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Mykola Suchek*
PhD in Agricultural Sciences
National University of Life and Environment Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0006-2773-1307
Svitlana Kalenska
Doctor of Agricultural Sciences, Professor
National University of Life and Environment Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-3392-837X
Bruce Knight
Doctor of Philosophy
Legume Technology LTD
DE7 5EP, Furnace Road Str., Ilkeston, United Kingdom
https://orcid.org/0009-0002-3659-1677
Roman Sonko
Head of Laboratory
National University of Life and Environment Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-2309-7226

Photosynthetic activity of oat crops under combined application of mineral fertilisers and biological preparation

Abstract. The effectiveness of photosynthesis in oat crops with the combined use of mineral fertilisers and biological products in order to reduce mineral fertiliser rates and increase productivity is extremely relevant. The aim of the study was to establish the effectiveness of the combined use of mineral fertilisers and biological preparations by activating the photosynthetic activity of oat crops and their productivity. The study was conducted using field, laboratory and mathematical methods of analysis. The research results were statistically calculated and interpreted. The results of research on the formation of leaf surface area and net photosynthetic productivity of the 'Ivory' oat variety in the right-bank forest-steppe zone of Ukraine depending on fertiliser rates, pre-sowing treatment of seeds with biological preparations of phosphate-mobilising action Polymixobacterin based on the bacterium *Paenibacillus polymyxa*, and Mycofix based on the mycorrhizal fungus *Glomus*

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*Corresponding author

intraradices using treated and untreated seeds. With combined treatment of seeds with a fungicide and Mycofix, the maximum leaf area was formed – 44.6-64.5 thousand m²/ha depending on the fertilisation background. When sowing with treated seeds against the background of $N_{90}P_{90}K_{90}$, 60.9 thousand m²/ha of leaf area was formed, and when treated with fungicide and additional treatment with Polimixobacterin or Mycofix against a background of $N_{90}P_{60}K_{90}$, 61.3 and 63.9 thousand m²/ha, respectively. With a reduction in phosphorus to $N_{90}P_{30}K_{90}$ and seed treatment according to the same scheme, the leaf area was 61.0 and 63.2 thousand m²/ha, respectively, at the BBCH 62-65 stage. A close positive correlation was established – the correlation coefficient between yield and leaf area at the BBCH 63-64 stage was 0.87-0.89. The practical value of the study was to establish a compensatory effect of the combined use of biological preparations and mineral fertilisers, which made it possible to reduce fertiliser application rates without reducing the photosynthetic activity of crops and oat yield

Keywords: leaf area; net photosynthetic productivity; fertiliser rates; Polymixobacterin; Mycofix; yield

INTRODUCTION

The relevance of the study was associated with the search for ways to increase the production of a valuable crop – oats (*Avena sativa*). Oats are a versatile crop, in particular, oat grain is a valuable raw material for the production of dietary and baby food products. The production of such grain requires the use of technologies that reduce the use of chemical fertilisers while activating the genetic potential of varieties through the use of biological preparations.

Oats have a fairly short growing season, during which intensive synthesis of organic matter occurs through photosynthesis. The directions for improving the efficiency of photosynthesis are quite different from the modelling of the selection genome, according to N. Smith *et al.* (2019) and F. Morales *et al.* (2020), as indicated by O. Todosiichuk (2024), crop cultivation technologies that increase leaf surface area, effective transpiration and solar energy absorption. M. Duda *et al.* (2021) emphasise that one of the main technological factors determining the intensification of photosynthesis and increased disease resistance is the fertilisation system, dry matter accumulation, and yield formation with targeted grain quality. When producing such grain, it is necessary to adhere to technologies that reduce the use of chemical fertilisers while activating the genetic potential of varieties through the use of biological preparations. Research by A. Kravchenko *et al.* (2023) demonstrates that F2 hybrids of naked oats exhibit transgressive variability in productive traits, which opens up prospects for increasing yield through breeding and agrotechnical measures. This emphasises that increasing the productivity of oats is possible not only through external agrotechnical factors, but also through the use of the internal potential of plants, which opens up additional opportunities for optimising cultivation technologies.

For a long time, it was believed, as emphasised by M. Stepanenko (2023), that global plant growth on the planet is largely limited by nitrogen supply – more so than by other nutrients. At the same time, research results are emerging, in particular from J. Paz-Ares *et al.* (2022) and S. Wang *et al.* (2025), which analytically prove that over the last four decades, phosphorus has been a stronger constraint on global photosynthesis than nitrogen. V. Volkogon (2023) argues that chemical fertilisers and pesticides are widely used to ensure food security and increase crop productivity. At the same time, V. Volkogon *et al.* (2019) emphasise that the reckless use of agrochemicals in turn leads to environmental pollution, which poses a threat to public health and soil degradation, deterioration of their chemical and biological condition. To increase the efficiency of mineral fertilisers applied to crops, scientists suggest combining the use of mineral fertilisers with microbial preparations for seed inoculation. The research is unquestionably novel in that it is the first study conducted on oats using a combination of mineral fertilisers, biological preparations, pre-sowing seed treatment, which made it possible to establish the possibility of controlling the photosynthetic activity of oat crops and compensatory reduction of mineral fertiliser rates through their combined use with biological preparations and seed treatment.

The aim of the study was to establish the effectiveness of the combined use of mineral fertilisers and biological preparations through the photosynthetic activity of oat crops. The objectives of the study were to identify: the characteristics of the formation of the leaf surface area of oat plants and the net productivity of photosynthesis depending on the rates of mineral fertilisers, pre-sowing treatment of seeds with biological preparations and seed dressing; the compensatory effect of biological preparations and other nutritional components, pre-sowing seed treatment on the formation of leaf surface area and net photosynthetic productivity of oat crops at reduced rates of mineral fertilisers, in particular phosphorus fertilisers; correlation dependencies between the photosynthetic activity of oat crops and yield depending on the factors studied.

