НАУКОВІ ГОРИЗОНТИ

УДК 63

Редакція, видавець:
Поліський національний університет
Рік заснування: 1998
Періодичність випуску: щомісячно

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Поліського національного університету
(протокол № 1 від 27 серпня 2025 року)

Рішення національної ради України
з питань телебачення і радіомовлення № 1533.
Ідентифікатор медіа – R30-01593

Науковий журнал включено до категорії А Переліку наукових фахових видань України, у яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора та кандидата ветеринарних, економічних, сільськогосподарських і технічних наук зі спеціальностей:
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(наказ МОН України № 1166 від 23 грудня 2022 р.)

Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах: Інституційний репозитарій Поліського національного університету, AGRICOLA, CAB Abstracts and Global Health (CABI), Реєстр наукових видань України, Національна бібліотека України імені В. І. Вернадського, Crossref, ERIH PLUS, International System for Agricultural Science and Technology (AGRIS), Dimension, Polska Bibliografia Naukowa, Google Scholar, Ulrichsweb Global Serials Directory, UCSB Library, EBSCO, Scopus, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, OUCI (Open Ukrainian Citation Index), Worldcat, CORE, COPE, Litmaps

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SCIENTIFIC HORIZONS

UDC 63

Editorial and Publisher:
Polissia National University

Year of foundation: 1998
Frequency of issue: monthly

Recommended for printing and distribution via the Internet by the Academic Council of Polissia National University (Minutes No. 1 of August 27, 2025)

Decision of the National Council of Television and Radio Broadcasting of Ukraine No. 1533.
Media identifier – R30-01593

The scientific journal is included in category A of the List of scientific professional publications of Ukraine, in which the results of dissertations for the degree of doctor and candidate of veterinary, economic, agricultural, and technical sciences can be published in the following specialties: 051 – Economy; 071 – Accounting and Taxation; 072 – Finance, Banking and Insurance; 073 – Management; 075 – Marketing; 076 – Entrepreneurship, Trade and Exchange Activities; 101 – Ecology; 133 – Sectoral Engineering; 201 – Agronomy; 202 – Plant Protection and Quarantine; 203 – Horticulture and Viticulture; 204 – Technology of Production and Processing of Livestock Products; 205 – Forestry; 206 – Park and Gardening Management; 208 – Agricultural Engineering; 211 – Veterinary Medicine
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НАУКОВІ ГОРИЗОНТИ

Том 28, № 9
2025

НАУКОВИЙ ЖУРНАЛ
Засновано 12 березня 1998 р.
Періодичність випуску: дванадцять разів на рік

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SCIENTIFIC HORIZONS

Vol. 28, No. 9
2025

SCIENTIFIC JOURNAL
Year of establishment: Since March 1998.
Publication frequency: Twelve times a year

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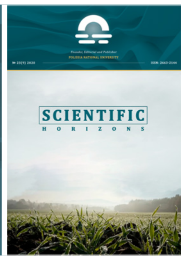
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(9), 9-23

UDC 631.4; 504.054; 504.055 DOI: 10.48077/scihor9.2025.09



Methods for improving the ecological state of a chemically contaminated soil-plant system under the influence of military-technogenic factors on agrocoenoses

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Article's History:
Received: 20.03.2025
Revised: 22.07.2025
Accepted: 27.08.2025

Abstract. The purpose of the study was to investigate the effectiveness of new methods of *in situ* remediation of contaminated soils under complex military and technogenic influences on the soil-plant system in areas of atmotechnogenic emissions from an electricity and heat production facility (using the example of DTEK Kurakhiv TPP LLC in Donetsk Oblast). A systematic approach was used with the involvement of a complex of universal general scientific methods; methods of field and current methods of chemical and analytical research of soils and test plants of agrocoenoses with the determination of indicators of the elemental status of the soil-plant system, indicators of plant quality under the influence of chemical pollution and military influence; using the developed methods of chemical and biological remediation of the soil-plant system; using desk

Suggested Citation:
Samokhvalova, V., Vinyukov, O., Bondareva, O., & Zuza, V. (2025). Methods for improving the ecological state of a chemically contaminated soil-plant system under the influence of military-technogenic factors on agrocoenoses. *Scientific Horizons*, 28(9), 9-23. doi: 10.48077/scihor9.2025.09.

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methods of statistical processing of the obtained data. New knowledge was obtained on the control of chemical contamination of soils and the soil-plant system under the conditions of complex influence of the military factor and chemical pollution in the zones of atmotechnogenic emissions at the electric and thermal energy production facility. New data were obtained from the analysis of the effectiveness of using the elaborated innovative methods of chemical and biological remediation of contaminated soils under new conditions of military and technogenic impacts. Priority contamination of the soil-plant system with mobile forms of lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and nickel (Ni) compounds during shell and rocket explosions has been established. Excess of the standard values of the content of toxic metals Cd, Pb, Cu in the grain and vegetative mass of test plants *Hordeum vulgare* and *Triticum aestivum* L was found. The advantages of using the new synthesised chelate-humate preparation Smaragd and the biological product Haupsin BT for effective improvement of the ecological state of the contaminated soil-plant system were determined. The findings were the basis for further implementation of the developed methods in various farms to restore soil health in the conditions of military-technogenic impacts on the soil cover, the soil-plant system; for carrying out remediation and environmental rehabilitation of chemically contaminated soils to improve the ecological state of soils and minimise the effects of chemical pollution and military factor; in research practice – to elaborate methods and technologies for the remediation and environmental rehabilitation of chemically degraded soils in areas of pollution; to control degradation for chemical contamination of soils, promote food and environmental safety

Keywords: soil; chemical pollution; heavy metals; military-technogenic impacts; methods of soil restoration

INTRODUCTION

Researchers are developing strategies for environmental rehabilitation to restore soils and reduce the area of their chemical contamination. In particular, J. Norrman *et al.* (2020) found that pollutant removal measures have higher scores due to high scores in social and economic dimensions based on the expected increase in property values after the restoration of territories. In the critical review by P. Song *et al.* (2022) on the restoration of soils contaminated with heavy metals(HM) summarised the experience of developing new methods of *ex situ* and *in situ* physical (thermal desorption and excavation), chemical (leaching and stabilisation, electrokinetic reduction, oxidation/reduction), and biological (phytoremediation, microbial reduction) remediation and combined reduction methods. The methods are valuable for evaluating effective technologies for site remediation and rehabilitation in conditions of excessive emissions from industrial facilities.

Significant developments in physical and chemical remediation complexes were presented by researchers from China (Wu *et al.*, 2022; Mu *et al.*, 2024). To promote the protection of soil resources from pollution and land use, combined methods of restoration were proposed: physico-chemical and chemical-biological technologies, physico-biological technologies on soils contaminated with HM. It was found that the combination of phytoremediation and microbial remediation is a promising environmentally safe method. The methods are suitable in areas of mining, industrial production, wastewater irrigation, excessive fertiliser application, intensive urbanisation and growth of household waste. The studies evaluated innovative methods of physical and chemical remediation to solve the problem of soil contamination with cadmium (Cd) with the combined use of phosphate fertilisers and sepiolite, CaAl-layered double hydroxide (LDH) immobilisation and hydrotreatment. The adsorption capacity, ion exchange mechanisms, and remediation efficiency were evaluated. The combined use of phosphate fertilisers and sepiolite provided up to 72.6% removal of Cd extracted by HCl from the soil.

The international arsenal of methods for bioremediation of contaminated soils is significant. The review by M. Kumar *et al.* (2022) presented the developed methods of *in situ* remediation of chemically contaminated soils. Biological methods of controlled natural bioremediation, bioventilation (bio-spraying), nano-bioremediation, bioaugmentation, and biostimulation for the degradation of soil pollutants have gained the preference *in situ*. However, bioaugmentation methods have risks of inefficiency due to the possible failure of microbial adaptations to environmental conditions. Bioventilation methods are unsuitable for low-permeable or heterogeneous soils, which narrows the possibilities of their use. According to M. Kumar *et al.* (2022), nanobioremediation methods, despite their advantages, have a risk of toxic effects on soil biota.

Based on the analysis, it is advisable to use biostimulation for the remediation of contaminated soil-plant system with ensuring possible positive effects on yield indicators, translocation of toxic metals, and environmental safety of plants due to technogenic impacts. The relevance of solving the problems of reducing pollution areas in Ukraine, scientific substantiation for the restoration of sites and their return to economic circulation, and the elaboration of remediation methods in the zones of influence of industrial facilities has increased due to the increase in military and technogenic impacts on soils due to the ongoing Russian aggression and military operations on the territory of Ukraine.

Researchers are actively developing tools to minimise military impacts and chemical pollution. C. Fernández-Lopez *et al.* (2024) established the expediency of introducing methods of chemical leaching, stabilisation photolysis, electrokinetic remediation, and bioremediation in conditions of soil contamination with explosives from military facilities, heavy metals, perfluoroalkyl and polyfluoroalkyl compounds (PFAS), polycyclic aromatic hydrocarbons (PAH) has been established. However, foreign experience does not consider the specifics of military influence and the properties of chemical soil contamination in Ukraine, which reduces the potential for using existing remediation methods. This requires updating the best practices of suitable remediation methods and their use for contaminated soils in Ukraine.

In Ukraine, such researchers as S. Baliuk *et al.* (2024), in accordance with certain priorities, developed conceptual and methodological approaches to the restoration and use of affected soils, features of their monitoring for military and technogenic impacts. The main types of military soil degradation were identified, and the impact of armed aggression and military operations on the soil cover was determined. In the context of the complex impact on the soils of Ukraine that have undergone physical, chemical and biological degradation due to military operations, the tasks of developing new and using existing methods have been updated, in particular, in the Donetsk Oblast, which is characterised by significant levels of military-technogenic impacts on agrocoenoses, especially in the areas of energy production enterprises, in particular DTEK Kurakhiv TPP LLC. Before dismantling in 2024, DTEK Kurakhiv TPP LLC (with a capacity of 1,460 MW) operated under constant shelling (Kurakhiv Thermal Power Plant, 2016).

According to the State Ecological Inspectorate of Ukraine in the Donetsk Oblast (2024), the amount of certain damage to land resources and atmospheric air around DTEK Kurakhiv TPP LLC and the city of Kurakhove was approximately UAH 1 billion. As a result of systematic Russian attacks, significant contamination of soils close to the energy production facility with organic and inorganic substances was recorded. The above determines the relevance of research aimed at finding ways to solve the important problem of reducing the military-technogenic load on agroecosystems, improving the ecological state and restoring agrocoenoses for the return of soils to agriculture.

The purpose of the study was to investigate the effectiveness of new patent-protected methods for *in situ* remediation of contaminated soils under military and technogenic influences on the soil-plant system in areas of atmotechnogenic emissions from an electricity and heat production facility (using the example of DTEK Kurakhiv TPP LLC in Donetsk Oblast) and to acquire additional insights into the controlling chemical pollution under new conditions of complex military and chemical pollution impacts.

MATERIALS AND METHODS

Research work on monitoring the effectiveness of the use of chemical and biological remedies on chemically contaminated soils due to military and technogenic impacts was carried out in 2022-2024. The study of the effectiveness of new patent-protected methods of remediation of chemically contaminated soils for monitoring their degradation due to military and technogenic impacts was carried out with the implementation of the Task 01.02.02.01.F. "To develop scientific and methodological bases for monitoring, environmental quality rationing, and remediation of chemically contaminated soils as the basis of soil and environmental management" (No. 0121U108037, NSC "ISSA named after O.N. Sokolovsky", soil protection department) in cooperation with the Donetsk State Agricultural Experimental Station of the National Academy of Agrarian Sciences of Ukraine (NAAS of Ukraine). Information, research work, and implementation of innovations provided for compliance with ethical standards, rules, and principles for the use of biological objects (in particular, plants of various species and varieties of domestic selection; test plants without genetic modifications; biologics containing microorganisms without genetic modifications) and eco- and biosafety during research, obtaining and using the results in accordance with the current Ukrainian regulatory framework on bioethics and biosafety in professional activities and the regulatory framework on soil quality and environmental protection (Convention on Biological Diversity, 1992).

