAI (green area index) in order to indicate the productivity and developmental effects of *Rhizobium inoculants* and microelement foliar fertilizer on pea crops. Two inoculants, Nitragina (a commercial inoculant) and IUNG (a noncommercial inoculant gel) and a foliar fertilizer (Photrel) were studied over a 4-year period, 2009–2012. The cultivars chosen for the studies were characterized by different foliage types, namely a semileafless pea 'Tarchalska' and one with regular foliage, 'Klif'. Foliar fertilizer significantly increased the length of the generative shoots and the number of fruiting nodes in comparison to the control, which in turn had a negative impact on the harvest index. Pea seed yield was highly dependent on the interaction between the years of growth and the microbial inoculant, and was greater for 'Tarchalska' (4.33 t ha^{-1}). Presowing inoculation of seeds and foliar fertilization resulted in a significantly higher value of GAI at the flowering (3.91 and 3.81, respectively) and maturity stages (4.82 and 4.77, respectively), whereas the value of NDVI was higher for these treatments only at the maturity stage (0.67 and 0.79, respectively). A significantly greater yield (5.0–5.4 t ha^{-1}) was obtained after inoculation with IUNG during the dry years.

Keywords

yield components; green area index; normalized difference vegetation index; inoculation

Introduction

Nodulation and nitrogen fixation of legumes are very important processes in natural ecosystems, agriculture, and hence the global circulation of nitrogen [1]. Leguminous plants are cultivated on approximately 12–15% of the world's arable lands, constituting about 25% of basic plant production and they provide 200 million tons of nitrogen a year [2]. In many regions, pea is an important food source for man and fodder for animals. Thus, new and more productive cultivars of pea species are constantly being developed. Next to the obvious potential of those with increased yields, it is crucial to understand the interaction between the pea plant (host) and rhizobia and its impact on yield. Zając et al. [3] have shown no effect of the inoculant Nitragina on the yield of pea seeds, indicating that weather conditions (notably observed drought or hydration) have a strong influence on lowering or raising the activity of the bacterial inoculants used. Furthermore, Cerezini et al. [4] showed that "the co-inoculation *Bradrizobium* with *Azospirillum* increased the soybean nodulation at early developmental stages and resulted in higher shoot N accumulation and plant growth, especially under drought". Environmental stresses (particularly water shortage) can impose limitations on a plant's ability to achieve its maximum yield potential [5]. Dry conditions and high temperatures impede plant growth and development by adversely affecting transpiration and nutrient uptake [6]. The consequences of stressful growing conditions are a change of plant metabolism and so a reduction in plant productivity [7,8]. Remote sensing techniques provide a platform from which plant stress and growth responses can be evaluated. The use of vegetative indices allows users to identify differences in changes in canopy characteristics [9,10] and to evaluate green leaf biomass and grain yield [11,12]. According to Jensen [13] and Pedroni [14], vegetation indices (especially normalized difference vegetation index – NDVI) are closely correlated with leaf area and photosynthetic activity. These authors claim that such indices are able to identify plant growing conditions, physiological state, and yield potential. Indices are sensitive to changes in plant biomass, vigor, and leaf size, which vary depending on crop types. The NDVI values of crops, as well as changes during the growing season, thus indirectly measure crop health and growing conditions. Zając et al. [3] have shown that the NDVI and GAI (green area index) indices are important in assessing the pea crop, especially in the phase of flowering and ripening, but have a minor importance in the early stages of plant growth. These authors showed that the bacterial inoculant increases the value of NDVI and GAI, as compared to controls, indicating a useful value of these indicators in assessing the impact of inoculants on biomass and crop yield. Similar results were obtained by Ali et al. [15] and Malik et al. [16], demonstrating that bacterial inoculants with rhizobia significantly increase the value of LAI (leaf area index), total dry matter and the HI (harvest index) in soybean plants.

In recent years, there has been an increase in awareness of the role of legumes and bacterial inocula in the protection of the environment as one of the techniques for a sustainable agriculture [17]. Therefore, research is ongoing for new, more effective cultivars of leguminous plants, not only in terms of productivity, but for those with a higher biological activity, especially under abiotic stress. Sulieman and Phan Tran [18] and Zhukov et al. [19] suggest that there is a significant potential for new pea genotypes to increase the effectiveness of nitrogen fixation through an increased activity of rhizobial associates. The improvement of nitrogen fixation is based not only on the creation of new genotypes, but also on the selection of new rhizobial strains. Belachew and Pant [20] have indicated that in unsterilized soil conditions, the interaction of pea cultivars and native strains significantly affected the nodulation processes. In comparison to native strains, which have greater adaptation capacities, the selected rhizobial strains introduced into soil or onto seeds have a limited gene pool enabling them to adapt to different types of habitats conditions. Rhizobial strains introduced into soil should be more effective than native strains, i.e., they should develop more nodules and so be capable of fixing greater amounts of nitrogen. Such improved efficiency in terms of nitrogen fixation may be reached by selecting strains of *Rhizobium* displaying a more efficient nodulation process, manifested by a higher seed yield. The continued search for a more effective combination of plant (host) and the symbiotic *Rhizobium* genotype is a prerequisite for the development of techniques of sustainable agriculture [17]. Different plant species vary in the efficiency of their nodule formation and nitrogen fixation [19]. Belachew and Pant [20] pointed out that in unsterilized soil conditions inoculations significantly affected nodulation, whereas biomass yield was dependent on the pea cultivar. Such an approach makes it necessary to presow good strains of the *Rhizobium* into the soil environment as well as the application of microelement foliar fertilizers [21]. It is expected that the foliar application of microelements may reduce the level of environmental stress and improve the efficiency of nitrogen fixation, thereby increasing the physiological, morphological, and yield parameters of the plants.