LITERATURE REVIEW

Photosynthesis – the only process in the biosphere that allows the Sun's energy to be absorbed and ensures the existence of both plants and all heterotrophic organisms. N. Smith *et al*. (2019) emphasise that primary photosynthetic production sets an absolute upper limit for all heterotrophs and modern agricultural production. The photosynthetic apparatus, its architecture, spatial and temporal parameters, optical and biological properties for autotrophic organisms, all other things being equal, are the main source of energy for their vital functions and a determining factor in their productivity. L. Hu *et al*. (2019) and X. Song *et al*. (2019) indicate that the activity of photosynthetic processes in plants depends on the species and variety characteristics of crops, soil and climatic conditions, and the level of nutrient availability. As R. Kholodchenko (2014) points out, photosynthesis processes, the rate of increase in leaf area and respiration have a direct impact on plant growth and development, determining the rate of organic matter accumulation, structure and yield.

D. Lawlor (1995) argues that there are two main ways to increase dry matter accumulation through photosynthesis: extending the growing season; increasing the efficiency of light absorption and conversion by crops, which can be achieved by increasing the leaf surface area. The extension of the growing season is achieved through genetic mechanisms, as well as through a fertilisation system, which at the same time significantly affects the formation of the leaf surface area and its activity, as proven by the research of R. Kholodchenko (2014). H. Tian *et al*. (2022) emphasise the importance of studying and increasing the photosynthetic activity of oats not only through the leaf surface, but also through other plant organs, especially the ear during grain filling, which is an important strategy for increasing crop yields, especially under stressful conditions. Oats are a moisture-loving crop, and drought significantly reduces the photosynthetic capacity of plants, leading to crop loss, although according to V. Sadras *et al*. (2017), non-leaf organs such as flower scales can compensate for this by increasing their photosynthetic contribution.

Scientists such as H. Zeng *et al*. (2024) show that droughts disrupt the internal physiological processes of plants, such as photosynthesis, reducing plant metabolism and causing premature ageing, which leads to lower yields. K. Juzoń *et al*. (2020) and H. Tian *et al*. (2022) show that drought causes accelerated degradation of photosynthetic components (chlorophyll, Rubisco, photosystem II, etc.) in the flag leaves of cereal crops. B. Zhao *et al*. (2021) prove that drought causes a 31-69% loss of oat grain yield. Compared to sufficient water supply, grain yield decreased by 36, 69 and 44% in the 'Shadow' variety and by 31, 33 and 41% in the 'Bia' variety under severe stress at the stages of stem elongation, heading or after flowering. Under conditions of sufficient water supply, the 'Shadow' variety showed a 13-16% longer leaf area functioning period and had a significantly larger leaf area at the heading and post-flowering stages, resulting in 13-20% more spikelets per panicle and 13-21% higher grain yield than the 'Bia' variety. Water stress at the heading stage for the 'Shadow' variety and at the post-flowering stage for the 'Bia' variety was detrimental to grain yield due to a decrease in the grain weight/leaf area ratio, duration of functioning and a decrease in leaf area.

Optimising the nutrition of oat plants helps to realise the biological potential of varieties at a higher level. S. Wang *et al.* (2025), based on the analysis of more than 80,000 field observations of nutrient elements in leaves, created a long-term global dataset on nitrogen (N) and phosphorus (P) concentrations in leaves during 1980-2017. A more intense decrease in phosphorus concentration in leaves (-0.80 ± 0.008% year^{-1}) than in N concentration (-0.31 ± 0.002% year^{-1}) was observed. This decline led to an increase in terrestrial areas with limited phosphorus content in leaves and a large-scale reduction in plant photosynthesis, more than 1.5 times stronger than the reduction due to lower nitrogen content in leaves. The increasing trend in global photosynthesis over the past four decades has been reduced by approximately 17.2% and 6.7% due to the reduction in phosphorus and nitrogen content in leaves, respectively. This stronger phosphorus limitation of global photosynthesis implies a weakening of terrestrial carbon sinks due to emerging phosphorus limitations and calls for more stringent strategies to reduce anthropogenic emissions to mitigate climate warming. S. Xu *et al.* (2020) also show a significant response of plants to the ratio of carbon, nitrogen, and phosphorus content in leaves and CO_2 uptake in relation to climate change and air emissions. Carbon accumulation in leaves mainly comes from the balance between photosynthesis and leaf respiration, a topic that remains insufficiently studied.

V. Volkogon *et al.* (2019) emphasise the extreme importance of improving the efficiency of phosphorus fertiliser use. According to J. Paz-Ares *et al.* (2022), the inefficiency of phosphorus fertilisers is related to their properties: only 15-25% is absorbed by plants, and the rest is washed away, causing soil degradation and water eutrophication. N. Smith *et al.* (2019) prove that by applying bacterial inoculation to cereal seeds, it is possible to improve their phosphorus supply and increase yields. Similar conclusions regarding the use of bacteria and their effectiveness when used in combination with mineral fertilisers were also reached by E. Kuter *et al.* (2023). According to S. Kumar *et al.* (2022) and K. Marchenko (2022), beneficial mechanisms for improving plant growth include increasing nutrient availability, modulating phytohormones, biocontrol of phytopathogens, and mitigating biotic and abiotic stresses. At the same time, according to P. Murgese *et al.* (2020), O. Fasusi *et al.* (2021), and S. Nacoon *et al.* (2021), the use of beneficial microbiomes as biofertilisers in sustainable agricultural practices has become an innovative and environmentally friendly technology for improving soil fertility and plant growth. B. Glick & E. Gamalaro (2021) point out that microbes, which are phylogenetically diverse and multifaceted, interact with plants in various ways: symbiosis, parasitism, commensalism, amensalism, and neutralism. At the same time, as A. Potapov & M. Hrabovsky (2023) point out, the growth of these microbes depends on plant photosynthesis, while simultaneously influencing plant growth, which is why they are collectively referred to as the plant microbiome.