In accordance with the set objective, the following were used as research objects: (1) the method of chemical remediation of contaminated soils (Patent for utility model No. 135145, 2019), which involved the use of a new synthesised chelate-humate preparation Smaragd (CHP Smaragd). The method was used under new conditions of military and technogenic impacts. (2) Method of bioremediation of the soil and soil-plant system contaminated with heavy metals (Patent for utility model No. 132724, 2019), which included the use of the biological product Haupsin BT with active strains of the bacterium of the species *Pseudomonas aureofaciens* for biostimulation *in situ*. The method was used under new conditions of military and technogenic impacts. (3) Soils (ordinary chernozems) of land plots consisting of background territories, agrocoenoses of territories of constant and periodic exposure to chemical pollution, and the potential risk of contamination of zones of influence of atmotechnogenic emissions of DTEK Kurakhiv TPP LLC. (4) Soils (mainly ordinary chernozems with low-humus light loamy composition on loessial rocks) of locally disturbed land plots of Volnovakha and Pokrovskyi districts of Donetsk Oblast, which were subjected to military influence, in particular, attacks from multiple launch rocket systems and missile strikes, as a result of Russian military operations. (5) Winter wheat (*Triticum aestivum* L.) variety «Yuzivska" and spring barley (*Hordeum vulgare*) variety "Avers" on an area of 1 ha were used as test plants in conditions of military and technogenic impacts.

The following research methods were used to conduct research in accordance with the set goal and objectives: (1) Universal general scientific methods, computational-analytical and comparative methods. (2) Field research methods according to the field experiment methodology (Dospekhov, 1985). Introduction of new CHP Smaragd into the soil was carried out before sowing test plants at a specific dose of 2.5-3 l/ha and 1.5-2 l/t – for seed treatment; at a dose of 2.5 – 3 l/ha – to optimise the growth and development of plants according to their phenophases. With the established polyelement contamination of the soil Cd, Pb, Zn, the applied doses of the drug were doubled. For *in situ* biostimulation, the biological preparation Haupsin BT with strains B – 306 and B – 111 (pH 6.7; titre 5.6 x 10^{10} viable CFU/cm^3) bacteria of the type *Pseudomonas aureofaciens*. Active agents of the biological product Haupsin BT have antifungal, entomocidal, antibacterial, and antiviral properties, the biological product contains bacteria-antagonists of soil phytopathogens. Haupsin BT is applied to the soil and used for seed treatment of test plants, their foliar treatment in the active phases of growth and development. In particular, the introduction of the biological product Haupsin BT was carried out in the spring directly into the soil during its cultivation 5-6 days before sowing plants at an air temperature above +12°C, in the form of a manufactured liquid in accordance with the current regulations TU 31. (3) Certified and standardised in Ukraine chemical and analytical methods for determining individual characteristics of the elemental status of soils: according to DSTU ISO 11047:2005 (2007) – gross forms of chemical elements in the soil; according to DSTU 4770.1:2007 (2009), in particular mobile forms of trace elements (TE) and heavy metals (HM) (manganese Mn, zinc Zn, cadmium Cd, iron Fe, cobalt Co, copper Cu, nickel Ni, chromium Cr, lead Pb) in the soil; acid-soluble forms of Cd compounds in the soil according to DSTU 7607:2014 (2014) were determined by atomic absorption spectrophotometry; Cu in the soil – according to DSTU 7831:2015 (2016); Pb in the soil – according to DSTU 7832:2015 (2016); Zn in the soil – according to DSTU 7853:2015 (2016). Soil sampling of background areas was carried out in accordance with the current DSTU 4287:2004 (2005). Soil sampling of control variants, zones of military-technogenic impacts was carried out in accordance with the standardised methods of DSTU ISO 10381-1:2004 (2006), DSTU ISO 10381-2:2004 (2006), DSTU ISO 10381-5:2009 (2011) and the international standard ISO 18400-102:2017 (2017). Plant sampling and mineralisation were carried out in accordance with DSTU 7670:2014 (2015).

Assessment of the microelement status and HM content in soils was carried out using the established background levels of their content for soils of a certain natural and climatic zone of Ukraine according to A. Fateyev and V. Samokhvalova (2019) and in accordance with the current threshold limit value of hazardous substances in soils. (4) Methods for conducting phenological observations of cultural phytocoenoses and determining indicators of productivity of test plants and crop structure (field germination, bushiness of test crops) according to method by B. Dospekhov (1985). (5) Atomic absorption method for determining the content of TE/HM (Cu, Pb, Zn, Cd) in plants according to methods of soil and plant analysis (1999). Assessment of the element status of test plants was carried out according to the threshold limit values (TLV) of toxic elements in plants in accordance with the Addendum No. 122-12/805 (1991), DSTU 3769-98 (1998), DSTU 3768:2019 (2019) regulatory documents in force in Ukraine. (6) Statistical data processing methods of the statistical analysis software suite Statistica 10 and Microsoft Excel. The Fischer's criterion was applied when performing calculations.

RESULTS

Based on studies of agrocoenosis soils in chemical pollution zones from DTEK Kurakhiv TPP LLC, the spread of pollution at distances up to 3 km, 10 km, 20 km, and 30 km from the emission centre of the energy production facility was established. A regular increase in contamination of the soil-plant system with mobile forms of Pb, Cd, Cu, and Zn compounds was determined. In particular, the background values of acid- soluble forms of Cd compounds were exceeded by 1.7-2.3 times (extractant 1N HCl) and mobile forms of Cd compounds by 2 times (extractant AAB with pH 4.8) (Table 1). An increase in the content of gross and acid-soluble forms of Pb was found, respectively, by 38% and 12% compared to the background level of the toxicant metal content in the soil. An excess of background levels of mobile forms of Cu was found by 3.8 times, and by 1.7 times for the content of acid-soluble forms of Cu compounds in the soils under study. There was also an increase in the content of gross forms of Zn by 16%, acid-soluble forms of Zn compounds by 1.5-1.8 times in ordinary chernozems.

A decrease in the levels of heavy metal contamination of grain crops with a distance from the centre of pollutant emissions of DTEK Kurakhiv TPP LLC was revealed. The normative values of the elemental composition of plants *Hordeum vulgare* and *Triticum aestivum* L. are reached at a distance of 10-15 km to 30-40 km from the centre of emissions of pollutants (Table 2). Exceedances of standard Cu levels were found in *Hordeum vulgare* test plants, amounting to 5% in grain and 11-44% in straw.

Table 1. *Content of gross and mobile forms of heavy metal compounds in ordinary chernozems in zones of technogenic impact of DTEK Kurakhiv TPP LLC*

Object of analysis	Concentration of various forms of HM in soils, mg/kg											
	Cd			Pb			Cu			Zn		
	1	2	3	1	2	3	1	2	3	1	2	3
Soil	0.3-1.0	0.5-0.7	0.14-0.2	13.9-18.0	1.74-1.89	0.4-0.9	13.5-16.0	4.8-8.6	1.7-1.9	44-64	14.6-18.3	0.9-1.7
Background content	1.0	0.30	0.10	13.0	5.0	0.8	22.0	5.0	0.5	55.0	10.0	1.6
TLV	3.0	0.7		32.0	6.0		100	3.0		300	23.0	

Note: *1 – gross forms, 2 – acid-soluble forms (extractant 1N HCl), 3 – mobile forms (extractant ammonium acetate buffer solution with pH 4.8)*
Source: *created by the authors based on the results of chemical and analytical studies*

Table 2. *HM content in plants in areas affected by different levels of technogenic impact*

Object of analysis	HM content, mg/kg											
	Cu (TLV[1] = 10)			Pb (TLV = 0.5)			Zn (TLV = 50)			Cd (TLV=0.1)		
	Distance to the source of emissions, km											
	⩽3	5-15	>30	⩽3	5-15	>30	⩽3	5-15	>30	⩽3	5-15	>30
Spring barley (*Hordeum vulgare*):												
grain straw	10.5 14.4	6.5 11.1	6.6 9.3	1.8 1.9	1.0 1.3	0.7 0.9	26.4 31.9	14.0 17.0	14.7 15.0	1.28 1.62	0.56 0.45	0.38 0.51
LSD^2_{05} grain / straw	0.94/ 0.95	0.95/ 0.69	0.86/ 0.63	0.43/ 0.37	0.19/ 0.55	0.85/ 0.83	0.64/ 0.64	0.38/ 0.06	0.69/ 0.38	0.08/ 0.05	0.16/ 0.30	0.14/ 0.24
Winter wheat (*Triticum aestivum*):												
grain straw	4.5 4.9	2.5 3.7	1.2 1.9	2.5 2.8	1.3 2.3	0.7 1.0	37.0 42.2	19.1 22.5	19.3 22.2	0.78 0.96	0.51 0.58	0.48 0.52
LSD_{05} grain / straw	0.63/ 0.95	0.64/ 0.69	0.95/ 0.63	0.63/ 0.63	0.31/ 0.63	0.63/ 0.44	0.63/ 0.85	0.31/ 0.57	0.95/ 0.31	0.76/ 0.12	0.06/ 0.13	0.12/ 0.12

Note: *[1]TLV – threshold limit values in accordance with the current regulatory documents of Ukraine (DSTU 3769-98, DSTU 3768:2019); [2]LSD_{05} – the least significant difference*
Source: *created by the authors based on the results of chemical and analytical studies*

The standard Pb content was exceeded in barley grain by 1.4-3.6 times, in straw of the test crop – by 1.8-3.8 times. The established values of Zn content in spring barley plants did not exceed the current TLV. However, the accumulation of the toxic metal Cd was recorded both in the grain and in the straw of spring barley. In comparison with the current TLV, the excess of Cd content in barley grain was 3.8-12.8 times, in barley straw – 4.5-16.2 times. Analysis of test plants of *Triticum aestivum* L. found an excess of the standard Pb content in wheat grain by 1.4-5 times, in straw of the test crop – by 2.-5.6 times. The established values of Zn and Cu content in winter wheat test plants did not exceed the current TLV. The determined levels of Cd content exceeded the standard TLV in grain by 4.8-7.8 times, in straw – by 5.2-9.6 times (Table 2). Research into areas affected by military activity has revealed destruction of the soil surface and the formation of craters of various diameters (Fig. 1), chemical contamination of the soil at the sites of shell and rocket explosions, and physical contamination with metal debris of various sizes. An increased content of toxic metals Pb, Cd, Ni, Cu was observed in the explosion locations. The results of the analysis of soil samples indicate an excess of the background levels of pollutants in the soil of shelled locations or existing craters by 7-17 times; in combat locations, the excess of the background levels of Cd and Pb in the soil was 1.1-1.3 times.

Craters formed as a result of the use of various types of weapons by the aggressor during massive attacks on the territory under study were examined. The characteristics of craters are determined and categorised based on the tactical and technical parameters of the weapons used by the aggressor. In particular, mortars with 82-mm fragmentation shells and high-explosive fragmentation mines (82 mm calibre) created craters with the smallest diameter of about 1 m. "Grad" installations and field and self-propelled howitzers (120 mm calibre) left craters with a diameter of 2.5-3.5 m. Craters from mortars with 152-mm shells, towed guns, howitzers and self-propelled howitzers (152 mm calibre) had a diameter of 4-6 m. Characteristic signs of the impact on the soil from multiple launch rocket systems "Uragan" (calibre 220 mm) were craters with a diameter of 7 m. Thus, it was determined that at the time of the surveys, the maximum number of craters in the areas under study was the result of attacks from "Grad" launcher installations, field and self-propelled howitzers of 120 mm calibre, and the use of mortars with 82 mm fragmentation shells and high-explosive fragmentation mines of the same calibre. The applied algorithm of ecological rehabilitation of chemically contaminated chernozem soils in the zones of atmo-technogenic influence of DTEK Kurakhiv TPP LLC and disturbed soils of land plots included preliminary determination of the ecological state of the soil-plant system, the use of the developed composition of the new CHP Smaragd in the soil-plant system and on soils with crater locations (diameter 1-4 m); consideration of the established laws of translocation of HM and TE in grain crops under study. Additionally, the method allowed determining the types of weapons based on individual characteristics and diameters of craters formed in areas of military and technogenic impacts.

Figure 1. *Typical craters of various diameters identified from the surveyed chemically contaminated areas in the zones of influence of technogenic emissions of pollutants of the energy facility (DTEK Kurakhiv TPP LLC)*
Source: *created by the authors based on soil research conducted in 2022-2024*

Under conditions of chemical contamination and military impact on the soil-plant system, the new preparation is used for seed treatment, fertilising plants and applying to the soil to obtain remediating and fertilising effects. Positive results of exposure to CHP Smaragd in the conditions of military-technogenic impacts are conditioned by a certain ratio of interacting agents of the drug composition. The composition of CHP Smaragd, proposed for use in chemically contaminated soil-plant systems, contains chelated compounds of TE (Fe, Mn, Zn, Cu, Co, Mo, and B), obtained based on the OEDP (oxyethylidenediphosphonic acid) complexon. The humate component of CHP Smaragd is obtained based on a preparation of known humate from organic raw materials of natural origin, followed by introduction into a chelate solution. Phenological observations were carried out to analyse the effect of CHP Smaragd on the yield of barley (*Hordeum vulgare*) and assess the quality and environmental safety of grain and straw of test plants on chemically contaminated soils. The positive effect of the Smaragd preparation was determined based on identifying an improvement in the indicators of field germination and bushiness of plants that characterise the yield structure of test plants under military and technogenic impacts (Fig. 2).