The aim of the present research was (***i***) to investigate the effect of rhizobial inoculant and foliar micronutrient fertilization on morphological parameters, vegetative indices, and yields of different pea (*Pisum sativum* L.) cultivars and (***ii***) to study the relationship between yield and physiological indices at different growth stages.

Material and methods

Study site and the experiment methodology

A three-factor field experiment with a randomized block design was conducted in the years 2009–2012 at the experimental station located in Modzurów, Poland (50°09′ N, 18°07′ E), at an altitude of 274 m a.s.l. in the province of Silesia, a district of Racibórz. The soil type at the experimental field is a degraded chernozem, generated from loess and characterized by a high content of plant-available phosphorus, potassium, and magnesium.

Winter wheat was a precrop for pea during the years 2009–2012. A presowing fertilization with N, P, and K was applied at 20, 48, and 72 kg ha^{-1}, respectively, in the form of Polifoska (8-24-24) and potassium salt (57%). Seed sowing was carried out on the following dates: 2009 – April 16, 2010 – April 9, 2011 – April 4, 2012 – March 30. Plants were flowering on May 1, 2009, May 3, 2010, April 21, 2011, and April 17, 2012. Harvesting of mature plants was carried out on the following dates: 2009 – August 11, 2010 – August 6, 2011 – August 3, 2012 – July 25, using a Wintersteiger plot combine.

The experimental design consisted of 12 combinations of three factors. The first factor included two different cultivars of pea: a semileafless – 'Tarchalska', and one with regular foliage – 'Klif'. The second factor was inoculation of pea seeds before sowing, using formulations containing *Rhizobium legiminosarum*. There were two types of inoculants used: dry – a commercial product called Nitragina (BIOFOOD), and of a gel obtained from the Department of Agricultural Microbiology at the Institute of Soil Science and Plant Cultivation (IUNG), State Research Institute in Puławy (Poland), hereafter referred to as "IUNG". The third factor was micronutrient foliar fertilization, using Photrel fertilizer, hereafter referred to as "Photrel", which was applied at a rate of 3 L ha^{-1} after development of the first tendrils on the plants. Along with this fertilizer, 150 g ha^{-1} of boron, 210 g ha^{-1} of manganese, 12 g ha^{-1} of molybdenum, 400 g ha^{-1} of magnesium oxide, and 1,081 g ha^{-1} of sulfur trioxide were also added. The experiment was performed in triplicate. The row spacing adopted was 15 cm and the area of each plot harvested each year was 10 m^2.

Weed control was carried out annually by an application of clomazone linuron (96 g ha^{-1}), bentazone (1,344 g ha^{-1}), and MCPB (1,200 g ha^{-1}). Insecticides containing zeta-cypermethrin were applied for pest control (10 g ha^{-1}).

An Oyord plot drill was used each year for sowing the following amounts of seeds: 120 seeds m^{-2} of 'Tarchalska' and 100 seeds m^{-2} of 'Klif'. One day before sowing, the seeds were dressed with the fungicide Funaben T 75 DS/WS and inoculated with *Rhizobium* Nitragina or IUNG. A foliar application of Photrel fertilizer was made at the commencement of the plant budding stage (BBCH 51).

NDVI measurements were taken using a GreenSeeker Handheld Optical Sensor Unit (NTech Industries, Inc., USA) in the central rows of all plots of the 12 treatment plots. Measurements were made at two phases (***i***) the flowering phase (BBCH 60–69) and (***ii***) the flat-pod phase (BBCH 71–75) – fruit development,

The NDVI value can be calculated from reflectance measurements in the red and near infrared (NIR) portion of the spectrum. $NDVI = R_{\mathrm{NIR}} - R_{\mathrm{Red}} / R_{\mathrm{NIR}} + R_{\mathrm{Red}}$, where R_{NIR} is the reflectance of NIR radiation and R_{Red} the reflectance of visible red radiation. The NDVI values range from −1 to +1, so that the closer to 1, the greener is the vegetation. GAI measurements were taken with a Sunscan System (Delta-T) for all plots. Measurements of GAI, as for the case of NDVI, were carried out three times at each growth phase, i.e., the flowering phase (BBCH 60–69) and at the flat-pod phase (BBCH 71–75). At the flowering phase (BBCH 60–69), measurements of the density of generative shoots on an area of 1 m^2 were made. During the ripening phase, 15 plants were sampled from the plots for biometric analysis. These measurements involved 10 different traits for shoots (Tab. 1).

Weather conditions

During 4 years of the investigation, the agroclimatic conditions were unusual in that they were highly variable due to varied amounts of precipitation and air temperature

Tab. 1 Morphological characteristics of pea pants' traits (1–10) and lodging (11) according to cultivars, *Rhizobium* inoculant, and foliar fertilizer.