A. Johnston *et al.* (2014) found that the determining factor in the mobilisation of phosphorus for plants is the activity of soil microbiota, namely microorganisms that have the potential to convert poorly soluble soil phosphates into a form accessible to plants and produce physiologically active substances. The hyphae of mycorrhizal fungi are able to penetrate plant root cells, forming vesicles (swelling) and arbuscules (tree-like branches). Once established in the root system of a plant, mycorrhizal fungi multiply and spread into the surrounding soil in the form of a large mass of absorbent threads, increasing the plant's absorption of water and nutrients (Brisson *et al.*, 2022). However, these studies are insufficient, especially given the establishment of the photosynthetic activity of oat plants and their productivity depending on a complex of environmental factors, cultivation technologies and soils.

MATERIALS AND METHODS

The research was conducted in 2019-2021 in a demonstration and production experiment by the Vitagro group of companies, Agrarian Company 2004 (experimental field 5/3 of the "Tovtry" Cluster, Lisovody village, Horodok municipal community, Khmelnytskyi district, Khmelnytskyi region. Geolocation: 49°09'35.8'N

26°28'32.9'E). A field experiment was set up to achieve the set goal. The soil of the experimental plots is podzolised chernozem, which is considered favourable for the formation of highly productive crops. The soil humus content is 3.7-3.9%; alkali-hydrolysed nitrogen – 108-115 mg/kg of soil; mobile phosphorus – 170-180; exchangeable potassium – 115-120 mg/kg of soil. The soil solution reaction is neutral – pH 6.8-7.1; hydrolytic acidity is low – 0.60-0.80 mg – eq/100 g of soil; the sum of absorbed bases is 38-42 mg – eq/100 g of soil. The main physical and water properties of the soil are good: specific gravity – 2.55 g/cm³, bulk density – 1.20-1.25 g/cm³, porosity – 55%. The maximum hygroscopicity was 5.1%; the minimum moisture capacity was 23.0%, and the total moisture capacity was 51.0%.

The field experiment was set up in accordance with the methodological requirements for conducting experiments (Rozhkov *et al.*, 2016). The area of the sowing plot was 50.4 m². The experiment was repeated three times, with the variants arranged sequentially. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976). According to the experiment scheme, mineral fertilisers were applied in the form of ammonium nitrate, simple granulated superphosphate, and granulated potassium chloride (Table 1). The full fertiliser rate was based on an equal ratio of nitrogen:phosphorus:potassium (N: P: K). Subsequently, for each full dose of nutrients, the phosphorus dose was reduced in increments of 30 kg/ha a.i. in order to determine the level of compensatory capacity of phosphate-mobilising biological products. The main application of fertilisers was carried out during pre-sowing soil cultivation.

Table 1. Scheme of the field experiment

Fertilisation, kg/ha a.i. – Factor A		**Seed treatment – Factor B**		**Biopreparation treatment – Factor C**	
Variant designation	Rate	Variant designation	Treatment	Variant designation	Seed treatment
K	Control (no fertilisers)	K1	Without treatment	K1	Control (no seed treatment)
U 1	$N_{30}P_{30}K_{30}$			K1P	Polymixobacterin
U 2	$N_{30}K_{30}$			K1M	Mycofix
U 3	$N_{60}P_{60K6}0$	K2	Seeds treated	K2	Control with seed dressing
U 4	$N_{60}P_{30}K_{60}$			K2N	Seed treatment + Polymixobacterin
U 5	$N_{90}P_{90}K_{90}$			K2M	Seed treatment + Mycofix
U 6	$N_{90}P_{60}K_{90}$				
U 7	$N_{90}P_{30}K_{90}$				

Source: scheme developed by the authors

For pre-sowing seed treatment, in accordance with the experimental design, Vincit 050 SC seed treatment was used at a rate of 2.0 l/t; phosphate-mobilising biological products: Polymixobacterin and Mycofix. The active ingredient of Polymixobacterin is phosphate-mobilising bacteria *Paenibacillus polymyxa* KB (Patent No. 99009 Ukraine), whose mechanism of action is related to the ability of bacteria to produce gluconic, acetic, succinic, uronic, lactic, butyric and other acids, as well as the enzyme phosphatase, which promotes the dissolution of poorly soluble minerals and the hydrolysis of organic phosphates in soil and fertilisers, resulting in the release of phosphorus into the soil. acids, as well as the enzyme phosphatase, which promotes the dissolution of poorly soluble minerals and the hydrolysis of organic phosphates in soil and fertilisers, thereby activating the process of phosphorus assimilation by plants. In addition to their effect on the dissolution of phosphorus compounds, *Paenibacillus polymyxa* KB bacteria produce phytohormonal substances that stimulate plant growth and development, influence the formation and development of the root system and its absorptive capacity, which also optimises phosphate uptake.

The Mycofix mycorrhizal inoculant (mycorrhizant) was developed by the British company Legume Technology Ltd. The mycorrhizal inoculant is based on the mycorrhizal fungus *Glomus intraradices* (CMCCROC7) – living vegetative cells, spores of the mycorrhizal fungus – 1% (minimum 2000 propagules (spores)/gram), with the remaining 99% being an extract of the marine alga *Ascophyllum nodosum* with a naturally low content of micro- and macroelements (surface-active substances). On the day of sowing, the seeds were treated according to the experimental scheme (Table 1). During the growing season in the field experiment, plant samples of oats were selected at the stages of plant growth and development: BBCH 27-29 (end of tillering), BBCH 37-39 (emergence of the flag leaf), BBCH 52-55 (formation of the panicle – appearance of 20-50% of the panicle – panicle node still in the leaf sheath).