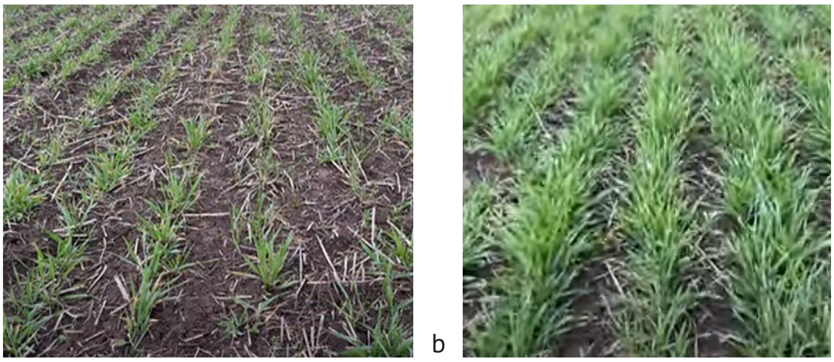

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Figure 2. *Phenotypic features of Hordeum vulgare in the surveyed areas of complex impacts of chemical pollution and military factor in the emission zones of DTEK Kurakhiv TPP LLC when using CHP Smaragd in chemically contaminated areas*
Note: *a – control (contaminated soil due to military and technogenic impacts); b – option of using CHP Smaragd in conditions of chemical contamination of the soil-plant system*
Source: *created by the authors based on soil research conducted in 2022-2024*

It was found that the bushiness indicator of *Hordeum vulgare* increased from 1.7 (control option) to 2.3 when using CHP Smaragd. It was recorded that the bushiness coefficient increased to 1.5-1.7; the indicator of productive bushiness in the control was 1.3. It was also established that field germination of *Hordeum vulgare* increased by 4.5% compared to the control version, where this figure was 87.5%. At the experimental sites located at a distance of 0-3 km and 3-10 km from DTEK Kurakhiv TPP LLC, the degree of technogenic impact of the power plant on the agrophytocoenosis of barley was determined in accordance with the average annual wind rose and zones of the greatest dispersion of emissions from the enterprise. In studies of the soil-plant system, the influence of chemical pollution and military factor when using CHP Smaragd was considered. The use of the proposed variants of the experiment allowed assessing the relationship between the intensity of technogenic load and the reaction of test crops. The results are presented as analytical data (Table 3).

***Table 3**. Efficiency of using CHP Smaragd considering individual test indicators of spring barley (Hordeum vulgare)*

Experiment options	Test crop yield, t/ha	Accumulation of heavy metals in plants, mg/kg		
		Zn	Cd	Pb
1. Control (contaminated soil of areas affected by pollutant emissions from Kurakhiv TPP)	2.88	50.5 60.4	0.11[1] 0.64 [2]	0.59 3.42
2. Contaminated soil of the Kurakhiv TPP pollutant emission zones + *CHP Smaragd*	3.40	40.75 45.9	0.09 0.46	0.45 2.60
3. Contaminated soil of the Kurakhiv TPP pollutant emission zones + military factor	2.73	52.9 56.9	0.13 0.69	0.65 3.8
4. Contaminated soil of the Kurakhiv TPP pollutant emission zones + military factor + *CHP Smaragd*	3.33	42.52 47.2	0.08 0.49	0.50 2.80
TLV of HM in grain/vegetative mass of plants 50.0		50.0 0.3	0.1 5.0	0.5
		grain / straw		
LSD_{05}	0.21	0.21/ 1.32/	0.01// 0.09	0.07/ 0.23
LSD_{01}	0.32	0.31/ 2.0	0.02/ 0.13	0.11/ 0.36
		grain / straw		
Fischer's criterion Ffact. $F_{05} = 4.76$ $F_{01} = 9.80$	26.70	98.90/ 72.30	38.8/ 24.79	26.41/ 53.28

Note: *[1]numerator – HM content in the grain; [2]denominator – HM content in the vegetative mass*
Source: *created by the authors based on soil research conducted in 2022-2024*

The results of field studies indicate an improvement and restoration of the productivity of spring barley (*Hordeum vulgare*), as a factor for further restoration of the overall efficiency of agricultural production due to military and technogenic impacts. In particular, the positive effect of using CHP Smaragd on the yield growth indicators of test plants in comparison with the control version was confirmed. An additional barley yield of 0.52 t/ha was obtained in relation to the control using the biological product CHP Smaragd on chemically contaminated chernozem soils and an increase in the yield of 0.45 t/ha in the zones of influence of atmo-technogenic emissions of pollutants and military factor (Table 3). In the conditions of pollutant emission and military impact of the surveyed territories, the effect of CHP Smaragd on the accumulation of HM by *Hordeum vulgare* was investigated. A decrease in the Zn content was found by 16% in grain and by 22% in vegetative mass of *Hordeum vulgare* under military conditions and the use of CHP Smaragd in the soil-plant system. In the studied areas of industrial emissions of energy production, it was found that the use of CHP Smaragd provided a reduction in the Zn content in test plants. The recorded decrease in the content of toxicant metal in the grain of test plants was 19.3%, in the vegetative mass of *Hordeum vulgare* – 24%.

The use of CHP Smaragd in contaminated areas by energy company emissions contributed to a significant reduction in the Pb content in plant products. It was determined that the level of Pb accumulation in the grain and vegetative mass of the test culture decreased by 24%. Under military conditions, the Pb content decreased by 15% in grain and by 18% in vegetative mass of *Hordeum vulgare*. It was found that under the conditions of military influence and chemical contamination of the soil-plant system, the use of this method of chemical remediation helped to reduce the level of Cd in grain of *Hordeum vulgare* by 27%, in the vegetative mass – by 23%. It was determined that the use of the drug by the proposed method in the soil-plant system when exposed to pollutants in the zone of action of the Kurakhiv TPP contributed to a decrease in the Cd content in grain of *Hordeum vulgare* by 18%, in the vegetative mass – by 28%. Thus, an improvement in the ecological state of the soil-plant system has been established, which is conditioned by the detected remediation effect of CHP Smaragd with a fertilising and stimulating effect, which ensures the effectiveness of the proposed remediation method under conditions of chemical pollution and the influence of military factors.

Based on the results of comprehensive research in the soil-plant system on the effectiveness of an innovative method of activating the natural biological potential of the soil in the conditions of military-technogenic impacts, effective bioremediating cleaning of toxic pollutants has been established. The basis of the proposed method of biological remediation is the use of the biological product Haupsin BT, the detection of its remediation properties and the processes of activation of microbiological and biochemical properties of chemically contaminated soils due to the use of the biological product. The basic principle of remediation action of active agents of biologics consists in the establishment of specific microbial-plant associations that increase the effectiveness of the specified biologics, which allows neutralising the harmful effects of pollutants at established load levels and also partially restoring the productive properties of plants under military-technogenic impacts. Thus, the new method used under the new conditions ensures the restoration of test plants and an integrated increase in the biological efficiency of remediation agents and contributes to the rehabilitation of the ecological functionality of the contaminated soil-plant system.

Phenological observations on the effect of Haupsin BT biologics on the yield of winter wheat (*Triticum aestivum*) and on the indicators of grain quality and environmental safety on chemically contaminated soils, ensured the identification of the effective effect of the proposed method of bioremediation of the soil-plant system. An improvement in the structural indicators of the test crop yield was recorded using the biological product Haupsin BT on contaminated soils. In particular, ensuring increased productivity of *Triticum aestivum* (Fig. 3) contributed to the growth of the tillering coefficient to 1.6-1.8 compared to the productive bushiness of 1.4 in the control, it was determined that the bushiness indicator of *Triticum aestivum* increased from 1.9 (control variant) to 2.8 when using the biological product Haupsin BT. Field germination of the test culture under the influence of a biological product increased by 3.5% compared to the control version (86.7%). Given the current military-technogenic factors at the experimental sites used and distances of 0-3 km and 3-10 km, in accordance with the maximum dispersion of HM emissions and the average annual wind rose, the degree of influence of the Kurakhiv TPP on the agrophytocoenosis of winter wheat (*Triticum aestivum)* was determined (Table 4). The restoration of productivity of phytocoenosis crops using the proposed bioremediation method using the drug Haupsin BT was established, which was confirmed by the indicators of an increase in the yield of the test crop compared to the control. In particular, an increase in the yield of *Triticum aestivum* of 0.6 t/ha was obtained by using the biological product Haupsin BT in the case of chemical soil contamination, and an additional yield of *Triticum aestivum* of 0.52 t/ha was obtained in relation to the control of military-technogenic influences.

Table 4*. Efficiency of using the biological product Haupsin BT based on individual test indicators of winter wheat (Triticum aestivum)*

Experiment options	Test crop yield, t/ha	Accumulation of heavy metals in plants, mg/kg		
		Zn	Cd	Pb
1. Control (contaminated soil of areas affected by pollutant emissions from Kurakhiv TPP)	3.38	59.5 62.4	0.11[1] 0.9[2]	0.80 5.2
2. Contaminated soil of the Kurakhiv TPP pollutant emission zones + *CHP Smaragd*	3.98	39.75 50.9	0.07 0.52	0.55 3.22
3. Contaminated soil of the Kurakhiv TPP pollutant emission zones + military factor	3.05	60.9 67.92	0.10 0.92	0.75 5.9
4. Contaminated soil of the Kurakhiv TPP pollutant emission zones + military factor + *CHP Smaragd*	3.90	45.3 42.5	0.08 0.64	0.52 3.59
TLV of HM in grain/vegetative mass of plants 50.0		50.0 0.3	0.1 5.0	0.5
		grain / straw		
LSD_{05}	0.25	4.59/ 4.94	0.02// 0.09	0.11/ 0.26
LSD_{01}	0.38	6.96/ 7.47	0.02/ 0.13	0.17/ 0.40

Table 4. Continued

Experiment options	Test crop yield, t/ha	Accumulation of heavy metals in plants, mg/kg		
		Zn	Cd	Pb
Fischer's criterion Ffact. $F_{05} = 4.76$ $F_{01} = 9.80$	46.76	grain / straw		
		50.03/ 72.30	13.0/ 53.74	13.44/ 255.47
Significance between parameters is indicated by p <0.05 and p <0.01				

Note: *[1]numerator – HM content in grain; [2]denominator – HM content in the vegetative mass*
Source: *created by the authors based on soil research conducted in 2022-2024*

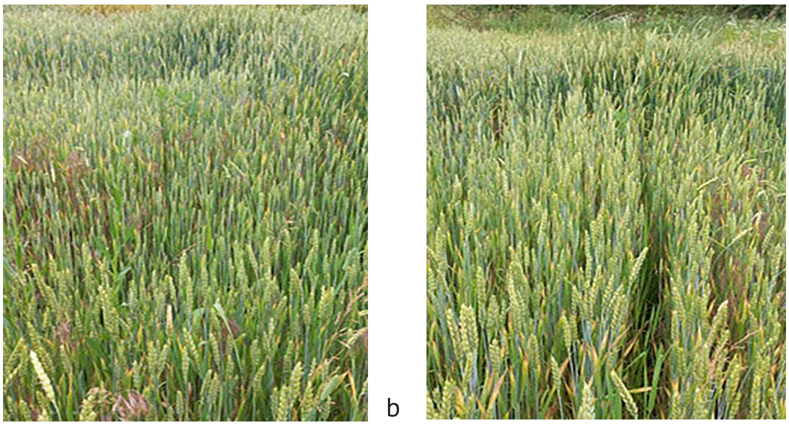

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***Figure 3**. Effect of using a biological product Haupsin BT on the soil-plant system of chemically contaminated territories of the zone of influence of atmotechnogenic emissions of pollutants of DTEK Kurakhiv TPP LLC and military-technogenic impacts*
Note: *a – control (contaminated soil due to military-technogenic impacts); b – option of using a biological product Haupsin BT in conditions of soil-plant system contamination*
Source: *created by the authors based on soil research conducted in 2022-2024*

The results of the research determined that the use of the new method and biologic preparation Haupsin BT in conditions of exposure to pollutant emissions from Kurakhiv TPP provided a reduction in Cd accumulation in test plants *Triticum aestivum*. It was found that a decrease in the concentration of toxicant metal in grain of *Triticum aestivum* was 36.4%, and an even more pronounced decrease in the Cd content was noted in the vegetative mass of the grain crop, which was 42%. The results demonstrated the effectiveness of the biological product in reducing the toxic load on plants, thus contributing to improving the environmental safety of the soil-plant system.

