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Nitrogen-fixing and phosphate-mobilising bacteria improve photosynthetic activity and productivity of buckwheat (*Fagopyrum esculentum* Moench)

Abstract. One effective way to increase the yield of agricultural crops is pre-sowing seed treatment with nitrogen-fixing and phosphate-mobilising bacteria. The specific features of productivity formation in buckwheat restrict the planned yield and the realisation of varietal potential, leading to an increase in vegetative growth indicators at the early stages of growth and development. The research was conducted on three buckwheat cultivars during 2022-2023 under the conditions of the forest-steppe zone of Ukraine. This study aimed to determine the effect of seed treatment on the content of photosynthetic pigments, biomass accumulation, and leaf area index in buckwheat during the generative period of development. It was found that the influence on biomass growth from mid-flowering to fruit formation was limited, though different trends in the formation of photosynthetic pigments in leaves were observed. The biopreparations significantly increased the content of photosynthetic pigments at the budding stage (BBCH 51), mainly due to chlorophyll a, while at the flowering stage (BBCH 65), phosphate-mobilising complexes were most effective. It was established that seed treatment with nitrogen-fixing bacteria enabled buckwheat to form a leaf area index of 5.27-5.48 at the fruit formation stage, which was significantly higher compared with the control (4.19). At the same time, biomass accumulation during the generative period changed insignificantly across the seed treatment options, but morphological changes were noted that contributed to higher yields and, consequently, greater productivity. It was established that pre-sowing seed treatment has a significant effect on biometric indicators and yield, though the varietal factor often manifests itself, indicating the prospects for further research into evaluating the formation of the buckwheat generative apparatus under the influence of microbiological preparations

Keywords: chlorophyll content; dry matter; leaf area index; net photosynthetic productivity; yield

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INTRODUCTION

Global food security has long been under the scrutiny of many governments and international organisations (Kuchechuk, 2022). This is driven by population growth, which requires ever-increasing production of agricultural products – products that must meet the standards of environmental safety and the quality of food and feed (Shuvar *et al.*, 2019). One approach to addressing this issue is the development of technologies for growing crops on an organic basis. Organic production is gradually becoming more popular in Ukraine (Kotykova & Ten, 2018). Even those farms that previously engaged exclusively in non-organic crop production and traditionally used mineral fertilisers and pesticides are now showing interest in organic crop production (Kunsook *et al.*, 2024; Hudzovskyi *et al.*, 2024). The basis of organic production is weed control (in which the observance of crop rotations is of great importance, because herbicides are not used), plant nutrition, and storage of finished products.

Since the use of chemicals is prohibited in the organic cultivation of crops, the introduction of biological preparations based on beneficial microorganisms with different mechanisms of action into crop-growing technologies is gaining popularity, including in buckwheat production (Almashova & Skok, 2022). As noted by X. Wei *et al.* (2024), their use in crop production technologies helps reduce the application rates of mineral fertilisers, increase plant productivity, and improve product quality. The optimal combination of plant life factors contributes to the formation of ecological equilibrium in agrobiocenoses and affects both the yield and quality of agricultural products. Therefore, it is important to use measures aimed at increasing the number and activity of agronomically valuable microorganisms in the rhizosphere of plant root systems.

Ukraine grows approximately half of all organic buckwheat in the world. Growing interest in the production of organic buckwheat from both agricultural producers and the state makes this area highly promising (Vieites-Álvarez *et al.*, 2024b). As buckwheat is cultivated organically, the use of readily available synthetic fertilisers is prohibited. According to U. Karbivska *et al.* (2024), to increase the yield of organic buckwheat, it is advisable to apply fertilisers of organic origin. Therefore, the study of the use of organic preparations in buckwheat seed cultivation technologies where mineral fertilisers are not used is relevant. The use of such preparations in buckwheat cultivation has been shown to improve the phytosanitary condition of crops. Seed treatment and spraying of buckwheat crops contributed to enhanced plant growth, greater increased branching, and greater vegetative mass (Honchar *et al.*, 2020). As established by Y. Vieites-Álvarez *et al.* (2024a), the competitiveness of buckwheat plants against weeds throughout the growing season also increased.

The value of buckwheat is determined by its exceptional characteristics, both as an agricultural crop – including its role as a precursor, soil improver, and component of organic cultivation technology – and as a source of raw materials obtained from cultivation: grain (for processing into cereals), biologically active substances, honey, and waste-free processing technology (Breslauer *et al.*, 2023). Despite these positive qualities, buckwheat remains a niche crop. Producer interest is also positively influenced by new varieties with yields exceeding 2.5-3.0 t/ha, capable of realising this potential in diverse environmental conditions. One of the main priorities in introducing buckwheat to modern agrocenoses is the waste-free nature of its production technology and its versatile use, which must be taken into account when calculating the economic efficiency of buckwheat production.

A key issue in modern buckwheat cultivation is increasing its grain productivity. It is known that the biomass potential it synthesises is sufficient to form a yield of 4-7 t/ha of seed if it were cultivated as a grain crop. However, the biological characteristics of buckwheat limit its productivity, so the conversion of photosynthetic activity into seed biomass faces several constraints. According to research results, yield increases often occur extensively – through biomass growth. Therefore, studying the production processes of crops during the generative period of development will enable the prediction and selection of an effective cultivation strategy. Previous research has shown that bio-preparations containing PGPM influence stress adaptation in buckwheat and induce plant modifications in other crops by improving nutrient availability and synthesising phytohormones in the rhizosphere. A comprehensive assessment of plant growth processes and photosynthetic activity under the influence of rhizosphere modification factors using bio-preparations is the core of the present research.