To determine the leaf area of oats and calculate the net photosynthetic productivity, samples were taken at certain macro- or micro-stages in two non-contiguous replicates of 0.33 running metres, in which the wet weight, dry matter content and leaf area were determined. All leaves were separated from the sample and weighed. Ten leaves were selected, tightly folded together, and 10 punctures were made with a laboratory sampler of a specified diameter and calculated area – 100 "cuts" were selected, which were immediately weighed. The leaf surface area of the selected sample was determined by proportional ratio and converted to hectares. The net photosynthetic productivity of crops was determined by measuring the absolutely dry mass of plants in grams per 1 m² at the same stage (phase) as the determination of leaf surface area The net photosynthetic productivity (NPP) of plants was calculated using formula (1):

$$NPP = \frac{Usi - Us2}{0.5(L_1+L_2)T}, \tag{1}$$

where *Usi* and *Us2* – dry matter of plants at the studied stages of development, g/m^2; *L1* and *L2* – the average leaf area of plants during the studied period of development.

Laboratory tests were conducted in the scientific and production laboratory of Vitagro Partner TM Bayton (LLC "Ahrokhim Tekhnologii"). Oat cultivation technology. The experiment involved growing the 'Ivory' oat variety, bred by Saaten Union and registered in 2011. The variety belongs to the early maturing group. The sowing rate was 3.5 million viable seeds per hectare. The predecessor in the experiment was soybeans. After harvesting the predecessor, disc harrowing was carried out with a Rubin 12 (Lemken) heavy harrow to a depth of 14-16 cm in two passes. Fertilisers were applied with a Kuhn MDS 19.1 R2 mounted mineral fertiliser spreader during pre-sowing cultivation according to the experiment scheme. Pre-sowing cultivation was carried out with an AP-3 Europak unit. Sowing was carried out with a Horsch Pronto 6 DC PPF (Germany) seeder to a depth of 3.0-3.5 cm.

The protection system included a number of measures. During microstudies BBCH 21-29 (macrostage 2: tillering), the crops were treated with a tank mixture: herbicide protection – Pride (TM Bayton (2-ethylhexyl ester 2,4-D, 452, 42 g/l florasulam, 6.25 g/l) – 0.6 l/ha; fungicide protection – Duncan (TM Bayton Carbendazim, 250 g/l, Flutriafol, 125 g/l) – 0.6 l/ha; insecticide protection TOP (TM Bayton (Lambda-cyhalothrin, 50 g/l) – 0.2 l/ha. In microstage BBCH 41-49 (macrostage 4: panicle formation), oat crops were treated with a tank mixture: fungicide protection – Platon (TM Bayton (Prochloraz, 300 g/l + tebuconazole, 140 g/l + cyproconazole, 50 g/l) – 0.8 l/ha; insecticide protection – Shocker (TM Bayton (Imidacloprid, 300 g/l + lambda-cyhalothrin, 100 g/l) – 0.15 l/ha.

RESULTS AND DISCUSSION

The formation of the optimal leaf area directly depends on the technology used to grow crops, as indicated by D. Liubytska & R. Mialkovskyi (2024). K. Marchenko (2022) asserts that the best conditions for high yields are created by forming a larger leaf surface area, longer vegetation period, and photosynthetic potential. For the synthesis of organic matter and the formation of vegetative and generative organs, it is important that the total leaf surface area of the crop is optimal. The optimal area is considered to be one that ensures maximum gas exchange in plants. N. Smith *et al.* (2019) prove that the optimal size of the assimilation apparatus, which ensures intensive absorption of solar energy and high photosynthetic productivity, is between 40 and 45 thousand m^2/ha. Further growth of leaf area slightly increases photosynthetically active radiation and causes a decrease in net photosynthetic productivity due to the shading of leaves in the middle and lower tiers.

It has been established that the leaf area changed significantly depending on the plant fertilisation system, which caused both the intensification of photosynthesis and changes in plant parameters, in particular the size of the leaf area. The use of mineral fertilisers in various fertilisation schemes contributed to an increase in leaf surface area at all microstages of plant development, compared to the control variant, where fertilisers were not used. Oat plants form leaf surface area quite intensively already in the early stages of development, unlike other spring cereals, responding positively to fertiliser application. Thus, at microstages BBCH 27-29, the leaf area ranged from 11.6 to 31.8 thousand m^2/ha (Table 2). When sowing with untreated seeds, an area of 11.6 to 25.0 thousand m^2/ha was formed, depending on the nutrient background; when treating seeds with Polymixobacterin – 12.5-28.1; when treating seeds with Mycofix – 12.5-29.1. When sowing with treated seeds, 13.3-30.3 thousand m^2/ha of leaf surface area was formed; with additional treatment with Polymixobacterin – 13.7-13.3 thousand m^2/ha; with additional treatment with Mycofix – 13.6-31.8 thousand m^2/ha. The application of complete mineral fertiliser ensured increased growth intensity of the leaf surface of oats. In particular, in the 'Buh' variety, with intensive fertiliser application, the leaf surface area, depending on the fertilisation option, was: in the tillering phase 12.6-14.7; at the booting stage – 51.6-59.1; at milk ripeness 23.3-33.1 thousand m^2/ha.