	Cultivar			*Rhizobium* inoculants				Foliar fertilizer		
Traits[a]	'Tarch-alska'	'Klif'	LSD	Control	Nitra-gina	IUNG	LSD	Without	Photrel	LSD
1	58.8	65.9	1.47*	62.4	62.4	62.4	NS	61.3	63.5	1.47*
2	23.4	22.5	NS	22.3	22.9	23.5	NS	21.8	24.1	1.67*
3	4.33	4.44	NS	4.27	4.38	4.49	NS	4.22	4.55	0.26*
4	7.38	7.19	NS	7.09	7.27	7.50	NS	7.17	7.40	NS
5	3.96	4.29	0.154*	4.05	4.13	4.19	NS	4.23	4.02	0.154*
6	28.9	31.1	2.09*	28.3	30.2	31.5	NS	30.4	29.6	NS
7	256.2	211.4	8.32**	235.2	230.1	237.0	NS	233.2	234.3	NS
8	7.37	6.65	0.548*	6.58	6.93	7.51	0.809*	7.06	6.95	NS
9	12.17	11.72	NS	11.30	11.90	12.64	1.18*	11.86	12.04	NS
10	0.599	0.547	0.016*	0.567	0.570	0.582	NS	0.581	0.565	0.016*
11	3.6	1.6	0.54**	2.65	2.75	2.6	NS	2.70	2.50	NS

* Significant at $p = 0.05$ probability level. ** Significant at $p = 0.01$ probability level. NS indicates statistically nonsignificant differences.
[a] Traits: 1 – height to first pod (cm); 2 – length of fruiting stem (cm); 3 – reproductive node per stem (pcs); 4 – pods per stem (pcs); 5 – seeds per pod (pcs); 6 – seeds per plant (pcs); 7 – mass of first seeds in pod (mg); 8 – seed mass per plant (g); 9 – shoot mass (g); 10 – harvest index (g g^{-1}); 11 – lodging at harvest (1–9 scale).

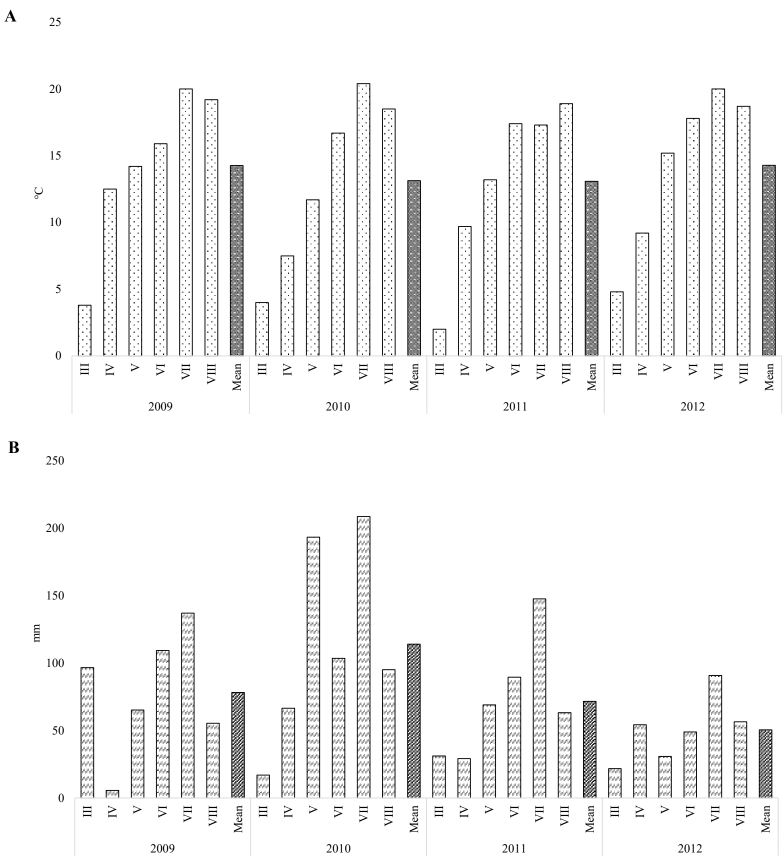

Fig. 1 Weather pattern during pea vegetation. (**A**) Temperature. (**B**) Precipitation.

in individual months (Fig. 1). Weather conditions in the first year of the research (2009) were exceptionally unfavorable due to heavy precipitation in March. In May, the weather was warm, which limited the degree of plant branching. The consecutive months of the vegetative phase (June and July) were relatively humid. On the other hand, 2010 was the most humid year of all in the 4-year period of investigation, mainly due to heavy precipitation in May and July (193 and 208 mm, respectively). In the following years, 2011 and 2012, lower amounts of precipitation were registered over the whole of the vegetative period, although in 2011 July was relatively wet (168 mm). The last year of the research, 2012, was warm, particularly in May and June, and this accelerated the growth of the pea crop. Consequently, full maturity was earlier and so the harvest took place in the third week of July.

Statistical analysis

Analysis of variance (ANOVA) was performed separately for each year for the individual experiments for the randomized block design using Statistica 12 software

(StatSoft, Poland). The significance of differences between means was tested using the LSD test at $p = 0.05$. A statistical analysis of lodging was performed on the transformed data (square root of $x+0.5$). The significance of differences between the groups was evaluated by means of the Scheffe test at a probability level of $p = 0.05$.

Results

Morphological characteristics and seed yield

Analysis indicated the low diversity of morphological characteristic between the two cultivars (Tab. 1). Both had a similar length of the fruiting stem ('Tarchalska' 23.4 cm, 'Klif' 22.5 cm, on average). However, the application of the foliar fertilizer Photrel significantly increased the mean height to the first pod by 2.2 cm and the length of the fruiting stem by 2.3 cm, and the number of reproductive nodes per stem by 0.33. A greater mean number of seeds per pod (4.29) and per plant (31.1) was obtained for 'Klif'. However, this pea morphotype developed seeds with a lower mean unit weight (211.4 mg) compared to 'Tarchalska' (256.2 mg); its yield from a single plant was therefore lower (6.65 g) compared to the latter cultivar (7.37 g) (Tab. 2).