It was determined that in the conditions of military-technogenic impacts on the soil-plant system, the use of the developed method of biological remediation contributes to a significant decrease in the concentration of toxic metals in *Triticum aestivum plants*. In particular, in the test areas where the biological product Haupsin BT was used under military conditions, a decrease in Zn content of 24% and 32% was observed in the grain and vegetative mass of the test crop, respectively. Reduction of bioaccumulation of Zn by test plants was determined *Triticum aestivum* due to the use of the biological product Haupsin BT in the areas of exposure to pollutants of the Kurakhiv TPP. A decrease in the concentration of Zn in grain and vegetative mass of plants was recorded by 33% and 18.4%, respectively. The Cd content in the grain of the grain crop decreased by 27%, in the vegetative mass of plants – by 29%. The use of the biological product Haupsin BT under military impact on agrocoenoses provided a decrease in the concentration of Pb by 35% in grain, by 31% in vegetative mass of *Triticum aestivum*. Under the conditions of technogenic impacts, it was found that the use of the developed bioremediation method led to a decrease in the Pb content by 31% and 38%, respectively, in the grain and vegetative mass of test plants *Triticum aestivum*. Thus, the use of Haupsin BT biological product based on active strains of bacteria of the genus in the soil-plant system of *Pseudomonas sp.* provided a bioremedical effect and ecological stabilisation of the contaminated soil-plant system while simultaneously neutralising negative pollution processes due to the complex action of the biological product by activating the natural biological potential of the soil.

Statistically, data processing is performed using the univariate variance analysis module. The Fischer's criterion was applied when performing calculations. Variances of options and errors are determined for calculating the least significant difference (LSD) (Tables 2-4) and for calculating the Fischer's criterion (Tables 3-4). The significance between the parameters is indicated by the levels $p < 0.05$ and $p < 0.01$. The condition $F_{fact} > F_{theor}$ is performed for all variants of the proposed experiments (Tables 3-4), which proves the correctness of the schemes and the reliability of the results obtained. Thus, an alternative hypothesis is accepted, according to which the difference between the sample averages in experiments is significant. The results of statistical analysis of the obtained data prove the significance of the influence of the studied factor of applying remediants on the effective feature – the content of toxic metals in plants and the yield indicators of test crops. Reliable remediation effects on reducing the content of toxic metals in grain crops on soils contaminated with Cd, Pb, Zn have been established; the positive impact of the proposed methods of remediation of contaminated soils on the restoration of cultural phytocoenoses under new conditions of complex military-technogenic impacts.

DISCUSSION

The results of research under the conditions of military-technogenic impacts revealed the positive effects of the application of the developed algorithms using the new synthesised CHP Smaragd and the well-known biological product Haupsin BT (Ukraine) with its established remediation property in the soil-plant system with the background of chemical contamination. Methods of remediation according to the mechanism of action of the used drugs have been developed, aimed at biostimulation in the contaminated soil-plant system, at creating favourable conditions for soil microorganisms to degrade pollutants, and ensuring environmental effects of *in situ* remediation methods. Bioremediation, as a method of restoring chemically contaminated soil *in situ*, is considered by researchers as an alternative to excavating soil contaminated with pollutants of various kinds (Wang *et al.*, 2021; Michael-Igolima *et al.*, 2022). The range of soil restoration methods *in situ* was tested with varying success in the field. The research focus for developing new methods is on identifying and eliminating factors that limit biodegradation. The identified limiting factors for the biodegradation of soil pollutants are as follows: lack of oxygen and nutrients, soil structure and moisture, soil temperature; bioavailability of pollutants, soil pH, nature of pollution, potential for decomposition of pollutants, etc. (Cavazzoli *et al.,* 2022; 2023).

The results obtained confirmed the feasibility of using the advantages of the principles and mechanism of biodegradation in biostimulation for remediation of the contaminated soil-plant system. Researchers from Finland emphasises that in order to enhance biostimulation, it is advisable to use chemical and physical methods of remediation of contaminated soils (Romantschuk *et al.*, 2023). In the current research, the method of chemical and biological remediation of soils contaminated with HM has been successfully combined and it is recommended to use algorithms for sequential involvement of the proposed methods and/or a combination of methods for remediation of chemically contaminated soils of technogenic and military impact zones.

It should be noted that the results obtained are consistent with individual scientific data of other Ukrainian researchers. In particular, the findings of L. Biliavska *et al.* (2024) and M. Galkin *et al.* (2024) developed effective practical solutions to an important problem of modernity – the restoration of disturbed soils after military operations. Based on the bioindicatory role of microorganisms in determining the ecological state of soils, comprehensive solutions for restoring soil fertility have been developed (Biliavska *et al.*, 2024). In order to accelerate the restoration of soils damaged as a result of Russian military operations, it was recommended to use microbial biotechnologies in combination with phytoremediation, which will contribute to the re-involvement of restored soils in economic circulation (Galkin *et al.,* 2024). It was proposed to use newly developed and patented methods involving the application of CHP Smaragd, the biological preparation Haupsin BT and grain crops to overcome military-technogenic impacts on the soil-plant system in areas affected by energy enterprises and military factors.

Comparison of the data obtained with the results by M. Salam *et al.* (2022) found consistency of the results with proven provisions for improving the effectiveness of phytoremediation on contaminated soils by introducing stimulating carbon compounds into the soil-plant system, which should be considered as an indirect form of biostimulation. The obtained remediation effects in the soil-plant system are obviously also associated with the phytoremediation effects of grain test crops and their rhizosphere for biodegradation of pollutants by biostimulation using humate-chelate compounds in the composition of the Smaragd preparation. The potential of grain test crops that are resistant to Cd, Pb, and Zn contamination due to the functioning of physiological barriers was used. Similar scientific results of Ukrainian researchers on the use of chemical remediants and biologics to reduce and overcome chemical pollution with soil restoration were obtained and presented in publications by S. Korsun *et al.* (2019), S. Korsun (2024). In particular, studies of HM translocation in the soil-plant system have established the ability of plants to localise pollution due to the accumulation and partial transformation of pollutants. The functioning of the root systems of test plants in contaminated areas, in addition to the accumulation of heavy metals, promotes the development of microorganisms in the soil by stimulating native microflora to accelerate the degradation of pollutants.

It is noted that the basic prerequisite for the successful implementation of bioremediation is a careful selection of plants and biologics that can optimally stimulate their growth and development (Korsun *et al.,* 2019). New bioremediation measures were used at the locations of military impacts (hotbeds of burning equipment and explosions of ammunition for reducing the biogenicity of the soil by 30%, increasing the content of HM by 3-470 times), which provided for the introduction of compositions of carbohydrate-oxidising bacteria, organic substances and certain biogenic elements (doses of 5-12% by weight of the soil) with local contamination with petroleum products. During the 90 days of the experiment, the content of petroleum products in the soil on variants using biologics decreased by 59-92%. Ecostern detox (normally 1.5 l/ha, applied in full) containing microorganisms was used. Organic fertiliser was applied (peat and soil mixed in a ratio of 1:1). A decrease in the total biogenicity of the soil, the transformation coefficient of its organic matter, and an increase in the number of soil microorganisms that are trofically associated with nitrogen of organic compounds were recorded (Korsun, 2024). The positive consequences of using the proposed remediants for agrocenoses with grain crops are the impact on the yield, quality and environmental safety of grain and vegetative mass of test plants compared to the control on chemically contaminated soils. A decrease in the content of priority toxic metals Cd, Pb, Zn, Cu was revealed in grain and vegetative mass of grain crops *Hordeum vulgare, Triticum aestivum*. Studies have confirmed the positive effect of the applied remediants on the components of the crop structure, including such important indicators as field germination and the level of bushiness of plants grown on soils contaminated with harmful substances due to military and technogenic impacts. The results indicate the restoration of productivity of cultural phytocenoses, improvement of the ecological state of the soil-plant system.

Given the low level of sorption potential of explosives and the relatively low solubility of their solid particles in water, which contributes to their longer preservation in the soil and adjacent environments, therefore, the introduction of sorbents is impractical for neutralising the remains of explosives and their components in the locations of disturbed soils. It was proposed to use a patent-protected method of chemical remediation of contaminated soils using CHP Smaragd, which also contains humic substances for binding HM to complex compounds, physical absorption of soil pollutants, and their further possible transformation through ion exchange, surface adsorption, complex formation, and coagulation in the soil. For a more complete understanding of the mechanisms of action of remediants in the soil-plant system and assessment of the benefits obtained for using the chemical preparation Smaragd, data from foreign and Ukrainian researchers on the functionality of humic components in the soil were revealed. In particular, the amphiphilic properties of the supramolecular structure of humic acids determine the activity of humic substances, which is associated with a significant content of hydrophobic and hydrophilic functional groups that make up humic components (Korotkova & Chaika, 2022).

The mechanism of soil remediation using chelated compounds and humic acids is confirmed by the above provisions on the interaction of metal cations with phenolic and carboxyl groups in the molecular structure of humic acids, which leads to the formation of spherical complexes (Chaika & Korotkova, 2023). Humic substances play a significant role in the water-retaining and ion-exchange capacity of the soil, in regulating the pH and activity of soil enzymes, macronutrients and their availability for plants. Algorithms for sequential use and combination of bioremediation methods for chemically contaminated soils (Zheng *et al.,* 2022). It was noted that the necessary conditions for positive results in the remediation of contaminated soils were the determination of the effectiveness of the proposed remediation methods in conditions similar to those of the areas where it is to be scaled up. Professional experience and qualifications of researchers are important. The focus should be on the use of native microbial pollutants and evaluation of their effectiveness. Based on the results of field research, the advantages were identified (in particular, reducing the bioavailability of pollutants, increasing the efficiency of their degradation in the soil-plant system) and the effectiveness of using the proposed methods of chemical and biological remediation of contaminated soils for chemical pollution and military impacts was confirmed, which is the basis for further scaling of the proposed patent-protected author's developments; to increase the effectiveness of management decisions and further development of remediation methods for chemical pollution and military impacts in Ukraine to ensure food and environmental safety.

CONCLUSIONS

The effectiveness of using a new method of chemical remediation of the contaminated soil-plant system by introducing a new CHP Smaragd was investigated and established. The effectiveness of using a new method for activating the biological potential of soil in the conditions of bioremediation of the soil-plant system contaminated with HM was determined and evaluated. The proposed methods were used under new conditions of complex negative military-technogenic loads on agrocoenoses in the emission zones of the electric and thermal energy production facility (on the example of DTEK Kurakhiv TPP LLC in Donetsk Oblast). Analysis of the effectiveness of the use of CHP Smaragd in the soil-plant system established growth-stimulating and remediating effects in the soil-plant system due to the use of a new effective composition of the drug, which provided an improvement in the quality and environmental safety of grain and straw test plants by reducing the intake of pollutants; improving the indicators of the crop structure and field germination, and bushiness of grain crops, restoring the productivity of agrocoenosis plants on chemically contaminated soils; reducing chemical pollution caused by military and technogenic factors, improving the ecological state of the soil-plant system.

Analysis of the effectiveness of the use of the biological product Haupsin BT determined the manifestation of the bioremediation effect in the soil-plant system that has been contaminated. This effect was observed against the background of increased processes of biological purification and restoration, which contributed to an improvement in the productivity of grain crops and was confirmed by an increase in their yield indicators. An improvement in the structural characteristics of the crop was recorded with an increase in field germination and bushiness indicators of *Hordeum vulgare, Triticum aestivum*. However, a decrease in bioaccumulation of HM by plants was found in comparison with the control variants, which indicates the effectiveness of the method used to optimise bioremediation. The suitability of the developed remediation methods for contaminated disturbed chernozem soils under complex technogenic and military impacts after bomb, rocket, and artillery strikes was established. In particular, the suitability for the soils of land plots damaged due to shelling from field and self-propelled howitzers (120 mm calibre), "Grad" launchers, mortars with fragmentation shells and high-explosive fragmentation mines (82 mm calibre) with created craters with a diameter of 1-4 m. The methods were aimed at reducing the complex impact of the military factor and chemical pollution to stabilise the soil-plant system. In order to reduce the intensity of the processes of chemical degradation of soils and their restoration and return of land plots to economic use, the methods used in the conditions of military-technogenic impacts should be recommended for use by agricultural producers for growing grain crops in areas with negative consequences of military operations and chemical exposure and increased risks of soil and plant pollution.

When establishing high levels of soil contamination due to military-technogenic impacts, it is also advisable to use algorithms for consistent application of the proposed methods and/or a combination of elaborated methods of remediation of chemically contaminated soils to enhance remediation effects in the soil-plant system. It is advisable to use new knowledge on the effectiveness of the proposed new patent-protected methods of remediation of contaminated soils in the zones of atmotechnogenic emissions of the electric and thermal energy production facility to control the chemical degradation of soils and the soil-plant system under military-technogenic impacts. Prospects for further research on the remediation of chemically contaminated soils for military-technogenic impacts is the development of scientific and methodological support (new methods, methodological approaches, techniques) for environmental rehabilitation of chemically contaminated soils, the soil-plant system considering the type of pollution to minimise the impact, improve the environmental condition and control degradation; to manage the elemental status of soils of contaminated territories considering the harmfulness of pollution and levels of soil degradation; making managerial decisions on soil restoration for military-technogenic impacts in the zones of existing and destroyed industrial facilities.