This research aimed to improve certain elements of buckwheat cultivation technology under the conditions of the forest-steppe zone and to determine the influence of the growing season's weather conditions, the content of photosynthetic pigments, biomass accumulation, and the leaf area index on achieving the highest crop productivity. The objectives of the study included determining the growth and development characteristics of buckwheat plants depending on the variety and pre-sowing treatment with biological preparations, and investigating the dynamics of external architectural development of buckwheat plants at different growth stages (according to the BBCH scale) under the influence of the studied factors. For the first time, the peculiarities of yield formation in buckwheat varieties under the influence of growing-season weather conditions in the Forest-Steppe zone were identified. The influence of biological preparations on the photosynthetic activity and productivity of buckwheat plants was established, and the technology of buckwheat cultivation in the forest-steppe zone was optimised.

MATERIALS AND METHODS

The field experiment was conducted in 2022-2023 in the Educational-Scientific Laboratory Demonstration Collection Field of Crops of the Department of Plant Science (Kyiv, Ukraine; 50º 22´ N, 30° 30´ E). The investigation was performed under field conditions. The soil of the experimental field was grey forest light loam, with 2.3%-3.0% humus content in the arable layer (0-20 cm), pH_{KOH} 5.8-6.1, hydrolysed nitrogen content 73 ± 6 mg per kg of soil, phosphorus 103 ± 17 mg per kg of soil, and potassium 78 ± 12 mg per kg of soil. The study complied with the principles of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973).

Climate conditions. The weather conditions during the research years and the buckwheat growing season were contrasting, allowing for a comprehensive assessment of the effects of the preparations. The primary difference between the years was precipitation, which is crucial for the activity of microbiota in the rhizosphere and for biomass growth (Table 1).

Table 1. Weather conditions during field trials in 2022-2023

Parameter	Year	Month					Average per vegetation
		April	May	June	Jule	August	
Air temperature, °C	2022	8.1	14.6	21.7	20.8	22.3	17.5
	2023	9.6	16.0	19.6	21.5	23.8	18.1
	MA*	10.0	15.8	19.5	21.3	20.4	17.4
Monthly precipitation, mm	2022	26	20	46	34	80	206
	2023	102	1	87	136	19	345
	MA*	42	65	74	68	56	305

Note: MA* – multi-annual parameter based on data from 1990 to 2015
Source: compiled by the authors from Meteopost (n.d.)

The average daily temperature during the buckwheat growing season in 2022 was 17.5°C (longterm average: 17.4°C), whereas 2023 was hotter, with an average daily temperature of 18.1°C. The air temperature at the time of sowing in May 2022 was 15.1°C, while in 2023 it was 16.4°C. May 2023 had a variable temperature regime: at the beginning of the month, the temperature was optimal for buckwheat sowing, fluctuating between 15°C-19°C, but on 6 May there was a sharp drop to 5.6°C. Later, the temperature increased, exceeding 25°C by 18 May, and there was no precipitation throughout the month. The year 2023 was marked by the most variable temperature indicators and precipitation sums, with frequent sharp fluctuations between day and night, affecting buckwheat plants. Precipitation was also uneven, with both absence (in May) and excess (in July), which hindered the ripening of buckwheat fruits.

Field trial design and cultivation conditions. Cultivar sensitivity to pre-sowing treatment with free-living bacteria was established in a two-factor field experiment. The first factor comprised three buckwheat (*Fagopyrum esculentum* Moench) cultivars: 'Volodar', 'Podilska', and 'Kamyanchanka'. The second factor was the treatment of buckwheat seeds before sowing with preparations based on microorganisms – a diazotroph complex and a phosphate-mobilising bacteria complex (Table 2).

Table 2. Experimental scheme

Cultivar	Seed treatment before sowing
C1. 'Volodar' C2. 'Podilska' C3. 'Kamyanchanka'	B1. Without treatment B2. Diazotroph complex, 1 L/t of seed B3. Phosphate-mobilising complex, 1 L/t of seed

Source: compiled by the authors

The diazotroph complex was based on free-living nitrogen-fixing bacteria: *Azotobacter chroococcum*, *Azotobacter vinelandii*, and associative nitrogen-fixing bacteria *Azospirillum brasilense*, *Azospirillum lipoferum* (1 mL contained 1×10^9 colony-forming units (CFU)). The phosphate-mobilising complex consisted of spores of *Bacillus megaterium*, *Bacillus amyloliquefaciens*, and micromycetes *Trichoderma harzianum* (1 mL contained 1×10^9 CFU).

The experiment was conducted in four replications. The size of the elementary plots was 36 m^2 (24 m^2 for harvesting). The tillage system included disking after the preceding crop (winter wheat) and autumn ploughing to a depth of 18-20 cm. Disking was carried out in early spring, followed by presowing cultivation to a depth of 3-4 cm before sowing. The fertilisation regime included the application of Ecosoil organic fertiliser at a rate of 250 kg/ha (P_2O_5 – 5.0%, K_2O – 20.0%, S – 3.5%, Ca – 8%, Mg – 5.5%, Fe – 1340 mg/kg, Zn – 300 mg/kg, Cu – 240 mg/kg, Mn – 200 mg/kg, Mo – 1.5 mg/kg, Co – 0.37 mg/kg), applied before autumn ploughing. Buckwheat was sown with 15 cm interrow spacing at a rate of 300 seeds/m^2. Sowing time (first ten-day period of May) depended on soil temperature (optimum 10°C-12°C). No pesticides were applied during the growing season.