Application of a bacterial inoculant (IUNG) considerably increased seed yield from a single plant by 14.1% and its total mass by 11.9% compared to the control. A lower yielding fraction (0.547) was observed in 'Klif'. The Photrel fertilizer also decreased this fraction (from 0.581 to 0.565), possibly due to the increase (by 2.3 cm) in the length of the pea stems, which slightly raised the weight of the vegetative parts. Nitragina exerted a weaker effect than did IUNG inoculation, for its application caused a slight increase in properties associated with pea yield.

Vegetative indicators

Statistical analysis highlighted the strong influence of growth year and the choice of cultivar on yield and both vegetative indicator values (Tab. 2). Presowing inoculation of

Tab. 2 Statistical analysis for pea seed yield and GAI, NDVI indicators.

Treatments	*df*	Seed yield (t ha^{-1})	GAI (cm^2 cm^{-2})		NDVI	
			BBCH 60–69	BBCH 71–75	BBCH 60–69	BBCH 71–75
Year (Y)	3	69.92**	9.558**	27.395**	0.247**	0.302**
Cultivar (C)	1	39.39**	20.608**	28.832**	0.383**	0.299**
Inoculation (I)	2	1.74**	1.206**	0.933**	0.0006	0.002**
Fertilization (F)	1	0.52	0.763**	1.472**	0.001	0.001*
C × I	2	0.04	0.011	0.062	0.0006	0.00007
C × F	1	0.16	0.367	0.025	0.0006	0.0003
Y × C	3	0.23	1.790**	1.234**	0.028**	0.004**
I × F	2	0.13	0.094	0.179	0.001	0.000007
Y × I	6	0.30*	0.135	0.072	0.0002	0.0003
Y × F	3	0.11	0.118	0.100	0.0001	0.0007*
C × I × F	2	0.31	0.561**	0.767*	0.001	0.002**
Y × C × I	6	0.23	0.169	0.204	0.001	0.0007**
Y × I × F	6	0.12	0.153	0.206	0.0008	0.0007**
Y × C × I × F	9	0.17	0.252*	0.447*	0.0004	0.001**

* Significant at $p = 0.05$ probability level. ** Significant at $p = 0.01$ probability level. NS indicates statistically nonsignificant differences.

pea seeds with different inoculants and foliar fertilization exerted a significant impact on the value of GAI at the same level as the growth year and the choice of cultivar. The NDVI index was less ($p > 0.05$) influenced by these factors, as the only significant effect was revealed in the canopy at a more advanced developmental phase (BBCH 71–75).

The first-order interaction between vegetation year and pea cultivar manifested itself in both vegetative indices (Fig. 2, Fig. 3). Seed yield depended on the interaction of growth year with the inoculants, as shown in Fig. 4.

Both GAI and NDVI values depended on complex interactions between factors, usually triple ones (Fig. 5A,B, Fig. 6B). Stronger interactions ($p < 0.01$) were detected at the flat-pod growth phase (BBCH 71–75).

Seed yield of the two pea cultivars varied seasonally (Tab. 2, Tab. 3, Fig. 4). In 2011, plants treated with IUNG yielded significantly better (ca. 0.49 t ha^{-1}) in comparison to the control. Also in 2012, IUNG inoculation resulted in a significant increase in yield of 0.47 t ha^{-1} compared to Nitragina treatment and 0.54 t ha^{-1} compared to the control (Fig. 4).

The pea 'Tarchalska' was characterized by a significantly higher number of shoots (Tab. 3). The yield was dependent on weather conditions during vegetative growth (Fig. 4). The years 2009 and 2010, which were cooler and abundant in precipitation, limited the effectiveness of the bacterial inocula. A contrary situation was observed in 2011 and 2012 when warmer weather conditions and a lower precipitation were noted. These circumstances allowed for a positive and significant effect of IUNG inoculation on pea yield. Plant productivity increase was about 0.5 t ha^{-1} in 2011, and about 0.49 t ha^{-1} in 2012 compared to the control and 0.47 t ha^{-1} in comparison to Nitragina treatment.

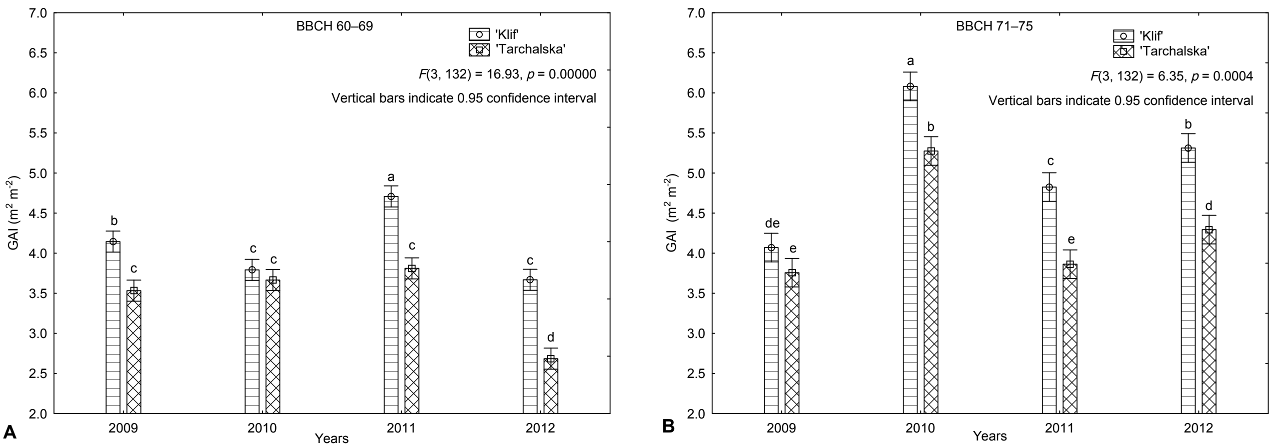

Fig. 2 Values of GAI in different years and cultivars. (**A**) BBCH 60–69. (**B**) BBCH 71–75.