ACKNOWLEDGEMENTS

The research was conducted with the support of the NAAS of Ukraine for the implementation of the task of HDP NAAS 1 "Rational use and sustainable management of soil resources, preservation of soil fertility and health, protection from degradation" (Soil resources of Ukraine: information support, rational use, management, technologies) (2021-2025) Subprogramme 02 "Systems for preventing and stopping land degradation processes to preserve soil health and harmonise their productive and environmental functions" ("Soil protection"). Task 01.02.02.01. F. "To develop scientific and methodological bases for monitoring, environmental quality rationing and remediation of chemically contaminated soils as the basis of soil and environmental management" and for conducting additional research in accordance with the resolution of the Presidium of the NAAS of Ukraine dated April 19, 2023 No. 05/01 "State and tasks of scientific support for soil resource management at the stage of armed aggression of the Russian Federation and post-war reconstruction of Ukraine".

FUNDING

The study did not receive additional funding.

CONFLICT OF INTEREST

None.

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Методи покращення екологічного стану хімічно забрудненої системи ґрунт-рослина за впливу мілітарно-техногенних факторів на агроценози

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Анотація. Мета роботи – дослідити ефективність нових методів ремедіації *in situ* забруднених ґрунтів при комплексних мілітарно-техногенних впливах на систему ґрунт-рослина в зонах атмотехногенних викидів об'єкту виробництва електричної та теплової енергії (на прикладі ТОВ «ДТЕК Курахівська ТЕС» Донецької області). Використано системний підхід із залученням комплексу універсальних загальнонаукових методів; методів польових і чинних методів хіміко-аналітичних досліджень ґрунтів і тест-рослин агроценозів із визначенням показників елементного статусу системи ґрунт-рослина, індикаторних показників якості рослин за впливу хімічного забруднення та мілітарного впливу; використанням розроблених методів хімічної і біологічної ремедіації системи ґрунт-рослина; застосуванням камеральних методів статистичної обробки отриманих даних. Отримано нові знання з контролю хімічного забруднення ґрунтів і системи ґрунт-рослина за умов комплексного впливу мілітарного фактору і хімічного забруднення в зонах атмотехногенних викидів об'єкту виробництва електричної та теплової енергії. Отримано нові дані з аналізу ефективності використання розроблених інноваційних методів хімічної та біологічної ремедіації забруднених ґрунтів за нових умов мілітарно-техногенних впливів. Встановлено пріоритетне забруднення системи ґрунт-рослина рухомими формами сполук свинцю (Pb), кадмію (Cd), цинку (Zn), міді (Cu) та нікелю (Ni) за вибухів снарядів і ракет. Встановлено перевищення нормативних значень вмісту металів-токсикантів Cd, Pb, Cu у зерні та вегетативній масі тест-рослин *Hordeum vulgare* і *Triticum aestivum* L. Визначено переваги використання нового синтезованого хелатно-гуматного препарату Смарагд та біопрепарату Гаупсин БТ для ефективного поліпшення екологічного стану забрудненої системи ґрунт-рослина. Результати досліджень є підставою для подальшого впровадження розроблених методів у господарствах різних форм господарювання для відновлення здоров'я ґрунтів за умов мілітарно-техногенних впливів на ґрунтовий покрив, систему ґрунт-рослина; за проведення заходів ремедіації та екологічної реабілітації хімічно забруднених ґрунтів для покращення екологічного стану ґрунтів і мінімізації впливів хімічного забруднення і мілітарного фактору; у науково-дослідній практиці – для розробки методів і технологій ремедіації та екологічної реабілітації хімічно деградованих ґрунтів територій забруднення; контролю деградації за хімічного забруднення ґрунтів, сприяння забезпеченню продовольчої та екологічної безпеки

Ключові слова: ґрунт; хімічне забруднення; важкі метали; мілітарно-техногенні впливи; методи відновлення ґрунту

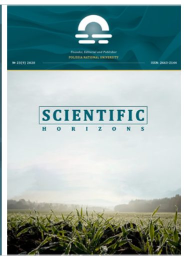
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(9), 24-36

UDC 630.63:630.91(477.41/.42)

DOI: 10.48077/scihor9.2025.23



Characteristics of the Forest Fund of Ukrainian Polissia

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Article's History:
Received: 11.04.2025
Revised: 05.08.2025
Accepted: 27.08.2025

Abstract. The study examines the spatial and forestry structure of the Ukrainian Polissia forest fund based on forest management materials from four branches of the State Specialised Forest Enterprise «Forests of Ukraine»: «Poliskyi Forest Office», «Pivnichnyi Forest Office», «Stolychnyi Forest Office» and «Podilskyi Forest Office». The methodology included several stages: spatial analysis using GIS tools and forest management materials to determine administrative units within the natural zone of Polissia; creation of a database based on key taxation indicators (species composition, forest site conditions, forest stand origin, age class, forest site conditions class); analytical summarisation of the structure of forests by administrative units. The study determined that natural forests predominate (52% of the area), but their share varies by region. The dominant species is Scots pine, which occupies approximately 63% of the total area. A high mosaic pattern of forest site conditions was identified, with a predominance of fairly poor and fairly rich forest types site conditions. The structure is dominated by high-level site conditions class plantations (class I and above, 58% of

Suggested Citation:
Siruk, Yu., Siruk, I., Turko, V., & Diachuk, P. (2025). Characteristics of the Forest Fund of Ukrainian Polissia. *Scientific Horizons*, 28(9), 24-36. doi: 10.48077/scihor9.2025.24.

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the area). Certain patterns were identified in the forest inventory structure, which are associated with an increase in the continentality of the climate from west to east, namely: an increase in the proportion of artificial plantations, a change in the predominance of moist and wet hygrotypes to fresh ones, a decrease in the proportion of softwood species in the composition, an increase in forest productivity, and an increase in the proportion of maturing and mature tree stands. The results of the study can be used to optimise forest resource management, develop regional strategies for sustainable forest use and preserve the ecosystem stability of the Polissia forests

Keywords: forest stand origin; forest site conditions; forest productivity; spatial analysis; GIS

INTRODUCTION

The forest fund, as a collection of land covered with forest vegetation and intended for forestry, is a significant component of the natural resource potential of any country, including Ukraine. In the context of growing environmental challenges, including climate change, biodiversity loss and intense anthropogenic pressure, a detailed study of the structure, spatial organisation and functional state of forests in individual natural-geographical regions requires special scientific attention. The forest fund is a fundamental component of the natural resource potential of European countries, supporting biodiversity, regulating the climate, and providing ecosystem services. According to the European Environment Agency (EEA), forests cover about 160 million hectares, which is approximately 39% of the EU's area, and more than 90% of these forests are semi-natural, while primary and old-growth forests account for less than 4% (European Parliament, 2022). According to H. Mauser (2023), between 1961 and 2020, forest cover in EU countries increased by 37%, timber stocks grew by 138% and productivity by 95%. Forecasts indicate that the forest area will continue to grow as a result of sustainable forest management and natural regeneration. The creation of new forests through afforestation programmes and the spontaneous reforestation of low-productivity land are also contributing to this trend (Corticeiro *et al*., 2024).

However, forest ecosystems are currently facing a range of challenges, the most significant of which are climate change, intensified logging, droughts, forest fires, mass outbreaks of pests and destructive windstorms. According to the results of a large-scale review by Z. Vacek *et al.* (2023), the effects of climate change are manifested in pronounced regional asymmetry in productivity: in southern Europe, growth rates are declining by 1249%, while in northern regions, on the contrary, there is an almost twofold increase (+99%). Such spatially heterogeneous dynamics indicate the need for regionally differentiated forest management strategies, as universal approaches are losing their effectiveness. In addition to changes in growth rates, the structure of degradation factors is also undergoing a significant transformation. According to data from the European Environment Agency (2023), the share of fires, storms and mass pest outbreaks in the structure of destructive factors for European forests has effectively doubled over the last decade. This indicates not only an increase in the vulnerability of ecosystems but also the cumulative effect of climate stress, which makes forests more prone to catastrophic disturbances. A key tool for monitoring forest conditions and forecasting these trends is the Global Forest Resources Assessment (FRA), which covers the period from 1990 to 2025 and includes more than 60 indicators, including forest area, biomass volumes, annual growth, ownership structure and sustainability characteristics (FAO, 2025). A unique advantage of the FRA is the comparability of data between countries, but its limitation remains the high aggregation of indicators, which limits analysis of regional characteristics. To overcome this shortcoming, studies conducted highly detailed spatial analysis. For example, V. Avitabile *et al.* (2024) presented harmonised statistical series and maps of biomass and annual wood growth with a resolution of up to 100 m across 38 European countries. These results significantly contribute to analysis of regional variability and provide a basis for adapting management decisions at the national and local levels. However, even these maps are not always able to reflect micro-scale processes, in particular local differences in soil and hydrological conditions, which maintains the need to combine global and local data.

Ukrainian Polissia is one of the most forested regions of the country, where forests combine relevant economic functions with a critical ecological role in maintaining the hydrological balance and preserving biodiversity. Unique climatic, soil and hydrological conditions determine the formation of specific types of forest ecosystems. The predominance of pine and sub-pine forests, a significant proportion of marshy and peaty lands, as well as the mosaic nature of the landscapes, create a complex spatial structure of the forest fund, which requires in-depth analysis and differentiated approaches to management. Climatic studies by S. Boychenko *et al.* (2025) showed that during the period 1990-2021, the average annual temperature in Polissia increased by 0.60 ± 0.08°C per decade, while precipitation decreased by approximately 6 mm. This trend not only increases the risk of summer droughts but also leads to a gradual transformation of forest growing conditions. A significant consequence of this process is a decrease in the groundwater level. As noted by S. Sydorenko *et al.* (2024), the combination of lower soil moisture and the dominance of pine plantations create particularly favourable conditions for the occurrence and spread of fires, confirming Polissia's high vulnerability to climate-related threats.

The study aimed to provide a scientifically substantiated description of the forest fund of the Ukrainian Polissia region, including an analysis of its area, age structure, species composition of tree stands, origin, types of forest site conditions, and productivity.

MATERIALS AND METHODS

The research was based on forest management data from the last audit period (basic forest management 2014-2025) for the structural divisions of four branches of the State Enterprise (SE) "Forests of Ukraine": "Poliskyi Forest Office", "Pivnichnyi Forest Office", "Stolychnyi Forest Office" and "Podilskyi Forest Office". At the first stage of the study, a geospatial analysis was conducted to identify the divisions of the branches located within the Ukrainian Polissia region according to the comprehensive forest management zoning (Hensiruk, 1991). The geospatial analysis was conducted using the "Forests of Ukraine" geoportal and the Geoinformation System for Forest Resource Management (State Forest Resources Agency of Ukraine, n.d.). When using the "Forests of Ukraine" geoportal, the territorial affiliation of the unit was assessed using the "Map" tab and the "Plantations" section in the context of four interregional administrations: North-Western, Central, Northern and South-Western. The geographic information system for forest resource management was used as a cartographic basis for determining the correspondence of the territory of forest districts to the Ukrainian Polissia zone. For this purpose, the layers "Region of distribution (forestry zoning)", "Quarters" and "Allotments" were used in the "Permanent forest seed base" section. The forest fund of all Forestry Management Unit, with the exception of Baranivske, Volodymyr-Volynske, Korostyshivske, Makarivske, Nizhynske and Shepetivske, was completely attributed to the Ukrainian Polissia. In the second stage of the study, a sample was formed based on such inventory indicators as tree species composition, types of forest site conditions, forest stand origin, age class, and forest site conditions class. The indicators of the structural subdivision of the Forestry Management Unit served as a sampling option. The source of information was the forest management information database of the Ukrainian Research Institute of Forestry and Agroforestry (n.d.). In cases where only part of the Forestry Management Unit territory (Baranivske, Volodymyr-Volynske, Korostyshivske, Makarivske, Nizhynske and Shepetivske) belonged to the natural zone of the Ukrainian Polissia, the analysis of forest management information was conducted using data from the relational database of the Ukrderzhlesproekt Production Association for 2017, using the Lisovporadnyk geoinformation system. The database query was performed using the following algorithm: "SQL" → "Allocation area" (grouping/sum) → "Plant growth conditions" ("Main species", "Bonitet class", "Type of forest growing conditions", "Age group") → "Characteristics of tree species components" ("Sequential number of tree species" – 1, "Origin"). Forest stand origin (artificial or natural) was determined by the main species in the main stand storey. The average site conditions class was calculated as a weighted average (sum of the products of areas and site conditions class / total area). At the third stage, the forest fund data was analysed and interpreted in terms of Forestry Management Unit and Branches. The processing and analysis of forest management materials were conducted following the instructions in force in Ukraine (Instruction for forest management of forest fund in Ukraine, 2006). Mathematical processing of data arrays was conducted using Excel.