Table 2. Leaf area of sown oat depending on fertilisation and seed treatment, tillering stage (BBCH 27-29), thousand m^2/ha

Fertiliser rate, kg/ha a.i.	Seed treatment									
	Untreated (К1)					Treated (К2)				
	Biopreparation seed treatment [1]									
	К1	P	M	Mean	+/- from fertiliser	К2	P	M	Mean	+/- from fertiliser
Control	11.6[2]	12.5	12.5	12.2	0.6	13.3[3]	13.7	13.6	13.5	-
$N_{30}K_{30}$	15.4	16.2	16.8	16.1	4.5	17.5	17.9	18.3	17.9	4.6
$N_{30}P_{30}K_{30}$	18.5	20.0	20.5	19.7	8.1	21.1	21.6	21.6	21.4	8.1
$N_{60}P_{60}K_{60}$	24.0	25.0	26.0	25.0	13.4	28.1	27.8	28.6	28.2	14.9
$N_{60}P_{30}K_{60}$	21.8	23.2	23.9	23.0	11.4	24.0	25.3	26.0	25.1	11.8
$N_{90}P_{30}K_{90}$	25.0	26.3	27.4	26.2	14.6	27.3	28.0	29.2	28.2	14.9
$N_{90}P_{60}K_{90}$	25.7	27.6	28.1	27.1	15.5	29.2	29.9	30.2	29.8	16.5
$N_{90}P_{90}K_{90}$	27.0	28.1	29.1	28.1	16.5	30.3	31.3	31.8	31.1	17.8
HIP	1.2	1.2	1.3	1.4		1.3	1.3	1.2	1.4	

Note: [1]P – Polymixobacterin; M – Mycofix; [2] and [3] – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021
Source: authors' research results

The process of leaf mass growth in oats is accelerated – already in the phase of plant emergence, the photosynthetic surface of oats increased almost twice – on average over the years of research from 11.6 in the tillering phase (BBCH 27-29) to 21.3 thousand m^2/ha in the booting phase (BBCH 37-39) in the variant without fertilisers, and from 31.8 to 40.6 thousand m^2/ha, respectively, with fertilisation and combined seed treatment with the Mikofix fungicide. At the same time, according to M. Stepanenko (2023), maize in the milk ripeness phase had a maximum leaf area of 35.7-42.1 thousand m^2/ha, significantly inferior to oats (Tables 2, 3, 4).

Table 3. Leaf area of sown oats depending on fertilisation and seed treatment, booting stage (BBCH 37-39), thousand m^2/ha

Fertiliser rate, kg/ha a.i.	Seed treatment									
	Untreated (K1)					Treated (K1)				
	Biopreparation seed treatment ^{1}									
	K1	P	M	Mean	+/- from fertiliser	K2	P	M	Mean	+/- from fertiliser
Control	21.3^2	23.0	23.7	22.7	1.4	23.7^3	25.1	25.4	24.7	-
$N_{30}K_{30}$	25.6	27.2	27.8	26.9	5.6	28.3	29.7	30.7	29.6	5.9
$N_{30}P_{30}K_{30}$	27.5	29.5	30.1	29.0	7.7	30.7	31.5	32.4	31.5	7.8
$N_{60}P_{60}K_{60}$	32.5	35.5	36.5	34.8	13.5	38.1	38.4	38.7	38.4	14.7
$N_{60}P_{30}K_{60}$	31.0	34.2	34.9	33.4	12.1	34.9	36.0	36.4	35.8	12.1
$N_{90}P_{30}K_{90}$	32.9	35.0	36.7	34.9	13.6	35.6	36.7	38.2	36.8	13.1
$N_{90}P_{60}K_{90}$	33.7	35.7	36.8	35.4	14.1	36.9	38.2	39.4	38.2	14.5
$N_{90}P_{90}K_{90}$	34.5	36.8	38.4	36.6	15.3	37.8	39.4	40.6	39.3	15.6
HIP										

Note: ^{1}P – Polymixobacterin; M – Mycofix; ^{2} and ^{3} – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021
Source: authors' research results

The assimilation surface of crops reached its maximum value during the flowering phase (BBCH 62-64). The range of changes in leaf surface area was from 38.1 thousand m^2/ha in the control variant (without fertilisers and without seed treatment) to 63.2-64.5 thousand m^2/ha when applying $N_{90}P_{30}K_{90}$, $N_{90}P_{60}K_{90}$, $N_{90}P_{90}K_{90}$ and sowing with seeds treated with a fungicide and Mycofix (Table 4).

Table 4. Leaf area of sown oats depending on fertilisation and seed treatment, beginning of flowering phase (BBCH 62-64), thousand m^2/ha

Fertiliser rate, kg/ha a.i., Factor A	Seed treatment, Factor B									
	Untreated (K1)					Treated (K2)				
	Biopreparation seed treatment ^{1}, Factor C									
	K1	P	M	Mean	+/- from fertiliser	K2	P	M	Mean	+/- from fertiliser
Control	38.1^2	41.3	42.0	40.5	-	42.3^3	44.0	44.6	43.6	-
$N_{30}K_{30}$	41.3	44.7	45.3	43.8	5.7	45.9	47.3	49.3	47.5	5.2
$N_{30}P_{30}K_{30}$	43.5	46.7	48.3	46.2	8.1	48.0	49.1	50.1	49.1	6.8
$N_{60}P_{60}K_{60}$	53.1	56.4	57.9	55.8	17.7	57.5	58.1	60.3	58.6	16.3
$N_{60}P_{30}K_{60}$	50.9	53.8	58.4	54.4	16.3	54.8	56.9	59.3	57.0	14.7
$N_{90}P_{30}K_{90}$	54.2	58.7	60.5	57.8	19.7	59.2	61.0	63.2	61.1	18.8
$N_{90}P_{60}K_{90}$	54.7	57.8	60.2	57.6	19.5	59.8	61.3	63.9	61.7	19.4
$N_{90}P_{90}K_{90}$	57.1	59.6	62.1	59.6	21.5	60.9	63.0	64.5	62.8	20.5
HIP	2.0	1.9	1.9	2.1	-	2.1	2.0	2.0	2.2	-