Plant sampling procedure. Plant samples were collected at five stages: BBCH 51 (inflorescence emergence), BBCH 65 (50% of inflorescences flowering), BBCH 67 (70% of inflorescences flowering), and BBCH 71 (beginning of fruit filling). Samples were taken from an area of 0.5 m^2, and biometric parameters were analysed on ten plants (n = 10) from each variant. The chlorophyll content was determined in the upper, fully developed leaf at the BBCH 51 and BBCH 65 stages. Fresh samples were collected and extracted in 96% ethanol. Optical density was measured using a UNICO 1201 spectrophotometer to determine the content of chlorophyll *a* and *b* in the solution (wavelengths 665 nm and 649 nm). These values were then recalculated per unit dry matter of leaf tissue. Chlorophyll concentration was determined using the following equations:

$$Cl_a = 13.7\ D_{665} - 5.76\ D_{649}, \quad (1)$$

$$Cl_b = 25.8\ D_{649} - 7.6\ D_{665}, \quad (2)$$

where Cl_a – chlorophyll *a* content, mg/L; Cl_b – chlorophyll *b* content, mg/L; D_{665} – optical density at 665 nm; D_{649} – optical density at 649 nm.

The leaf area index (LAI) was determined by scanning all leaf blades from ten plants and converting the results to 1 m^2 based on actual plant density. Dry matter accumulation (g/m^2) was assessed by evaluating the increase in dry biomass at each stage compared with the previous stage. Biomass was dried at 105°C to a constant moisture content.

Statistics. Statistical analysis was performed using Statistica version 13.0 (Tibco, USA). ANOVA was applied to each studied parameter and included the influence of weather conditions. Tukey's HSD test at a 95% confidence level was used to assess differences between variants. Bars in the figures represent the standard error (±SE).

RESULTS AND DISCUSSION

The content of photosynthetic pigments in buckwheat leaves varied significantly depending on the developmental stage (Table 3). Notably, seed treatment was a determining factor in pigment variation at the BBCH 51 stage, indicating qualitative modifications to the photosynthetic apparatus under the influence of these factors. The chlorophyll *a* content varied significantly across all factors, but the influence of the year and variety was significantly less than that of seed treatment. The chlorophyll *b* content also varied depending on seed treatment and variety, but was not directly sensitive to annual conditions. The variation in the interaction between seed treatment and variety or annual conditions was greater than the influence of the variety itself. The total content of photosynthetic pigments in the BBCH 51 stage varied due to the direct effect of the factors and their interaction, except for the "year ↔ treatment" interaction.

Table 3. ANOVA for photosynthetic pigments in leaves at BBCH 51 and BBCH 65

Effect	MS					
	$Cl_{a\ 51}$	$Cl_{b\ 51}$	$Cl_{a+b\ 51}$	$Cl_{a\ 65}$	$Cl_{b\ 65}$	$Cl_{a+b\ 65}$
Cultivar (C)	1.56**	0.1435**	2.48*	45.73**	7.2176**	75.36**
Treatment (T)	105.53**	2.7426**	83.32**	31.20**	2.8293**	48.00**
Year (Y)	11.05**	0.0022ns	11.36**	6.91**	0.0013ns	7.09**
C×T	8.41**	0.4360**	9.17**	2.05**	0.9335**	3.61**
C×Y	2.50**	0.0193ns	2.10*	1.48*	0.0029ns	1.35*
T×Y	1.89*	0.6793**	0.98ns	5.77**	0.6329**	10.18**
C×T×Y	1.84**	0.0326*	2.05*	1.86**	0.1483**	2.70**
Error	0.32	0.0089	0.42	0.19	0.0065	0.26

Note: ^{ns} – not significant ($p > 0.05$); ** – $p < 0.001$; * – $p < 0.05$; Codes: Cl_a – chlorophyll *a*, Cl_b – chlorophyll *b*, "51" – BBCH 51 stage (inflorescence emergence), "65" – BBCH 65 stage (50% of inflorescences flowering)

Source: compiled by the authors

The situation with photosynthetic pigments changed substantially in the flowering stage (BBCH 65). During this phase, the formation of new leaves ceased, so varietal characteristics became the primary factor. The cultivar accounted for the greatest variation in the content of chlorophyll *a*, chlorophyll *b*, and their total. The second most significant factor was seed treatment, while the influence of annual conditions was lower and, in the case of chlorophyll *b*, insignificant.

The dynamics of the leaf area index also varied significantly depending on the developmental stage (Table 4). It is noteworthy that the direct factors (cultivar, treatment, weather conditions/year) always had a significant impact, but their interactions were only significant at certain developmental stages. Seed treatment and weather conditions produced greater LAI variation in the BBCH 51 stage than in the cultivar. All factor interactions, except for "cultivar ↔ treatment", were insignificant.

Table 4. ANOVA for leaf area index (LAI) and dry matter accumulation (DMA) during the generative period of buckwheat development

Effect	MS						
	LAI_{51}	LAI_{65}	LAI_{67}	LAI_{71}	$DMA_{51\text{-}65}$	$DMA_{65\text{-}67}$	$DMA_{67\text{-}71}$
Cultivar (C)	0.5884**	5.8742**	7.719**	3.342**	4,877.1**	2,491.8**	2,491.8**
Treatment (T)	2.3207**	10.3486**	6.032**	11.572**	950.4**	284.8ns	284.8ns
Year (Y)	1.6928**	5.6224**	12.997**	16.589**	26,075.7**	35,161.1**	35,161.1**
C×T	0.2287**	0.9888**	0.930**	0.156*	261.6**	373.7ns	373.7ns
C×Y	0.0030ns	0.0713*	0.053ns	0.007ns	2,106.8**	1,065.6*	1,065.6*

Table 4, Continued

Effect	MS						
	LAI$_{51}$	LAI$_{65}$	LAI$_{67}$	LAI$_{71}$	DMA$_{51\text{-}65}$	DMA$_{65\text{-}67}$	DMA$_{67\text{-}71}$
T×Y	0.0075ns	0.0501*	0.017ns	0.018ns	313.5**	586.9*	586.9*
C×T×Y	0.0070ns	0.0116ns	0.090*	0.076ns	331.5**	295.3ns	295.3ns
Error	0.0036	0.0106	0.033	0.033	37.0	181.6	181.6