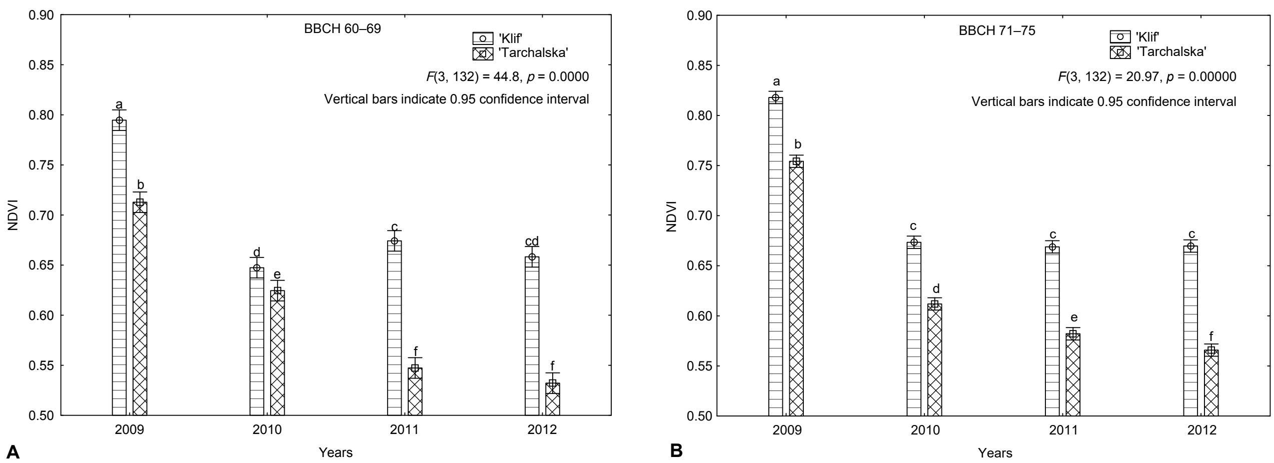

Fig. 3 Values of NDVI in different years and cultivars. (**A**) BBCH 60–69. (**B**) BBCH 71–75.

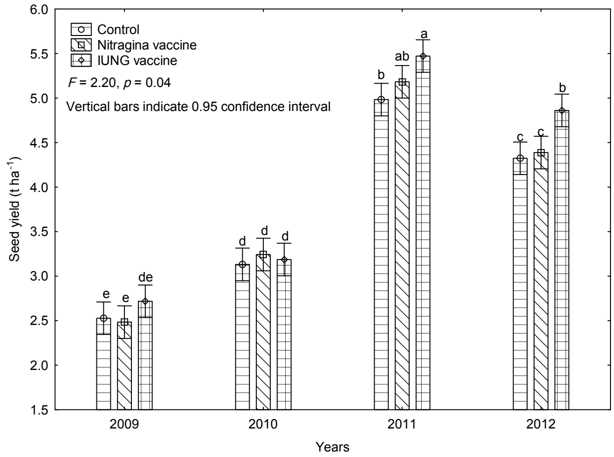

Fig. 4 Interaction effect of year and bacterial vaccine on pea seed yield.

At a less advanced pea growth phase – flowering (BBCH 60–69), variable green assimilation area rates were obtained for the years of the study (Tab. 4). It is worth noting that in the more humid years (2009), the pea crop was characterized by a considerably lower GAI. After the flowering phase in 2010, at the flat-pod phase (BBCH 71–75), the pea crop significantly developed GAI which was related to heavy precipitation and higher air temperatures in comparison to 2009 (Tab. 4). The pea 'Klif' achieved a higher value of GAI than did 'Tarchalska' at both growth stages [GAI for 'Klif' was higher by 0.66 (BBCH 60–69) and 0.77 (BBCH 71–75) than 'Tarchalska']. IUNG massively increased GAI (by 0.24 in both growth phases), whereas Nitragina influenced the index only at the flat-pod phase (BBCH 71–75), by 0.07. A similar effect was achieved by means of the microelement fertilizer (GAI increased by 0.12 at the flowering phase and by 0.17 at the flat-pod phase) (Tab. 4).