Note: ^{1}P – Polymixobacterin; M – Mycofix; ^{2} and ^{3} – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021
Source: authors' research results

Mineral fertilisers contributed to significant increases in leaf area. Thus, in the variant without fertiliser application and sowing with treated seeds, the assimilation area during the flowering phase was 42.3 thousand m^2/ha, while with the application of $N_{90}P_{90}K_{90}$ and the same seed treatment, it was 60.9 thousand m^2, or an increase of 43%. When sowing with non-treated seeds, the leaf surface area increased by 49.9%, or by 19.0 thousand m^2/ha, depending on the fertiliser rate. Similar results were obtained by M. Stepanenko (2023) in studies with corn to determine the effectiveness of new biological fertilisers. Pre-sowing seed treatment had a positive effect on the formation of leaf area. Thus, when seeds were treated only with a fungicide, the leaf area increased by 3.8-5.1 thousand m^2, depending on the fertilisation background, compared to similar nutrition backgrounds, but when sowing with untreated seeds. The growth is partly due to higher field germination of seeds and the formation of denser agrocenoses. Slightly higher increases compared to the control variant (untreated seeds) were achieved by treatment with the preparation Mikofix – 4.0-7.5 thousand m^2/ha; with the preparation Polymixobacterin – 2.4-4.5 thousand m^2/ha. With combined treatment of seeds with a fungicide and Mikofix, the maximum leaf area was obtained – 44.6-64.5 thousand m^2/ha depending on the fertilisation background, which is 6.5-9.1 thousand m^2/ha more than the control variant, and 2.3-4.0 thousand m^2/ha when treating seeds only with a fungicide. Similar results regarding the effectiveness of the combined use of the protection system and fertilisers were obtained in studies with sugar beet crops (Potapov & Hrabovskyi, 2023).

The compensatory effect of biological preparations was significant both against the background of different fertiliser rates and when using treated seeds for sowing compared to untreated seeds. The largest leaf area of oat crops was formed with the combined use of reduced fertiliser rates, in particular phosphorus, and seed treatment with phosphorus-mobilising preparations, compared to variants where full fertilisation with increased phosphorus rates was applied. Thus, when sowing with treated seeds against the background of $N_{90}P_{90}K_{90}$, 60.9 thousand m^2/ha of leaf surface area was formed, while when sowing with treated seeds and additional treatment with Polymixobacterin or Mycofix against the background of $N_{90}P_{60}K_{90}$, 61.3 and 63.9 thousand m^2/ha were formed, respectively. With a reduction in phosphorus by 60 kg/ha of active ingredient – to $N_{90}P_{30}K_{90}$ and seed treatment according to the same schem e, the leaf area was 61.0 and 63.2 thousand m^2/ha, respectively, at the BBCH 62-65 stage.

Thus, S. Ribou *et al.* (2013) and V. Volkogon *et al.* (2019) also assert that it is possible to reduce the rate of technical nitrogen through the use of biological products without reducing crop yields, which is realistic for low and medium mineral agro-backgrounds in the experiment. The intensity of plant foliage functioning is determined by net photosynthetic productivity (NPP). Net photosynthetic productivity is determined by both the dynamics of biomass accumulation by crops and the leaf area. NPP and leaf area are closely related. The results of the studies indicate a significant influence of mineral fertilisers, pre-sowing seed treatment and weather conditions of the year on the net productivity of crops (Table 5).

Table 5. Net photosynthetic productivity of oat crops depending on the level of mineral nutrition and seed treatment, period – stages BBCH 27-64 g/m2 per day

Fertiliser rate, kg/ha a.i., Factor A	**Seed treatment, Factor B**										**Gains from absolute control**
	Untreated					**Treated**					
	Biopreparation seed treatment [1], Factor C										
	-	**P**	**M**	**Mean**	**+/-from fertiliser**	**-**	**P**	**M**	**Mean**	**+/-from fertiliser**	
2019											
Control	1.68[2]	1.85	1.80	1.78	-	1.93[3]	1.95	1.92	1.93	-	0.25
$N_{30}K_{30}$	2.12	2.27	2.31	2.23	0.55	2.42	2.48	2.52	2.47	0.54	0.79
$N_{30}P_{30}K_{30}$	2.18	2.35	2.42	2.32	0.64	2.44	2.53	2.53	2.50	0.57	0.82
$N_{60}P_{60}K_{60}$	2.85	2.99	3.05	2.96	1.28	3.11	3.28	3.36	3.25	1.32	1.57
$N_{60}P_{30}K_{60}$	2.64	2.85	2.90	2.80	1.12	3.04	3.09	3.12	3.08	1.15	1.40
$N_{90}P_{30}K_{90}$	3.01	3.31	3.40	3.24	1.56	3.49	3.58	3.64	3.57	1.64	1.89
$N_{90}P_{60}K_{90}$	3.18	3.40	3.43	3.34	1.66	3.82	3.72	3.91	3.82	1.89	2.14
$N_{90}P_{90}K_{90}$	3.21	3.31	3.37	3.30	1.62	3.79	3.82	3.85	3.82	1.89	2.14