Note: ^{ns} – not significant ($p > 0.05$); ** – $p < 0.001$; * – $p < 0.05$; Codes: LAI – leaf area index, DMA – dry matter accumulation, "51" – BBCH 51 stage (inflorescence emergence), "65" – BBCH 65 stage (50% of inflorescences flowering), "67" – BBCH 67 stage (70% of inflorescences flowering)

Source: compiled by the authors

LAI variation during the BBCH 65 stage was determined by the main factors and their pairwise interactions (with the exception of the interaction of all three factors simultaneously). In the subsequent developmental stages (BBCH 67), weather conditions became the primary factor, and the variation attributable to seed treatment in relation to the cultivar increased up to and including the BBCH 71 stage. The formation of dry biomass during interphase periods differed significantly from that of the leaf apparatus. The fertilisation factor affected the variation in dry mass growth only between BBCH 51 and BBCH 65, while in subsequent periods it was insignificant. This pattern was also observed for the "cultivar ↔ seed treatment" interaction. Year-specific conditions caused the greatest variation in dry matter accumulation during the interphase periods. Although cultivar and interactions were significant in most cases, they were less influential compared with year-specific conditions.

The content of photosynthetic pigments in leaves during the BBCH 51 phase (Fig. 1a) varied significantly according to seed treatment, allowing identification of the best options based on the total chlorophyll content. 'Kamyanchanka' produced significantly fewer photosynthetic pigments (14.8 mg/g DM) without seed treatment with microbial preparations, compared with other cultivars (16.1-17.2 mg/g DM). However, the application of microbial preparations increased the content to 19.519.6 mg/g DM, with no significant difference between the preparations. A similar situation was observed in 'Podilska', while the application of a phosphate-mobilising complex (PMC) in 'Volodar' showed a significant difference from the control treatment. It is worth noting that 'Volodar' had a high pigment content in the control treatment, so the effect of the preparations was lower, indicating a maximum content limit for these indicators.

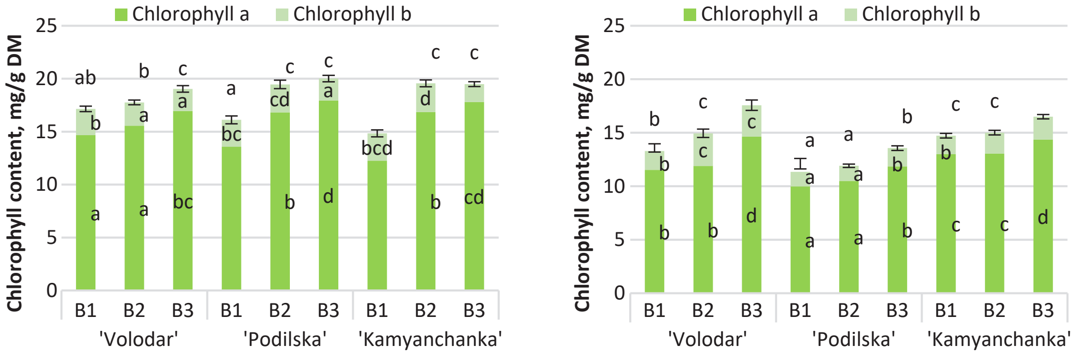

Figure 1. The content of photosynthetic pigments in buckwheat leaves, mg/g dry matter at BBCH 51 (left) and BBCH 65 (right)

Note: same letters indicate no difference between variants at a given stage according to Tukey's HSD post-hoc test; bars indicate standard error (±SE)

Source: compiled by the authors

The situation with pigment content changed during the BBCH 65 phase, as the highest concentration was observed in variants treated with the phosphate-mobilising complex (17.6 mg/g DM). In contrast, treatment with a diazotroph complex showed a significant difference from the control only in 'Volodar'. This indicates the importance of improving phosphate nutrition during the generative period and the reduced role of nitrogen. The content of chlorophyll *a* increased markedly with the application of PMC, while the content of chlorophyll *b* rose significantly with the application of both preparations. The increase in chlorophyll *b* content with seed treatment was greatest in the 'Volodar'.

The positive effect of improved trophic conditions is manifested in two ways – through increasing the linear dimensions of individual organs and increasing the intensity of green colouration due to the higher concentration of photosynthetic pigments (Honchar *et al.*, 2021). The results of the current study indicate that the content of chlorophyll *a* and *b* increases significantly both in the early generative period and in the middle of flowering. Previous studies, such as that by V. Karpenko *et al.* (2021), have noted that a significant increase often occurs with the combined application of seed treatment with biostimulants, which primarily leads to an increase in pigments in fresh mass, while the increase in dry mass can be more modest. In the studies by the authors of this article, it seldom exceeds 20% for chlorophyll *a*, but it can nearly double for chlorophyll *b*. According to M. Chen (2014), this phenomenon is related to the specifics of chlorophyll *b* synthesis, which can compensate for this factor when crops are grown under stressful conditions. Despite the substantial existing knowledge base about the impact of PGPM on agricultural crops, there remains a significant gap in the family *Polygonaceae*. For example, a meta-analysis of research on the relationship between nitrogen nutrition and microbiota in 'Tartary' buckwheat indicates that microbiota activity in the rhizosphere does not significantly change in the presence of fertilisers. Seed treatment of buckwheat with certain bacterial strains can improve indicators that affect NDVI, such as leaf area, chlorophyll concentration, and colour intensity (Witkowicz *et al.*, 2021). However, a plausible theory suggests an increase in soil microorganisms due to crop rotation and the introduction of a qualitatively new microbiota (Zhang *et al.*, 2021).