RESULTS

Territorially, the Ukrainian Polissia zone includes forest areas belonging to four branches of the State Enterprise "Forests of Ukraine": "Poliskyi Forest Office" – 1.08 million hectares (46%) of forested land, "Stolychnyi Forest Office" – almost 0.79 million hectares (34%), "Pivnichnyi Forest Office" – over 0.45 million hectares (19%) and "Podilskyi Forest Office" – 0.03 million hectares (1%). The Branch "Poliskyi Forest Office" has 15 of the 16 forest districts within the Ukrainian Polissia region under its jurisdiction (Table 1).

Table 1*. Areas of forest plantations of the Forestry Management Unit of the Branch "Poliskyi Forest Office", belonging to the Ukrainian Polissia*

Forestry Management Unit	Area of forested land, thousand hectares		Proportion of natural tree stands, %
	Total	Including artificial	
Volodymyr-Volynske	58.2	26.9	53.9
Kivertsivske	108.7	46.7	57.0
Manevytske	70.7	30.4	57.0
Liubeshivske	45.0	11.8	73.8
Kamin-Kashyrske	71.7	27.0	62.4
Ratnivske	43.4	19.3	55.6
Liubomlske	71.7	29.3	59.2
Kovelske	58.2	22.2	61.8

Table 1. Continued

Forestry Management Unit	Area of forested land, thousand hectares		Proportion of natural tree stands, %
	Total	Including artificial	
Vysotske	70.0	23.5	66.5
Kostopilske	75.4	42.0	44.3
Rafalivske	81.7	29.8	63.5
Sarnenske	93.1	39.9	57.1
Klesivske	139.1	44.4	68.1
Bereznivske	47.3	18.0	61.9
Sosnivske	44.9	17.4	61.1
Total	1079.3	428.6	60.3

Source: *compiled by the authors*

The Dubenske Forestry Management Unit and the southern part of the Volodymyr-Volynske Forestry Management Unit belong to the Forest-Steppe. In the forest fund of all Forestry Management Units except Kostopilske, natural tree stands prevail in terms of area. Of the 15 structural units of the Branch "Stolychnyi Forest Office", only 12 belong to the Ukrainian Polissia. Natural tree stands predominate in terms of area only in the forest districts in the north of Zhytomyr Region (Table 2).

Table 2*. Areas of forest plantations of the Forestry Management Unit of the Branch "Stolychnyi Forest Office", which belong to the Ukrainian Polissia*

Forestry Management Unit	Area of forested land, thousand hectares		Proportion of natural tree stands, %
	Total	Including artificial	
Baranivske	37.9	24.9	34.2
Bilokorovytske	106.9	35.4	66.9
Zviahelske	104.7	39.8	61.9
Slovechanske	66.1	28.9	56.3
Ovrutske	130.6	55.2	57.8
Radomyshlske	49.1	34.5	29.8
Korostenske	109.2	43.7	60.0
Korostyshivske	20.6	13.6	34.2
Ivankivske	53.5	33.9	36.6
Dymerske	53.4	32.1	40.0
Teterivske	32.1	24.2	24.6
Makarivske	23.4	15.6	33.1
Total	787.6	381.8	51.5

Source: *compiled by the authors*

The Boryspilske, Bilotserkivske, and Bohuslavske Forestry Management Unit belong to the Forest-Steppe zone. The southern parts of the Baranivske, Korostyshive, and Makarivske Forestry Management Unit also belong to this natural zone. Of the nine structural units of the Branch "Pivnichnyi Forest Office", only seven can be attributed to the Ukrainian Polissia (Table 3).

Table 3*. Forest areas of the Forestry Management Unit of the Branch "Pivnichnyi Forest Office" and Branch "Podilskyi Forest Office", which are part of the Ukrainian Polissia region*

Forestry Management Unit	Area of forested land, thousand hectares		Proportion of natural tree stands, %
	Total	Including artificial	
Branch "Pivnichnyi Forest Office"			
Shostkynske	83.4	62.5	25.1
Konotopske	42.3	26.1	38.2
Chernihivske	90.8	58.2	35.9
Koriukivske	70.6	44.6	36.9
Nizhynske	42.0	24.7	41.3
Novhorod-Siverske	56.9	42.0	26.2
Horodnianske	68.7	39.9	42.0
Total	454.8	298.0	34.5

Table 3. Continued

Forestry Management Unit	Area of forested land, thousand hectares		Proportion of natural tree stands, %
	Total	Including artificial	
Branch "Podilskyi Forest Office"			
Shepetivske	32.4	18.1	44.2

Source: *compiled by the authors*

In addition to the Sumske and Trostyanetske Forestry Management Unit, the southern part of the Nizhynske Forestry Management Unit is also not part of Polissia. In the forest fund of the Branch "Podilskyi Forest Office", only the western part of the Shepetivske Forestry Management Unit can be attributed to the natural zone of Polissia in Ukraine. The forest plantations of all structural units of both species, without exception, are predominantly of artificial origin. In general, natural tree stands dominate in the forests of Ukrainian Polissia, accounting for 52% of the forested land. While natural forests account for 60% of the forest areas of the Branch "Poliskyi Forest Office", they cover only 34% of the areas of the Northern Forestry (Fig. 1).

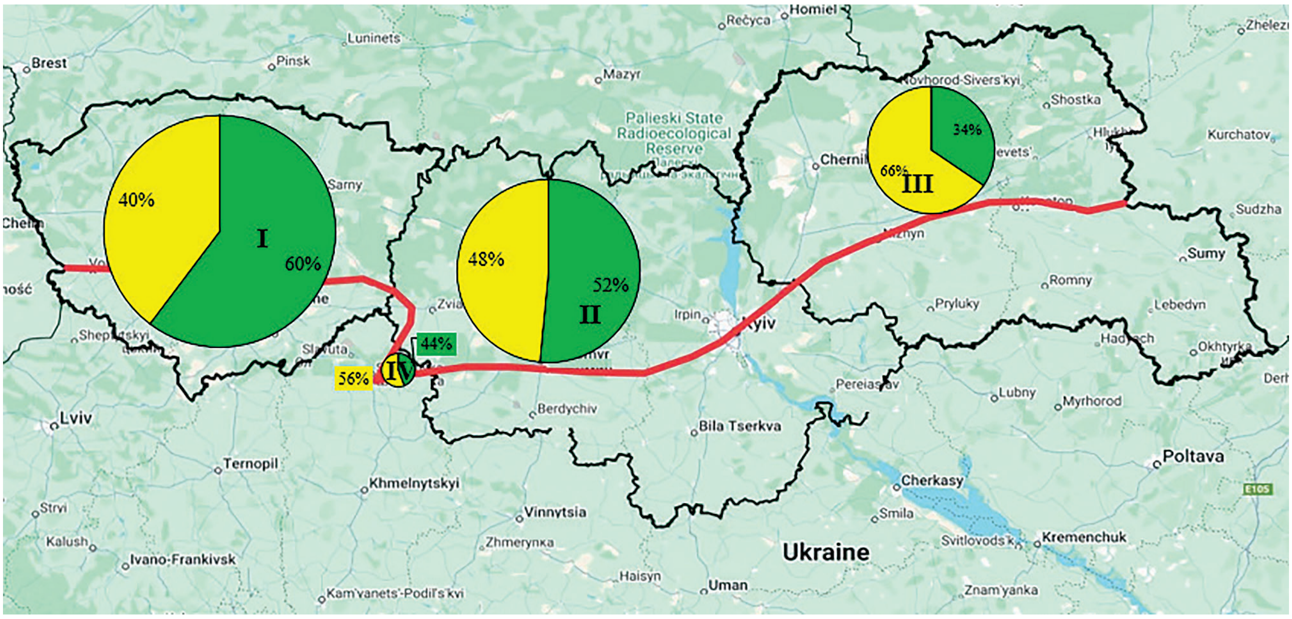

Figure 1*. Distribution of forest areas belonging to branches of the State Enterprise "Forests of Ukraine" located in the Ukrainian Polissia region, by origin*

Note: *yellow colour – artificial forests, green – natural forests. I – Branch "Poliskyi Forest Office", II – Branch "Stolychnyi Forest Office", III – Branch "Pivnichnyi Forest Office", IV – Branch "Podilskyi Forest Office"*

Source: *compiled by the authors*

In the forests of the Ukrainian Polissia, the proportion of poor forest site conditions is slightly more than 12% of the area, with fresh poor conditions being the most common at almost 8%. The proportion of fairly poor forest site conditions is significantly greater than 50%. The most common types of forest site among fairly poor conditions are fresh and moist, accounting for 23% and 19% respectively. Fairly rich forest site conditions are quite common, covering more than 34% of the area, including moist fairly rich conditions (almost 15%) and fresh and wet fairly rich conditions (more than 9% each). Fairly rich forest site conditions are the least common in Polissia, covering only 3% of the area, of which fresh fairly rich conditions accounts for almost 2% and moist suhrud for more than 1% (Fig. 2).

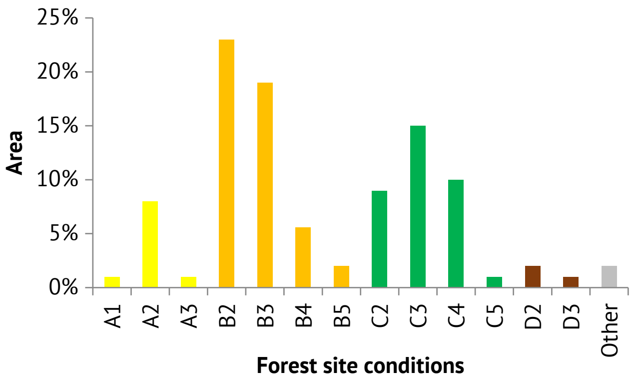

Figure 2*. Distribution of forest areas in the Ukrainian Polissia region by type of forest site conditions*

Source: *compiled by the authors*

Within Polissia, the most common forest conditions (poor) are found in the forests of the Branch "Poliskyi Forest Office", covering almost 16% of the area. In the Branch "Stolychnyi Forest Office", poor forest site conditions account for 11% of the area, and in the Branch "Pivnichnyi Forest Office", 7%. In the forests of the Branch "Podilskyi Forest Office", the share of pine forest conditions is insignificant. Fairly poor forest site conditions are the dominant trophic habitat in the three largest branches in terms of area, representing the natural zone. The share of fairly poor forest site conditions from 47% in the Branch "Poliskyi Forest Office" to 54% in the Branch "Stolychnyi Forest Office". In the Polissia part of the Branch "Podilskyi Forest Office", fairly poor forest site conditions occupies only 32%, while the most common here are fairly rich forest site conditions, which account for 63% of the area. In the other branches, dry forests are significantly less represented, ranging from 32% to 36%. The example of fairly poor and fairly rich forest site conditions clearly shows a trend towards a decrease in forest moisture content from west to east. While moist fairly poor and fairly rich forest site conditions predominate in the forests of the Western Polissia and Central Polissia forestry districts, fresh edaphic forests dominate in the Dnipro-Polissia and Eastern Polissia districts (Fig. 3).