Table 5, Continued

Fertiliser rate, kg/ha a.i., Factor A	Seed treatment, Factor B										Gains from absolute control
	Untreated					Treated					
	Biopreparation seed treatment [1], Factor C										
	-	P	M	Mean	+/-from fertiliser	-	P	M	Mean	+/-from fertiliser	
2020											
Control	2.80^2	3.00	3.02	2.94	-	3.14^3	3.28	3.30	3.24	-	0.24
$N_{30}K_{30}$	2.91	3.11	3.14	3.05	0.25	3.23	3.38	3.40	3.34	0.20	0.34
$N_{30}P_{30}K_{30}$	3.09	3.37	3.40	3.29	0.49	3.49	3.62	3.65	3.59	0.45	0.59
$N_{60}P_{60}K_{60}$	3.12	3.24	3.37	3.24	0.44	3.46	3.56	3.71	3.58	0.44	0.58
$N_{60}P_{30}K_{60}$	3.10	3.29	3.41	3.27	0.47	3.38	3.63	3.72	3.58	0.44	0.58
$N_{90}P_{30}K_{90}$	3.22	3.35	3.41	3.33	0.53	3.48	3.61	3.80	3.63	0.49	0.63
$N_{90}P_{60}K_{90}$	3.30	3.56	3.63	3.50	0.70	3.66	3.76	3.86	3.76	0.62	0.76
$N_{90}P_{90}K_{90}$	3.51	3.69	3.79	3.66	0.86	3.93	4.07	4.11	4.04	0.90	1.04
2021											
Control	2.22^2	2.33	2.42	2.32	-	2.42^3	2.46	2.62	2.50	-	0.28
$N_{30}K_{30}$	2.31	2.43	2.56	2.43	0.21	2.61	2.66	2.73	2.67	0.25	0.45
$N_{30}P_{30}K_{30}$	2.34	2.43	2.55	2.44	0.22	2.57	2.62	2.67	2.62	0.20	0.40
$N_{60}P_{60}K_{60}$	3.08	3.26	3.30	3.21	0.99	3.48	3.57	3.60	3.55	1.13	1.33
$N_{60}P_{30}K_{60}$	3.00	3.18	3.30	3.16	0.94	3.27	3.51	3.60	3.46	1.04	1.24
$N_{90}P_{30}K_{90}$	3.17	3.33	3.39	3.30	1.08	3.52	3.42	3.61	3.52	1.10	1.30
$N_{90}P_{60}K_{90}$	3.24	3.40	3.53	3.39	1.17	3.50	3.63	3.76	3.63	1.21	1.41
$N_{90}P_{90}K_{90}$	3.33	3.46	3.63	3.47	1.25	3.56	3.76	3.86	3.73	1.31	1.51
2019-2021											
Control	2.23^2	2.39	2.41	2.34	-	2.50^3	2.56	2.61	2.56	-	0.33
$N_{30}K_{30}$	2.45	2.6	2.67	2.57	0.12	2.75	2.84	2.88	2.82	0.32	0.59
$N_{30}P_{30}K_{30}$	2.54	2.72	2.79	2.68	0.14	2.84	2.92	2.95	2.90	0.40	0.67
$N_{60}P_{60}K_{60}$	3.02	3.17	3.24	3.14	0.12	3.35	3.47	3.56	3.46	0.96	1.23
$N_{60}P_{30}K_{60}$	2.91	3.11	3.20	3.07	0.16	3.23	3.41	3.48	3.37	0.87	1.14
$N_{90}P_{30}K_{90}$	3.13	3.33	3.40	3.29	0.16	3.50	3.54	3.69	3.58	1.08	1.35
$N_{90}P_{60}K_{90}$	3.24	3.46	3.53	3.41	0.17	3.66	3.70	3.84	3.73	1.23	1.50
$N_{90}P_{90}K_{90}$	3.35	3.49	3.60	3.48	0.13	3.76	3.88	3.94	3.86	1.36	1.63
HIP for the factor:											
A	0.18	0.18	0.19	0.21		0.19	0.21	0.20	0.22		
B						0.16	1.16	0.15	0.17		
C	0.05	0.04	0.05	0.6		0.06	0.05	0.06	0.07		

Note: [1]P – Polymixobacterin; M – Mycofix; [2] – absolute control by year and control for untreated seeds; [3] – controls by year for treated seeds
Source: results of authors' research and calculations

During the years of research, the highest NPP was in 2020 and 2021, and the lowest was in the dry year of 2019. The negative impact of drought on the photosynthetic activity of oats is also indicated by V. Sadras *et al.* (2017). B. Zhao *et al.* (2021) prove that drought causes a 31-69% loss of oat grain yield. At the beginning of vegetation, the NPP increases sharply until the booting stage. The assimilation surface area of the crop also increases sharply during this period. Further, the rate of increase in the size of the photosynthetic surface decreases, and, accordingly, the NPP also begins to decrease. Thus, when growing oats without fertilisers, the NPP was 2.23-2.61 g/m² per day, depending on seed treatment, while the application of complete mineral fertiliser increased it to 3.35-3.94 g/m² per day, or by 50-51%. The highest net photosynthetic productivity was observed when sowing with treated seeds in combination with the mycorrhizal preparation Mycofix against the background of $N_{90}P_{90}K_{90}$ – 3.94 g/m² per day, which is 0.59 g/m² per day more than the control variant (without treatment) and 0.42 g/m² per day more than with only treated seeds. In the variants where phosphorus fertiliser rates were reduced by 30 and 60 kg/ha a.i., and the seeds were treated with a fungicide and biological preparations, the NPP of the crops provided an increase to the level of treatment with only a fungicide against the background of full fertilisation, which proves the significant phosphate-mobilising and growth-stimulating effect of the studied biological preparations.