The value of NDVI was dependent on weather conditions, hence higher values (0.64–0.79) were recorded in more humid years (2009–2010). The lower values (0.60–0.63) were observed in the years 2011–2012, when vegetative

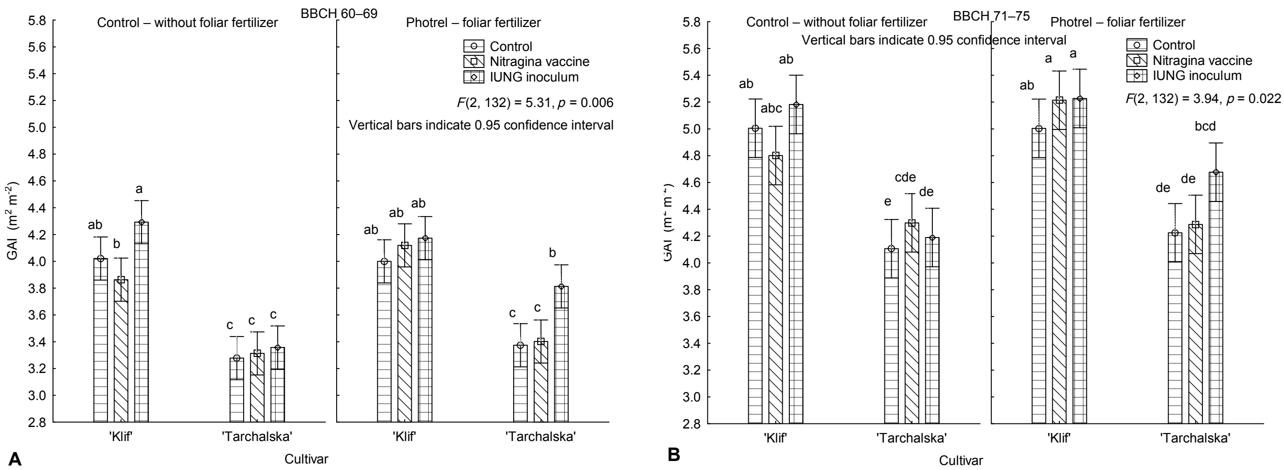

Fig. 5 Mean values of GAI obtained in the years of the test according to cultivar, type of inoculation, and foliar application of fertilizer. (**A**) BBCH 60–69. (**B**) BBCH 71–75.

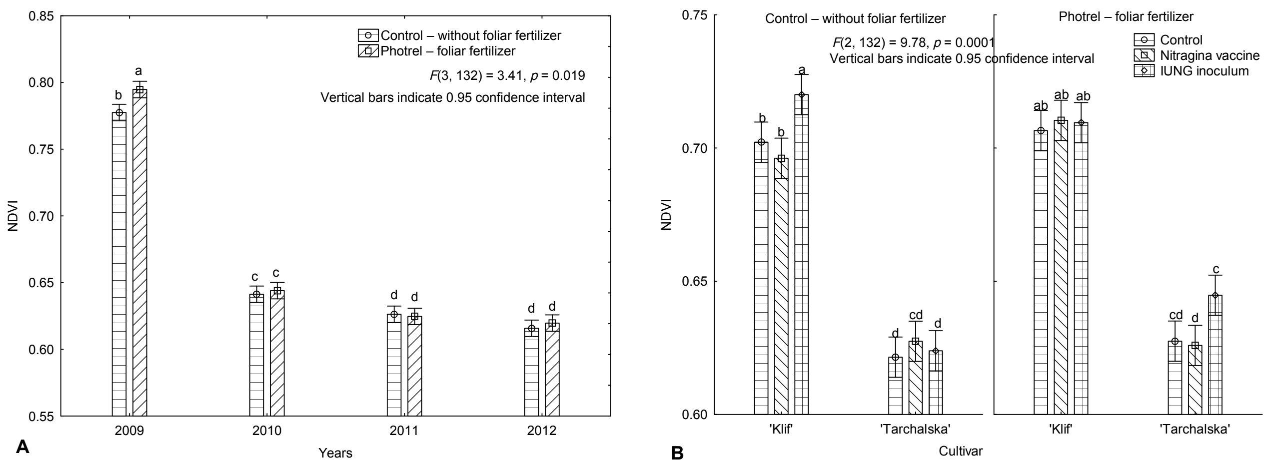

Fig. 6 Mean values of NDVI. (**A**) According to foliar application and years tested. (**B**) According to foliar application, cultivar, and bacterial inoculation.

Tab. 3 Shoots density and seed yield (t ha^{-1}) of pea varieties in different years, depending on presowing of seeds inoculated with *Rhizobium* bacteria and foliar fertilization with microelements.

Treatments	Shoots density (m^{-2})	Seed yield (t ha^{-1})
2009	55.8	2.58
2010	63.2	3.19
2011	64.3	5.21
2012	74.3	4.52
LSD	5.19*	0.532**
'Klif'	61.1	3.42
'Tarchalska'	67.7	4.33
LSD	1.37**	0.106**
Control	65.1	3.74
Nitragina	63.1	3.82
IUNG	65.1	4.06
LSD	2.01*	0.154**
Control	63.6	3.82
Photrel	65.2	3.93
LSD	1.37*	NS

* Significant at $p = 0.05$ probability level. ** Significant at $p = 0.01$ probability level. NS indicates statistically nonsignificant differences.

Tab. 4 GAI and NDVI indices at BBCH 60–69 and BBCH 71–75 stages according to different years, type of cultivar, type of inoculants, and application of foliar fertilizer.