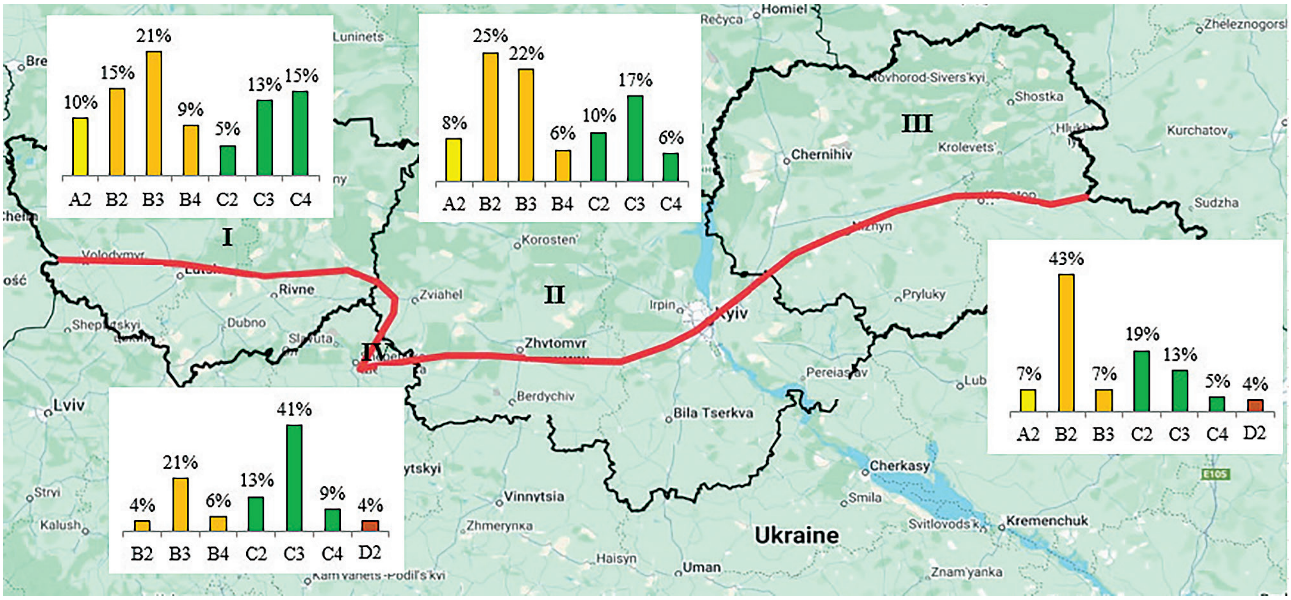

__Figure 3__. Distribution of forest areas belonging to branches of the State Enterprise "Forests of Ukraine" located in the Ukrainian Polissia region, by predominant types of forest site conditions
Note: *I – Branch "Poliskyi Forest Office", II – Branch "Stolychnyi Forest Office", III – Branch "Pivnichnyi Forest Office", IV – Branch "Podilskyi Forest Office"*
Source: *compiled by the authors*

Pine is the dominant tree species in 63% of forested areas. Plantations dominated by deciduous tree species, namely silver birch, common oak and black alder, are much less common (Fig. 4).

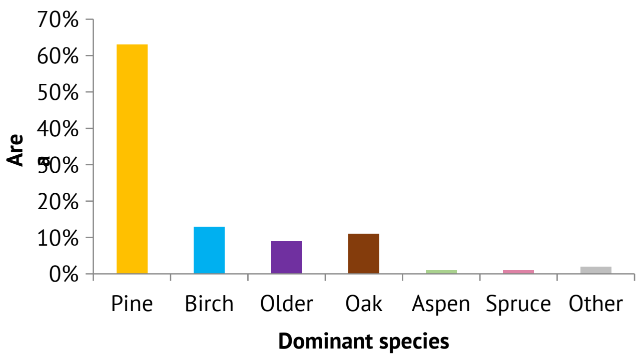

__Figure 4__. Distribution of forest areas in the Ukrainian Polissia region by predominant species
Source: *compiled by the authors*

The tree species composition of the forests of the Ukrainian Polissia varies across its branches, which is partly due to the differentiation of forest growing conditions. From west to east, the proportion of pine and oak stands increases, while the proportion of black alder decreases (Fig. 5).

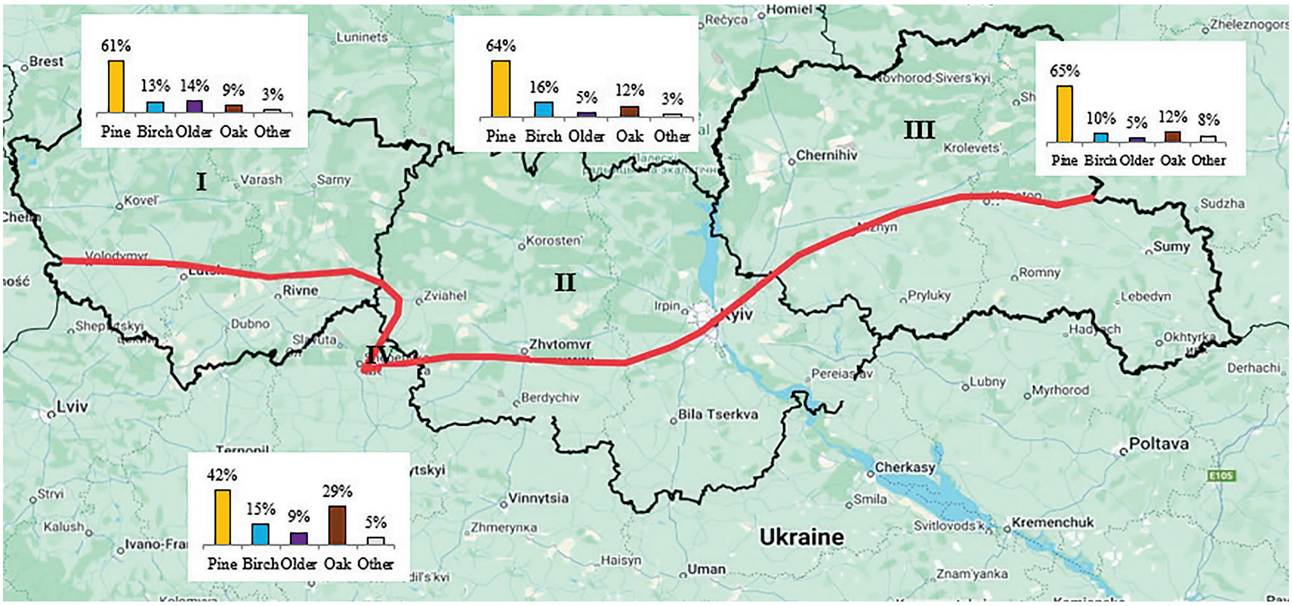

__Figure 5__. Distribution of forest areas belonging to branches of the State Enterprise "Forests of Ukraine" located in the Ukrainian Polissia region, by predominant tree species

Note: *I – Branch "Poliskyi Forest Office", II – Branch "Stolychnyi Forest Office", III – Branch "Pivnichnyi Forest Office", IV – Branch "Podilskyi Forest Office"*

Source: *compiled by the authors*

The tree species composition of the forests belonging to the Branch "Podilskyi Forest Office", which are in the Polissia region, is representative of the Forestry Management Unit located on the border between Polissia and the forest-steppe zone of right-bank Ukraine. Notably, among the less common tree species in these forests, in addition to aspen and European spruce, there are common ash and common hornbeam. The species composition of the forests of the Northern Forest Branch has certain differences. In the forests of the Eastern Polissia Forestry District, which includes most of the forest plantations of this branch, there is a relatively higher proportion of other tree species, in particular willow, common ash, European spruce, and black locust. The age structure of forests in the Ukrainian Polissia is unbalanced, as evidenced by the ratio of forest areas of different age groups (Fig. 6). The proportion of young trees is 40% less than optimal, and the proportion of mature trees is 30% less than optimal. Considering the duration of the age group, the largest proportion is that of middle-aged forest stands, which is at least twice the optimal level. The proportion of maturing stands is also disproportionate to the age range of this age group and exceeds the optimal level by 30%.

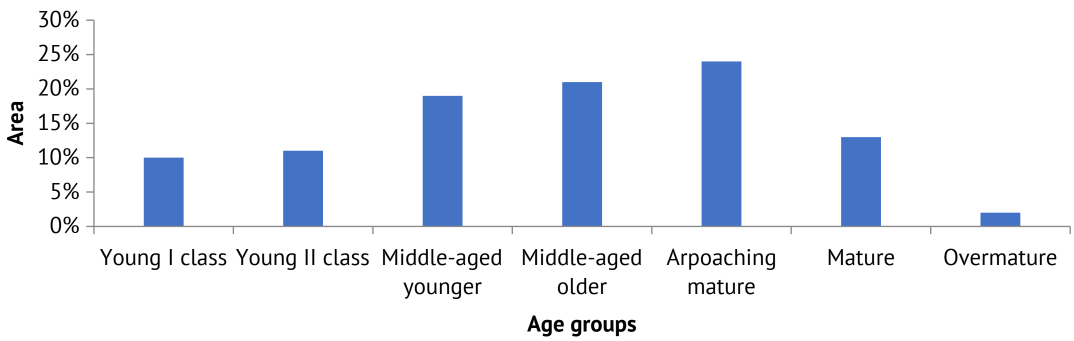

__Figure 6__. Distribution of forest areas in the Ukrainian Polissia by age group

Source:compiled by the authors

In terms of the four branches of the State Enterprise "Forests of Ukraine", whose territories belong to the Ukrainian Polissia zone, the age structure of forest plantations has certain differences. The most noticeable trend is an increase in the proportion of mature and overmature plantations from west to east. Thus, while in the Branch "Poliskyi Forest Office" and Branch "Podilskyi Forest Office", the proportion of mature (including overmature) tree stands is 10% and 12% respectively, in the Branch "Stolychnyi Forest Office", mature forests cover 16% of the territory, and in the Branch "Pivnichnyi Forest Office", 21% (Fig. 7).

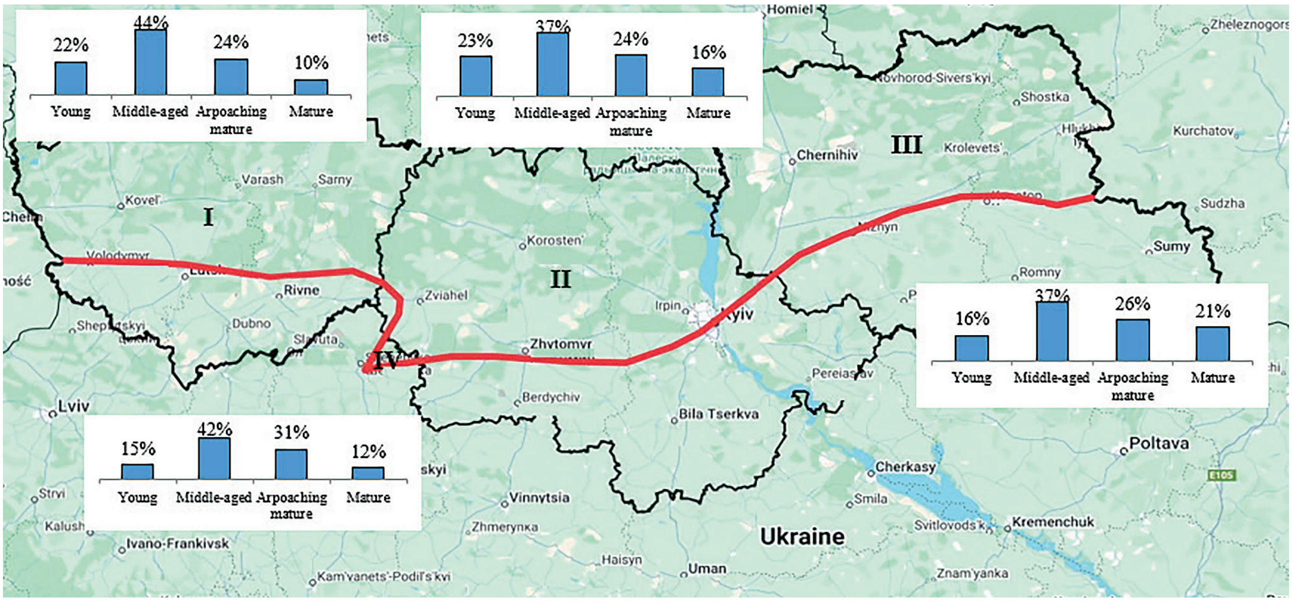

***Figure 7**. Distribution of forest areas of branches of the State Enterprise "Forests of Ukraine" located in the Ukrainian Polissia region, by age group*
***Note:** I – Branch "Poliskyi Forest Office", II – Branch "Stolychnyi Forest Office", III – Branch "Pivnichnyi Forest Office", IV – Branch "Podilskyi Forest Office"*
***Source:** compiled by the authors*

The productivity of the forests of Polissia in Ukraine is high, as indicated by the distribution of forest areas by forest site conditions classes. Plantations of forest site conditions classes I, II and Ia predominate in terms of area (Fig. 8). Highly productive forest plantations (forest site conditions classes I and above) account for almost 58% of the area, medium-productive plantations (forest site conditions classes II-IV) account for almost 41% of the area, and low-productive plantations (forest site conditions classes V and below) account for only slightly more than 1% (Fig. 8). The differentiation of forest site conditions in the forests of the Ukrainian Polissia region has led to a corresponding difference in the distribution of forest areas by forest site conditions classes across the branches of the State Enterprise "Forests of Ukraine". The highest productivity indicators are observed in the forests of the Branch "Pivnichnyi Forest Office", where tree stands of forest site conditions classes I and Ia predominate in terms of area (Fig. 9).