The results of the study coincide with the conclusions of V. Volkogon *et al*. (2019) that the combined use of microbial preparations with reduced fertiliser rates is an important strategy for managing and reducing environmental problems by reducing the use of chemical fertilisers. At the same time, unlike publications that justify the complete replacement of mineral fertilisers with agronomically valuable microorganisms, the results of the study are equivalent to the conclusions of V. Volkogon (2023) regarding the effective combination of mineral and biological factors in fertilising agricultural crops as a solution in which both resources can synergistically interact to improve nutrition and provide other biological functions necessary for the harmonious development of plants. Calculations of the correlation between yield and leaf area at variable rates of fertilisers and biological products revealed a very close positive correlation. The correlation coefficient between yield and leaf area at the BBCH 63-64 stage for sowing with untreated seeds was 0.87, and for sowing with treated seeds – 0.89.

CONCLUSIONS

Sown oat responds positively to the application of mineral fertilisers, which is manifested in an increase in leaf area. Photosynthetic activity of crops is activated as a whole due to an increase in net photosynthetic productivity. Oats intensively form leaf surface area already in the early microstages of development, effectively using the applied nutrients. The compensatory effect of the use of biological preparations is significant both against the background of different fertiliser rates and when using treated seeds for sowing compared to untreated seeds. The largest leaf area of oat crops was formed with the combined use of reduced fertiliser rates, in particular phosphorus, and seed treatment with phosphorus-mobilising preparations, compared to variants where full fertilisation with increased phosphorus rates was applied. When sowing with treated seeds against the background of $N_{90}P_{90}K_{90}$, 60.9 thousand m²/ha of leaf surface area was formed, and with treated seeds and additional treatment with Polimixobacterin or Mycofix against a background of $N_{90}P_{60}K_{90}$ – 61.3 and 63.9 thousand m²/ha, respectively. With a reduction in phosphorus to $N_{90}P_{30}K_{90}$ and seed treatment according to the same scheme, the leaf area was 61.0 and 63.2 thousand m²/ha, respectively, at the BBCH 62-65 stage.

Pre-sowing seed treatment contributes to the formation of a larger leaf area – when seeds were treated with a fungicide, the leaf area increased by 3.8-5.1 thousand m², depending on the fertilisation background, compared to untreated seeds. Increases over the control variant (untreated seeds) were achieved by treating the seeds with Mikofix – 4.0-7.5 thousand m²/ha; with Polimixobacterin – 2.4-4.5 thousand m²/ha. With combined treatment of seeds with a fungicide and Mikofix, the maximum leaf area was obtained – 44.6-64.5 thousand m²/ha, depending on the fertilisation background, or 6.5-9.1 thousand m²/ha more compared to the control variant and 2.3-4.0 thousand m²/ha compared to the control variant and by 2.3-4.0 thousand m²/ha compared to seed treatment with only a fungicide. A very close positive correlation was established between yield and leaf surface area at variable rates of fertilisers and biological products – the correlation coefficient at the BBCH 63-64 stage for sowing with untreated seeds was 0.87, and 0.89 for sowing with treated seeds. The prospect for further research lies in the need to conduct agrochemical and microbiological analysis of the soil with calculations of the balance of nutrients and their availability to plants.

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Микола Сучек
Кандидат сільськогосподарських наук
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0006-2773-1307
Світлана Каленська
Доктор сільськогосподарських наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-3392-837X
Брюс Найт
Доктор філософії
«Легум Технолоджі»
DE7 5EP, вул. Фернесс-Роуд, м. Ілкестон, Велика Британія
https://orcid.org/0009-0002-3659-1677
Роман Сонько
Завідувач лабораторії
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-2309-7226

Фотосинтетична активність посівів вівса посівного за комбінованого застосування мінеральних добрив та біопрепаратів

Анотація. Ефективність фотосинтезу посівів вівса посівного за комбінованого використання мінеральних добрив та біопрепаратів з метою зниження норм мінеральних добрив та підвищення продуктивності є надзвичайно актуальною. Метою дослідження було встановлення ефективності комбінованого використання мінеральних добрив та біологічних препаратів шляхом активізації фотосинтетичної діяльності посівів вівса та його продуктивності. Дослідження проведенні з використанням польового, лабораторних та математичних методів аналізування. Результати досліджень статистично обраховані та інтерпретовані. Представлено результати досліджень з формування площі листкової поверхні та чистої продуктивності фотосинтезу вівса посівного сорту ‘Айворі’ в умовах правобережного лісостепу України залежно від норм добрив, передпосівної обробки насіння біологічними препаратами фосфатмобілізуючої дії Поліміксобактерин на основі бактерії *Paenibacillus polymyxa*, та Мікофікс на основі мікоризного гриба *Glomus intraradices* з використанням протруєного і непротруєного насіння. За сумісної обробки насіння протруйником та Мікофіксом формувалась максимальна площа листкової поверхні – 44,6-64,5 тис. м^2/га залежно від фону удобрення. За сівби протруєним насінням на фоні $N_{90}P_{90}K_{90}$ формувалося 60,9 тис. м^2/га площі листкової поверхні, а протруєним насінням та додаткової обробки Поліміксобактерин або Мікофікс на фоні $N_{90}P_{60}K_{90}$ – 61,3 та 63,9 тис. м^2/га відповідно. За зменшення фосфору до $N_{90}P_{30}K_{90}$ та обробки насіння за тією ж схемою, листкова площа становила відповідно 61,0 та 63,2 тис. м^2/га на стадії BBCH 62-65. Встановлено тісний позитивний кореляційний зв’язок – коефіцієнт кореляції між урожайністю і площею листкової поверхні на стадії BBCH 63-64 – 0,87-0,89. Практична цінність дослідження полягала у встановлені компенсаційного ефекту за комбінованого застосування біологічних препаратів та мінеральних добрив, що дозволило знижувати норми внесення добрив без зниження фотосинтетичної активності посівів та урожайності вівса

Ключові слова: площа листкової поверхні; чиста продуктивність фотосинтезу; норми добрив; Поліміксобактерин; Мікофікс; урожайність