	GAI (m^2 m^{-2})		NDVI	
Treatment	BBCH 60–69	BBCH 71–75	BBCH 60–69	BBCH 71–75
2009	3.84	3.91	0.75	0.79
2010	3.73	5.68	0.64	0.64
2011	4.26	4.34	0.61	0.63
2012	3.18	4.80	0.60	0.62
LSD	0.312**	0.346**	0.015**	0.01**
'Klif'	4.08	5.07	0.69	0.71
'Tarchalska'	3.42	4.30	0.60	0.63
LSD	0.092**	0.125**	0.007**	0.004**
Control	3.67	4.58	0.65	0.66
Nitragina	3.67	4.65	0.65	0.66
IUNG	3.91	4.82	0.65	0.67
LSD	0.134**	0.182**	NS	0.006**
Control	3.69	4.60	0.65	0.67
Photrel	3.81	4.77	0.65	0.79
LSD	0.092**	0.125**	NS	0.004*

* Significant at $p = 0.05$ probability level. ** Significant at $p = 0.01$ probability level. NS indicates statistically nonsignificant differences.

growth periods were much warmer. The choice of cultivar markedly differing in foliage type profoundly shaped NDVI; 'Klif' had a significantly higher value at both growth stages, reaching NDVI higher by 0.09 (BBCH 60–69) and 0.08 (BBCH 71–75) higher than 'Tarchalska'. The inoculants and the microelement foliar fertilizer did not impact on the value of NDVI at a flowering phase, whereas a significant effect was noticed in the next phase, when Photrel fertilizer increased the NDVI value by 0.12, and IUNG inoculation raised it by only 0.01 (Tab. 4).

The GAI differed between the two cultivars, depending on the period of vegetative growth (Fig. 2). The pea 'Klif' achieved a higher (at BBCH 60–69: 'Klif' varied between 3.66 and 4.71 and 'Tarchalska' between 2.68 and 3.81; BBCH 70–75: 'Klif' varied from 4.06 to 6.08 and 'Tarchalska' from 3.76 to 5.28) values of GAI at these growth phases compared for all years. At the flowering stage in more humid years (2009, 2010) GAI was lower (2009 – 4.14, 2010 – 3.79) than in 2011 (4.71), characterized by warmer weather (a lower amount of precipitation and higher air temperatures), which stimulated plant growth. However, at maturity (flat-pod phase) in 2010 both cultivars achieved considerably higher GAI (6.08 'Klif', 5.28 'Tarchalska'). These results confirm that prevailing weather conditions are an important determinant of GAI.

The application of the microelement foliar fertilizer Photrel had a positive bearing in increasing GAI of the pea 'Tarchalska' (Fig. 5). At the BBCH 60–69 stage, Photrel application triggered a slight increase in the GAI (0.45) of the pea 'Tarchalska' (Fig. 5A), whilst at BBCH 71–75 the increase was greater (0.49), but not statistically significant (Fig. 5B). This phenomenon was particularly apparent after presowing seed inoculation with IUNG at both growth stages. The observed interaction exerted profound effects on both development and production. The treatment with the gel inoculant IUNG prompted a rise in total yield from a shoot (seed mass per plant 7.37 in 'Tarchalska') as well as a total shoot weight (shoot mass: 12.17 g), which is verified by detailed data for a single pea generative shoot demonstrated in Tab. 1 Another consequence of an application of the fertilizer was an increase in the number of fruiting nodes on the pea shoot for 'Tarchalska' (4.55 pcs), and the growth of these plant parts was manifested by the rise (0.33 pcs) of GAI.

Both cultivars achieved high values of NDVI in 2009 irrespective of growth stage (Fig. 3). However, 'Tarchalska' attained considerably lower values of NDVI regardless of the growth stage. In this case, the leaf arrangement of this cultivar proved to be a determinant, as photosynthetically active radiation could reach the soil surface.

Significantly higher (for the control: 0.78, for Photrel treatment: 0.79) values of NDVI in 2009 were obtained after foliar fertilization with Photrel (Fig. 6A). In the following cropping years, the value of NDVI was approximately 19% lower, with or without foliar fertilizer. Treatment with IUNG inoculant, without use of the microelement foliar fertilizer increased the value of NDVI in 'Klif'. However, application of the foliar fertilizer had an impact on 'Tarchalska' treated with IUNG inoculum, slightly increasing the NDVI value in comparison to the control (Fig. 6B).

Discussion

Morphological characteristics and seed yield

Results from our experiment showed that the yield potential of the semileafless pea 'Tarchalska' was always higher in comparison to the cultivar with standard foliage. The morphological features compared determining the productivity of a shoot (e.g., the number of seeds per shoot, the weight of a shoot, HI) can be classified as quantitative features of the crop. Dacko et al. [22] claim that the seed mass is affected mostly by hydrothermal conditions during vegetative growth of the pea crop, the length of the pod and the cultivar. In our studies, the production potential of contrasting pea cultivars was determined by the weather patterns during the vegetative growth phases in each year. During the growth period in 2009–2010 the biomass yield of the peas was impeded by cool weather. The results of our study confirmed that the high value of GAI in 2010 during heavy precipitation in the vegetative phase did not trigger maximization of seed yield. This outcome is additionally supported by previous results of Zając et al. [21], who noted that differences in production of the pea crop over years is a result of environmental stresses impacting on plant yield, as well as generative growth, which is manifested by a decrease in seed yield. However, any disadvantageous productivity and developmental effects can be improved by the introduction of enhanced semileafless genotypes demonstrating greater resistance to stressors.