Buckwheat is a plant with limited potential for leaf surface growth. The maximum leaf area index (LAI) depends on the cultivar characteristics and type of variety. Indeterminate cultivars are more flexible in this regard, but there is a biological limitation that makes buckwheat less productive than cereal crops. It has been established that seed treatment positively affects the LAI of buckwheat (Table 5). In the control variant during the BBCH 51 phase, the cultivars did not significantly differ from each other, whereas with treatment, there was a significant increase in LAI. 'Kamyanchanka' formed the maximum LAI of 2.05 ± 0.06, with no significant difference between the treatments, while the other cultivars had significantly lower values. For the 'Volodar' and 'Podilska', the phosphate-mobilising complex was more effective than the diazotroph one.

Table 5. Leaf area index of buckwheat at BBCH 51, 65, 67, 71

Cultivar	**Treatment**			**Average**
	B1	**B2**	**B3**	
BBCH 51				
'Volodar'	1.31 ± 0.06 a	1.59 ± 0.06	1.78 ± 0.07 b	1.56 ± 0.05
'Podilska'	1.22 ± 0.04 a	1.45 ± 0.05	1.70 ± 0.07 b	1.46 ± 0.05
'Kamyanchanka'	1.21 ± 0.07 a	2.05 ± 0.06 c	2.04 ± 0.07 c	1.77 ± 0.09
Average	1.25 ± 0.03	1.70 ± 0.06	1.84 ± 0.05	1.59 ± 0.04
BBCH 65				
'Volodar'	2.33 ± 0.10 ab	3.83 ± 0.13 cd	3.98 ± 0.16 d	3.38 ± 0.17
'Podilska'	2.02 ± 0.07	2.76 ± 0.11	2.47 ± 0.10 b	2.41 ± 0.08
'Kamyanchanka'	2.27 ± 0.09 a	3.24 ± 0.11	3.76 ± 0.11 c	3.09 ± 0.14
Average	2.21 ± 0.06	3.27 ± 0.11	3.40 ± 0.16	2.96 ± 0.09

Table 5, Continued

Cultivar	Treatment			Average
	B1	B2	B3	
BBCH 67				
‘Volodar’	3.89 ± 0.19	4.60 ± 0.17 a	4.61 ± 0.20 a	4.37 ± 0.12
‘Podilska’	3.11 ± 0.10	3.59 ± 0.14	4.73 ± 0.20 a	3.81 ± 0.17
‘Kamyanchanka’	4.54 ± 0.21 a	5.08 ± 0.18 b	5.20 ± 0.16 b	4.94 ± 0.12
Average	3.85 ± 0.16	4.42 ± 0.16	4.85 ± 0.12	4.37 ± 0.10
BBCH 71				
‘Volodar’	4.11 ± 0.20 a	5.00 ± 0.17 b	5.10 ± 0.21 bc	4.74 ± 0.14
‘Podilska’	3.94 ± 0.13 a	5.05 ± 0.19 b	5.37 ± 0.23 c	4.79 ± 0.17
‘Kamyanchanka’	4.50 ± 0.20	5.76 ± 0.20 d	5.97 ± 0.16 d	5.41 ± 0.17
Average	4.19 ± 0.11	5.27 ± 0.13	5.48 ± 0.14	4.98 ± 0.10

Note: B1 – without treatment, B2 – diazotroph complex, B3 – phosphate-mobilising complex. Same letters indicate no difference between variants at a given stage according to Tukey’s HSD post-hoc test

Source: compiled by the authors

LAI in the BBCH 65 phase differed notably from the previous observation. The maximum value of 3.98 ± 0.16 was observed for the ‘Volodar’, when treated with the phosphate-mobilising complex, but there was no significant difference compared with the diazotroph complex. The LAI in the ‘Podilska’ increased markedly less than in the other cultivars following seed treatment, with the maximum value observed when treated with the diazotroph complex. LAI in the ‘Kamyanchanka’ reached a maximum value when treated with the phosphate-mobilising complex (3.76 ± 0.11), which was also significantly higher than that recorded under treatment with diazotrophs (3.24 ± 0.11).

In the next phase (BBCH 67), the difference between the control and treated variants decreased. The maximum LAI value was recorded for the ‘Kamyanchanka’ (5.20 ± 0.16) when treated with phosphate-mobilising bacteria, with no significant difference from seed treatment with diazotrophs. A similar pattern was observed in ‘Volodar’, although with a lower LAI (4.61 ± 0.20). For ‘Podilska’, seed treatment with phosphate-mobilising bacteria resulted in a significantly higher LAI (4.73 ± 0.20) than with other treatments and the control. In the last accounting period (BBCH 71), the maximum LAI was again recorded for the ‘Kamyanchanka’ (5.97 ± 0.16). In the control variant, the LAI in this cultivar remained almost unchanged compared with the previous period, while it increased in the other cultivars. LAI increased to 5.00-5.37 in both cultivars in the treated variants, but phosphate-mobilising bacteria were more effective in the ‘Podilska’.

A significant increase in the leaf apparatus in cereal crops enhances assimilation processes, but in the case of buckwheat, which has indeterminate growth, these processes occur differently. The average biomass increase from BBCH 51 to BBCH 71 was 220 ± 12 g/m^2, but phase-by-phase distribution indicates that from the beginning of budding to the middle of flowering, more dry mass was accumulated than during the end of flowering and final fruit formation (Table 6).