In the present study, the greater biomass of shoot and the pea crop was in the semileafless cultivar, which in combination with a higher number of pods per unit of a surface of this genotype and a more advantageous HI, helped to produce a higher level of seed yield. In warmer and dryer years, both greater seed number and shoot biomass were obtained due to a presowing application of a bacterial inoculant as a donor of rhizobia. Foliar fertilization was also beneficial for the length of the fruiting part of a shoot, the number of seeds, and the HI. The results do not indicate any significant role of the interaction between the main experimental factors in increasing pea seed yield. However, a strong effect of the interaction ($p = 0.05$) between vegetation years and the choice of pea varieties on the yield level was noted. In more favorable years, better productive effects were obtained after the application of an IUNG inoculant. The obtained data indicate growth stimulation by means of the microelement fertilizer, which could have been observed by the two parts of a shoot – with and without pods. A measurable outcome of microelement fertilization was that a lengthening of both parts of the shoot as well as an increase in the number of fruiting nodes did not influence the productive potential of the pea. The increase in both these elements (length and number of fruiting nodes) resulted in higher values of GAI for the pea crop. Belachew and Pant [20] in their study demonstrate that a pea cultivar, as well as bacterial inoculants, had a bearing on yield height but no interaction between these factors in terms of creating crop productivity was noted.

Vegetative indicators

Our trial has shown that the pea cultivar with standard foliage had a higher value of GAI at the flowering stage, compared to the semileafless cultivar. However, at the maturity stage (green pod maturity) the value of GAI of the semileafless cultivar was higher, presumably due to its slowly decaying tendrils. The value of GAI obtained for the pea by Prusiński [23] in full bloom was 4.23–5.28, while the semileafless cultivar 'Venus' was characterized by a significantly lower value compared to the cultivars with standard foliage, although this did not hamper its achieving the highest biomass yield, and as a consequence, the highest yield. This relationship was also noted by a wide range of other researchers for other legumes, e.g., chickpea, faba bean, or vetch [12,17,24] As was confirmed by Ali et al. [15], Togay et al. [25], and Albayrak et al. [24], *Rhizobium* inoculation played a crucial role in increasing the LAI, the number of pods and plant seeds, which in turn lead to an increased seed yield. In the present research, the effects of inoculation shaped the values of GAI and NDVI in various ways. The IUNG inoculant generated considerably better results, while Nitragina did not increase the indices in any significant way. Foliar fertilization with Photrel positively stimulated the GAI of the cultivar with standard foliage. However, this interaction was important for the growth of a crop, which is supported by detailed results of GAI for the compared growth stages. The analysis of interrelationships between pea yield and the value of GAI at two growth stages pointed to a significantly important correlation of the two features. In the present study, the interrelationships of seed yield and the values of GAI were identical for the genotypes. Only the prediction of interdependencies for the semileafless cultivar examined at the flat-pod phase of the maturity stage (BBCH 71–75), was higher in comparison to the flowering stage, which shows the need for measurements at more advances stages of pea growth. The value of pea NDVI for both investigated growth stages (flowering, the flat-pod phase of the maturity stage) indicated notable differences between the compared cultivars. The pea 'Klif' had considerably higher values of NDVI. The present study shows that regardless of the stage and vegetation years, a higher value of NDVI was obtained for the cultivar with regular foliage.

Conclusions

The vegetative indices (GAI, NDVI) were useful in assessing the productivity and developmental effects of rhizobial inoculants and the foliar fertilizer Photrel on pea crops at specific stages of development of two contrasting cultivars ('Klif' with regular foliage and a semileafless 'Tarchalska'). Regardless of the growth stage and years, a higher value of NDVI was recorded for 'Klif'. Inoculants and foliar fertilizer, irrespective of growth stages and cultivar, exerted a significant impact on GAI. Foliar fertilization significantly stimulated the GAI of the pea 'Klif'. High values of GAI and NDVI gave a basis for prediction of high yield. Seed yield of the two pea cultivars investigated varied between years. For seasons with water shortage during the vegetative phases, peas treated with IUNG inoculation yielded significantly higher (about 0.49 t ha^{-1}) in comparison to controls.

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Ocena potencjału produkcyjnego grochu (*Pisum sativum* L.) przy pomocy wybranych wskaźników wegetatywnych (NDVI, GAI), zależnie od fazy wzrostu i warunków uprawy

Streszczenie

W badaniach oceniano wpływ szczepionek bakteryjnych i nawozu mikroelementowego na kształtowanie NDVI (ang. *normalized difference vegetation index*) i GAI (ang. *green area index*). W czteroletnim doświadczeniu polowym porównano (***i***) dwie odmiany grochu o normalnym ulistnieniu 'Klif' oraz odmianę wąskolistną 'Tarchalska', (***ii***) szczepionki bakteryjne: Nitraginę i IUNG, oraz (***iii***) wpływ działania nawozu dolistnego Photrel. Nawóz Photrel znacznie zwiększył długość pędów generatywnych i liczbę węzłów owocujących w porównaniu do warunków kontrolnych i negatywnie wpływał na wskaźnik plonowania (HI). Plon nasion grochu istotnie zależał od odmiany i był istotnie wyższy dla odmiany wąsolistnej (4,33 t ha^{-1}). Przedsiewna inokulacja nasion i nawożenie dolistne skutkowały uzyskaniem istotnie wyższej wartość GAI w fazie kwitnienia (odpowiednio 3,91 i 3,81) i fazie dojrzałości (odpowiednio 4,82 i 4,77), podczas gdy wartość NDVI była wyższa w przypadku tych zabiegów tylko w etapie dojrzewania (odpowiednio 0,67 i 0,79). Znacznie wyższy plon nasion (5,0–5,4 t ha^{-1}) uzyskano w warunkach przedłużającej się suszy po inokulacji za pomocą szczepionki bakteryjnej IUNG.