Table 6. Dry matter accumulation (g/m^2) of buckwheat during BBCH 51-65, 65-67, 67-71

Cultivar	Treatment	Period			BBCH 51-71
		BBCH 51-65	BBCH 65-67	BBCH 67-71	
‘Volodar’	B1	101.8 ± 10.8 c	63.6 ± 9.1 bc	68.7 ± 10.9 ab	234 ± 29 cde
	B2	111.9 ± 7.9	68.1 ± 13.5 c	63.3 ± 7.2 a	243 ± 25 de
	B3	123.5 ± 15.7	52.6 ± 9.7 abc	71.3 ± 7.9 ab	247 ± 29 e
‘Podilska’	B1	89.0 ± 7.2 ab	35.5 ± 4.8 a	67.7 ± 10.3 ab	192 ± 18
	B2	98.6 ± 4.6 bc	46.7 ± 8.2 abc	80.5 ± 7.7 ab	226 ± 17 abc
	B3	94.7 ± 4.6 bc	44.2 ± 8.2 ab	91.9 ± 12.4 b	231 ± 22 bcd

Table 6, Continued

Cultivar	Treatment	Period			BBCH 51-71
		BBCH 51-65	BBCH 65-67	BBCH 67-71	
'Kamyanchanka'	B1	81.5 ± 6.5 a	52.3 ± 11.4 abc	77.6 ± 6.7 ab	211 ± 22 a
	B2	79.6 ± 5.1 a	57.1 ± 12.5 abc	81.3 ± 7.7 ab	218 ± 22 ab
	B3	91.8 ± 4.9 b	63.2 ± 9.1 bc	76.9 ± 7.2 ab	232 ± 18 bcd
Average		96.9 ± 3.0	53.7 ± 3.3	75.5 ± 2.9	220 ± 12

Note: B1 – without treatment, B2 – diazotroph complex, B3 – phosphate-mobilising complex. Same letters indicate no difference between variants in the column according to Tukey's HSD post-hoc test
Source: compiled by the authors

It should be noted that 'Volodar' produced a significantly greater amount of dry matter (101.8-123.5 g/m^2) during the period BBCH 51-65 compared with other cultivars. Seed treatment with the phosphate-mobilising complex resulted in a significantly higher increase than with the diazotroph complex and the control variant. The difference between the variants was insignificant for the 'Podilska', while the phosphate-mobilising complex showed significant effectiveness in the 'Kamyanchanka'. As mentioned earlier in the ANOVA section, the seed treatment factor did not have a significant impact on the accumulation of dry biomass during BBCH 65-67 and BBCH 67-71, so individual variation was observed only among cultivars. 'Volodar' accumulated dry matter more intensively during BBCH 65-67 than the others, but the situation reversed during BBCH 67-71.

The results of this research confirm the well-known thesis regarding the effectiveness of the combined application of diazotrophs from different genera, manifested in increased plant biomass, yield, and individual productivity (Singh *et al.*, 2015; Mazurenko *et al.*, 2020). It should be noted that diazotrophs respond differently to weather conditions; therefore, the effect of their application may depend on available moisture, temperature, nutrient reserves, and varietal sensitivity. As noted by Y. Tao *et al.* (2004), diazotrophs can also participate in the decomposition of organic matter, thereby improving trophic interactions in the buckwheat rhizosphere. In their pot experiment, S. Tummaramatti *et al.* (2016) found that seed treatment complexes containing *Azotobacter chroococcum*, *Azospirillum brasilense*, *Trichoderma harzianum*, and mycorrhiza fully realise the potential of plants in biomass accumulation and the formation of maximum leaf parameters. In the present study, a similar complex proved highly effective, resulting in growth increases of several tens of per cent compared with the control. It should be noted that buckwheat productivity is limited; thus, biopreparations act as stimulants, with the productivity potential constrained by the nutrients available in the soil (Oljača *et al.*, 2012; Dykyi *et al.*, 2022). Photosynthetic activity in the post-anthesis period shows a significantly higher correlation with yield, as biomass is transferred to the fruits. For this reason, larger biomass usually leads to higher yield levels (Ehdaie *et al.*, 2008; Tang *et al.*, 2017). The obtained results for leaf area index and dry matter accumulation are also consistent with existing knowledge and confirm the importance of the post-anthesis period, when optimal conditions for plant productivity must be ensured (Guglielmini *et al.*, 2019). This underscores that the biostimulating effect of plant growthpromoting microorganisms is as important as supplying plants with nutrients.

CONCLUSIONS

In this study, the influence and interrelationship between the content of photosynthetic pigments and the leaf area index (LAI) of buckwheat plants under pre-sowing seed treatment were identified. Seed treatment with phosphate-mobilising and diazotrophic complexes enhanced vegetative indices and buckwheat productivity. The pigment content in buckwheat leaves largely depended on and varied under the influence of the pre-sowing seed treatment compared with the weather factor at the BBCH 51 stage. At the BBCH 65 stage, the varietal factor assumed significant importance in determining chlorophyll concentration relative to other studied factors. A variable trend in the formation of photosynthetic pigments in leaves was observed. Both preparations significantly increased the content of photosynthetic pigments during the budding phase (BBCH 51), mainly due to chlorophyll *a*, but only phosphatemobilising complexes were generally effective during the flowering phase (BBCH 65).

The leaf area index depended on the developmental stage of buckwheat and the studied factors. Seed treatment and weather conditions produced greater variation in LAI at the BBCH 51 stage than the varietal factor. The pre-sowing seed treatment factor had no significant effect on the leaf area index overall. The increase in indices does not have universal species-level significance, as the varietal factor influences all parameters. The application of biopreparations significantly increased the leaf area index and dry biomass accumulation until mid-flowering. However, the impact on biomass growth from midflowering to fruit formation was not statistically significant.

Despite previous studies on the use of biopreparations in buckwheat cultivation technology, no published results have examined their effect on chlorophyll content, leaf area index, and dry biomass accumulation at different growth and development stages. The present findings confirm the positive influence of pre-sowing buckwheat seed treatment on chlorophyll concentration, leaf area index, and dry biomass accumulation. These conclusions are particularly relevant for improving buckwheat cultivation technology under organic production systems using biopreparations. Further research should assess the impact of microbiological preparations on the generative development of buckwheat, including the formation of floral organs and subsequent seed yield components.

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CONFLICT OF INTEREST

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REFERENCES

[1] Almashova, V.S., & Skok, S.V. (2022). Effectiveness of application of biological preparations and plant growth regulators for growing agricultural crops in the Southern Steppe zone of Ukraine. *Bulletin of Sumy National Agrarian University. The Series: Agronomy and Biology*, 47(1), 11-17. doi: 10.32845/agrobio.2022.1.2.

[2] Breslauer, R., Nalbandian, E., Reinman, T., Rezaey, M., Ganjyal, G.M., & Murphy, K.M. (2023). Buckwheat production and value-added processing: A review of potential western Washington cropping and food system applications. *Sustainability*, 15(20), article number 14758. doi: 10.3390/su152014758.

[3] Chen, M. (2014). Chlorophyll modifications and their spectral extension in oxygenic photosynthesis. *Annual Review of Biochemistry*, 83(1), 317-340. doi: 10.1146/annurev-biochem-072711-162943.

[4] Convention on Biological Diversity. (1992, May). Retrieved from https://www.cbd.int/.

[5] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1973, March). Retrieved from https://cites.org/eng.

[6] Dykyi, O., Lykhochvor, V., & Bahay, T. (2022). Influence of mineral fertiliser and foliar dressing rates on buckwheat yield. *Scientific Horizons*, 25(2), 47-54. doi: 10.48077/scihor.25(2).2022.47-54.

[7] Ehdaie, B., Alloush, G.A., & Waines, J.G. (2008). Genotypic variation in linear rate of grain growth and contribution of stem reserves to grain yield in wheat. *Field Crops Research*, 106(1), 34-43. doi: 10.1016/j.fcr.2007.10.012.

[8] Guglielmini, A.C., Forcat, J.I., & Miralles, D.J. (2019). The critical period for yield determination in common buckwheat (*Fagopyrum esculentum* Moench). *European Journal of Agronomy*, 110, article number 125933. doi: 10.1016/j.eja.2019.125933.

[9] Honchar, L., Mazurenko, B., Shutyi, O., Pylypenko, V., & Rakhmetov, D. (2021). Effect of pre-seed and foliar treatment with nano-particle solutions on seedling development of tiger nut (*Cyperus Esculentus* L.) plants. *Agronomy Research*, 19(S1), 767-776. doi: 10.15159/ar.21.021.

[10] Honchar, L., Mazurenko, B., Sonko, R., Kyrpa-Nesmiian, T., Kovalenko, R., & Kalenska, S. (2020). Biochemical responses of 5 buckwheat (*Fagopirum esculentum* Moench.) cultivars to seed treatment by *Azospirillum brasilense*. *Agronomy Research*, 18(SI3), 1680-1688. doi: 10.15159/ar.20.080.

[11] Hudzovskyi, A., Demianenko, I., & Levtun, I. (2024). The impact of metal oxide-based nanofertilisers on the physicochemical properties of agricultural plants. *Biological Systems: Theory and Innovation*, 15(3), 28-40. doi: 10.31548/biologiya/3.2024.28.

[12] Karbivska, U., Kunychak, G., Dutchak, O., Karpuk, L., Tatarchuk, L., Kashtanova, T., Shelenko, D., Hryhoriv, Ya., Gniezdilova, V., & Sluchyk, I. (2024). Application of biologization elements in buckwheat organic cultivation technology. *Ecological Engineering & Environmental Technology (EEET)*, 25(5), 235-242. doi: 10.12912/27197050/186125.

[13] Karpenko, V.P., Mostoviak, I.I., Datsenko, A.A., Prytuliak, R.M., & Zabolotnyi, O.I. (2021). The content of photosynthetic pigments in buckwheat leaves under the influence of biological preparations. *Scientific Issue Ternopil Volodymyr Hnatiuk National Pedagogical University. Series: Biology*, 81(1-2), 83-89. doi: 10.25128/2078-2357.21.1-2.11.

[14] Kotykova, O.T., & Ten, I.V. (2018). Production and marketing of organic agricultural products in Ukraine. *Modern Economics*, 12, 106-111. doi: 10.31521/modecon.V12(2018)-16.

[15] Kuchechuk, L.V. (2022). Global food security: Trends and challenges. *The Journal of V.N. Karazin Kharkiv National University. Series: International Relations. Economics. Country Studies. Tourism*, 16, 34-40. doi: 10.26565/2310-9513-2022-16-04.

[16] Kunsook, K., Thammaboosadee, S., & Chuckpaiwong, R. (2024). Sustainable organic farming maturity model. *International Journal on Advanced Science, Engineering & Information Technology*, 14(2), 706-716. doi: 10.18517/ijaseit.14.2.19504.

[17] Mazurenko, B., Novytska, N., & Honchar, L. (2020). Response of spring and facultative triticale on microbial preparation (*Azospirillum brasilense* and *Bacillus polymyxa*) by different nitrogen nutrition. *Journal of Central European Agriculture*, 21(4), 763-774. doi: 10.5513/JCEA01/21.4.2914.

[18] Meteopost. (n.d.). Retrieved from https://meteopost.com/.

[19] Oljača, S., Dolijanović, Ž., Oljača, M.V., & Djordjević, S. (2012). Effect of microbiological fertilizer and soil additive on yield of buckwheat (*Fagopyrum esculentum* Moench) under high altitude conditions. *Ratarstvo i Povrtarstvo*, 49(3), 302-306. doi: 10.5937/ratpov49-2528.

[20] Shuvar, A.M., Rudavska, N.M., Begen, L.L., & Dorota, G.M. (2019). The effect of biological preparations for seed treatment under organic buckwheat cultivation technology. *Foothill and Mountain Agriculture and Animal Husbandry*, 66, 184-194.

[21] Singh, R., Babu, S., Avasthe, R.K., Yadav, G.S., Chettri, T.K., Phempunadi, C.D., & Chatterjee, T. (2015). Bacterial inoculation effect on soil biological properties, growth, grain yield, total phenolic and flavonoids contents of common buckwheat (*Fagopyrum esculentum* Moench) under hilly ecosystems of North-East India. *African Journal of Microbiology Research*, 9(15), 1110-1117. doi: 10.5897/AJMR2014.7357.

[22] Tang, Y., Wu, X., Li, C., Yang, W., Huang, M., Ma, X., & Li, S. (2017). Yield, growth, canopy traits and photosynthesis in high-yielding, synthetic hexaploid-derived wheats cultivars compared with non-synthetic wheats. *Crop and Pasture Science*, 68(2), 115-125. doi: 10.1071/CP16072.

[23] Tao, Y.P., Shf, Q., Zhangl, X., & Zhou, Y.N. (2004). Inoculation effect on growth and flavonoid content of Tartary buckwheat in a field experiment. *Fagopyrum*, 21, 45-50.

[24] Tummaramatti, S., Hegde, L., Vijaykumar, N., Chandra, J., & Narayanapur, V.B. (2016). Pot experiment: Studies on effect of bio-fertilizers on Buckwheat (*Fagopyrum esculentum* Moench). *Ecology, Environment and Conservation*, 22, 55-58.

[25] Vieites-Álvarez, Y., Hussain, M.I., Reigosa, M.J., Kolmanič, A., Meglič, V., Čepková, P.H., Zhou, M., Janovská, D., & Sánchez-Moreiras, A.M. (2024a). Potential of different common (*Fagopyrum esculentum* Moench) and Tartary (*Fagopyrum tataricum* (L.) Gaertn.) buckwheat accessions to sustainably manage surrounding weeds. *European Journal of Agronomy*, 153, article number 127040. doi: 10.1016/j.eja.2023.127040.

[26] Vieites-Álvarez, Y., Reigosa, M.J., & Sánchez-Moreiras, A.M. (2024b). A decade of advances in the study of buckwheat for organic farming and agroecology (2013-2023). *Frontiers in Plant Science*, 15, article number 1354672. doi: 10.3389/fpls.2024.1354672.

[27] Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., & Song, K. (2024). Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. *Agronomy*, 14(3), article number 609. doi: 10.3390/agronomy14030609.

[28] Witkowicz, R., Skrzypek, E., Gleń-Karolczyk, K., Krupa, M., Biel, W., Chłopicka, J., & Galanty, A. (2021). Effects of application of plant growth promoters, biological control agents and microbial soil additives on photosynthetic efficiency, canopy vegetation indices and yield of common buckwheat (*Fagopyrum esculentum* Moench). *Biological Agriculture & Horticulture*, 37(4), 234-251. doi: 10.1080/01448765.2021.1918579.

[29] Zhang, Y., Guo, R., Li, S., Chen, Y., Li, Z., He, P., Huang, X., & Huang, K. (2021). Effects of continuous cropping on soil, senescence, and yield of Tartary buckwheat. *Agronomy Journal*, 113(6), 5102-5113. doi: 10.1002/agj2.20929.

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Фотосинтетична активність та продуктивність гречки (*Fagopyrum esculentum* Moench) за дії азотфіксуючих та фосфатмобілізуючих бактерій

Анотація. Одним з ефективних способів підвищення урожайності сільськогосподарських культур є передпосівна обробка насіння азотфіксуючими та фосфатмобілізуючими бактеріями. Специфічні властивості формування продуктивності гречки обмежують планову врожайність та реалізацію сортового потенціалу, обумовлюючи зростання вегетативних показників на початкових етапах росту та розвитку. Дослідження проводилися на трьох сортах гречки протягом 2022-2023 рр. в умовах лісостепу України. Метою досліджень було встановити вплив обробки насіння гречки на вміст фотосинтетичних пігментів, накопичення біомаси, індекс листкової площі в генеративний період розвитку та врожайність. Встановлено вплив на ріст біомаси від середини цвітіння до формування плодів, який був незначним, але відзначено різну тенденцію формування фотосинтетичних пігментів у листі. Біопрепарати значно підвищили вміст фотосинтетичних пігментів у фазі бутонізації (BBCH 51), головним чином за рахунок хлорофілу *a*, але у фазу цвітіння (BBCH 65) у більшості випадків ефективні були тільки фосфатмобілізуючі комплекси. Встановлено, що обробка насіння азотфіксуючими бактеріями дала змогу сформувати у гречки у фазу утворення плодів індекс листкової площі 5,27-5,48, що достовірно вище порівняно з контролем (4,19). При цьому накопичення біомаси в генеративний період змінювалось несуттєво за варіантів обробки насіння, але виникали морфологічні зміни, що сприяли формуванню більш високого показника врожаю, а отже, і врожайності. Встановлено, що передпосівна обробка насіння суттєво впливає на біометричні показники та врожайність, але нерідко проявляється сортовий чинник, що свідчить про перспективу подальших досліджень у напрямі оцінки формування генеративного апарату гречки під впливом мікробіологічних препаратів

Ключові слова: вміст хлорофілу; суха маса; листковий індекс; чиста продуктивність фотосинтезу; урожайність