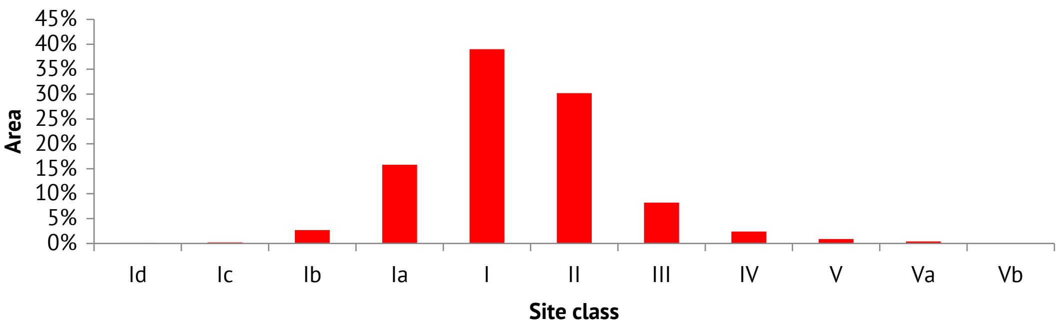

***Figure 8**. Distribution of forest areas in the Ukrainian Polissia by forest site conditions classes*
***Source:**compiled by the authors

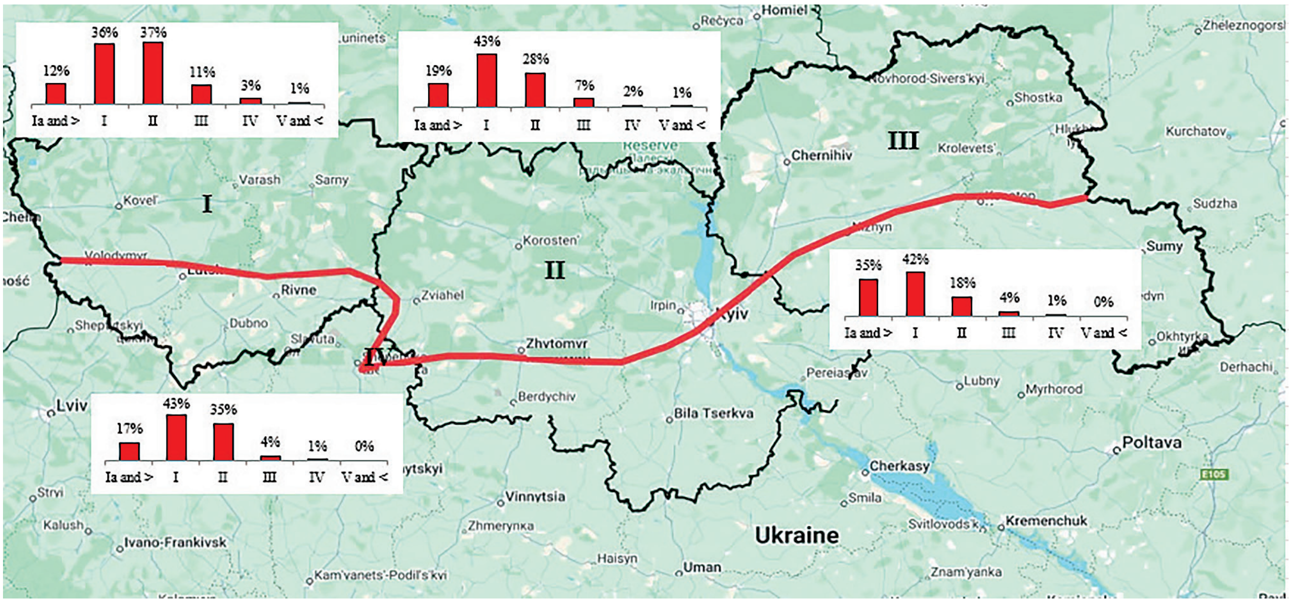

__Figure 9__. Distribution of forest areas belonging to branches of the State Enterprise "Forests of Ukraine" located in the Ukrainian Polissia region, by forest site conditions classes

Note: *I – Branch "Poliskyi Forest Office", II – Branch "Stolychnyi Forest Office", III – Branch "Pivnichnyi Forest Office", IV – Branch "Podilskyi Forest Office"*

Source: *compiled by the authors*

The average forest site conditions class in the forests of this branch is Ia,9. The distribution of forest areas by forest site conditions classes in the forests of the Branch "Stolychnyi Forest Office" and Branch "Podilskyi Forest Office" is quite similar, with forest site conditions classes I and II predominating. The average forest site conditions class in both branches is I,3. Productivity indicators are relatively lower in the forests of the Western Polissia Forestry District, which are represented by the plantations of the Branch "Poliskyi Forest Office", where tree stands of productivity classes II and I prevail in terms of area. The average forest site conditions class is I.6. The results of research at the regional level create a comprehensive typologically oriented picture of the forests of the Ukrainian Polissia, covering the origin, structure of forest site conditions, tree species and age profiles, and productivity levels. Stable west-east gradients of edatope moisture and changes in species and age structure were identified, which compared and identified imbalances in age structure, incorporating the correspondence of the main tree species to the types of conditions.

DISCUSSION

The latest scientific works on the analysis of the forest fund of the Ukrainian Polissia are materials from 10-30 years ago. The most comprehensive and detailed regional description of forests was conducted by S. Hensiruk (1991), but these data were presented in terms of natural zones of Ukraine. The results of studies on changes in the composition of forests and forest growing conditions in the Ukrainian Polissia are, to some extent, consistent with the author's data, in particular, the increase in the proportion of artificial pine stands in the composition of forests from west to east, and the conclusions regarding the dependence of forest site conditions and continentality are also similar. A more detailed description of the forest fund is presented in the monograph by V. Tkachuk (2004), but in this scientific work, the analysis was conducted on Scots pine in the Right-Bank Polissia. The results of a comparative analysis of the forest fund of the Volyn, Rivne and Zhytomyr regions in terms of forest growing conditions, age structure and productivity generally correspond to our analytical data. The most valuable data are presented in the scientific article by M. Savushchyk and M. Popkov (2008), which concerns the typological structure of the forests of the Ukrainian Polissia. These materials most successfully and comprehensively describe the typological, age and species structure of the region's forests and, similar to present research, are based on forest management materials from the relational database of the Ukrderzhlesproekt State Enterprise. The data on the typological structure of state-owned forests as of 2008 differ from our data in that they show a higher proportion of poor and fairly poor forest site conditions and a lower proportion of fairly rich and rich forest site conditions. This is due to changes in the structure of forests during the 2022-2025 reorganisation, as all of the above-mentioned authors used materials on forest users in the structure of the State Committee of Forestry of Ukraine, while the present data was obtained by processing forest management data on the structural units of the State Enterprise "Forests of Ukraine" as of 2025.

The increase in the proportion of fairly rich forest site conditions (~34%) in the eastern direction and the minimal representation of rich forest site conditions (~3%) reflect the natural decrease in edatope humidity from west to east. A similar west-east gradient of hydrothermal conditions and corresponding spatial differentiation of forest site conditions for Polissia and Ukraine as a whole was noted by V. Tkach (2024). The shift to "drier" edatopes in the east is accompanied by more frequent use of controlled regeneration regimes – from assisted natural regeneration to the creation of cultures – as interpreted by regional reviews (Zhezhkun *et al*., 2023; Skliar *et al*., 2024). V. Ovcharuk *et al.* (2020) showed an increase in evaporation by 110-185 mm and a drop in the humidity index to ≈101%, which explains why the need for artificial forest restoration is increasing in the east. In addition, Y. Nykytiuk *et al.* (2022) noted a degumification and a decrease in the buffer capacity of sod-podzolic soils – another argument in favour of artificial reforestation strategies in the fairly rich forest site conditions.

The observer 63% of the area under Scots pine and the simultaneous decrease in the proportion of alder from the east are consistent with studies on continentality as a driver of change in the composition of tree stands in Europe (Koch *et al*., 2022). The increased sensitivity of continental subzones to spring frosts and summer droughts, as shown by L. Chen *et al.* (2023) selectively support more xerophytic taxa (*Pinus*, *Quercus*) and displace the moisture-loving *Alnus* to the "wetter niches" of the terrain. In a study of forests in Central and Eastern Europe, M. Niemczyk *et al.* (2021), using Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (not native to Polissia, but a representative model) as an example, demonstrated an increase in relative productivity in more continental conditions, supporting the idea of mixed compositions and the selection of resistant species in eastern subzones. The observation of increased participation of hornbeam, ash, black locust, and willow is a sign of an "adaptive mosaic" of compositions to mitigate the risks of moisture deficiency and temperature extremes, which is consistent with the data of R. Seidl *et al.* (2017) and R. Sousa-Silva *et al.* (2018).

The imbalance in age structure identified by the authors typically arises due to "wave-like" histories of felling/restoration and cautious logging regimes in more continental regions. The results of studies by T. Wang *et al.* (2024) confirm the conclusions that the increase in the proportion of mature and overmature stands from west to east (≈10-21% depending on the branch) correlates with a higher frequency of droughts and heat extremes, which make it difficult to convert areas to younger classes. A. Di Sacco *et al.* (2021) showed that more continental regions are losing productivity due to droughts and are experiencing "stretched" transitions between age classes, while more humid regions have a more balanced age structure. The proportion of highly productive stands (~58% I–Ia) directly reflects the correspondence of the composition and age structure to forest growing conditions: in fresh/moist fairly poor forest site conditions, the potential is realised most fully; in fairly rich forest site conditions, productivity is more strongly modulated by water deficit and heat extremes. S. Song *et al.* (2024) showed that targeted artificial reforestation programmes, if they incorporate moisture deficit, species selection and water regime management, can stabilise growth in drier analogues of mixed forest conditions.

European reviews by M. Erdozain *et al.* (2023) and D. Thom and R. Seidl (2022) systematically justify the expansion of tools from assisted natural regeneration to mixed crops with stable genotypes in conditions of drought, pests and windbreaks. According to N. Mansuy *et al.* (2020), reforestation policy in North America is also biased towards the scaling of artificial regeneration. A. Di Sacco *et al.* (2021) noted an increase in artificial forests as a response to climate change, while J. Fargione *et al.* (2021) outlined the key challenges and prospects of this course. For the Polissia region of Ukraine, this means that in the "wetter" north-western of the fairly poor forest site conditions zones, natural regeneration should be prioritised, and in the "drier" eastern types of forest site conditions, artificial forest restoration with a mixed composition involving drought- and frost-resistant species. Thus, the geospatial dependence of the typological structure of forests and the trend of "drying" of edatopes to the east are fully consistent with long-term regional observations by domestic and foreign scientists, as well as modern hydroclimatic assessments. The leading role of pine (63%) and the eastern growth of pine and oak, with a simultaneous decline in alder, reflect the known patterns of continentality.

CONCLUSIONS

Natural tree stands occupy a slight majority in the structure of the region's forests (52%), but their share varies significantly between individual branches of the State Enterprise "Forests of Ukraine". In particular, the largest share of natural forests is characteristic of the Branch "Poliskyi Forest Office" (60%), and the smallest share is characteristic of the Branch "Pivnichnyi Forest Office" (34%). An analysis of trophic habitats showed the dominance of fairly poor forest site conditions (over 50% of the area), of which fresh and wet types are the most common. The share of fairly rich forest site conditions is about 34%, while forest conditions are the least common, at 3%. The spatial distribution of these types of conditions shows a regular decrease in the humidity of edaphic conditions from west to east of the region.

The leading tree species is Scots pine, which accounts for 63% of forests. The proportion of deciduous species (silver birch, common oak, black alder) is significantly lower. There are regional differences in species composition: from west to east, the proportion of pine and oak increases, while the proportion of alder decreases. In the transitional zones of Polissia and Lisostep, there is also an increased proportion of hornbeam, ash, black locust and willow. The age structure of forests is unbalanced: the low proportion of young and mature stands is accompanied by an excess of middle-aged and maturing stands. The proportion of mature and overmature forests increases from west to east and ranges from 10% to 21% depending on the branch. The productivity of the forests of Polissia in Ukraine remains generally high: the proportion of highly productive stands (forest site conditions classes I and Ia) is almost 58%. The highest forest site conditions classes were recorded in the Branch "Pivnichnyi Forest Office" (average class Ia,9), and the lowest in the Branch "Poliskyi Forest Office" (I,6). The results of the study confirm the close relationship between the productivity of plantations and forest site conditions and can be used as a basis for studying the natural productivity of native and secondary plantations in the Ukrainian Polissia.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Анотація. У статті досліджено просторову та лісівничу структуру лісового фонду Українського Полісся на основі матеріалів лісовпорядкування чотирьох Філій Державного спеціалізованого підприємства «Ліси України»: Поліського, Північного, Столичного та Подільського лісових офісів. Методика включала кілька етапів: просторовий аналіз з використанням ГІС-інструментів та лісовпорядних матеріалів для визначення адміністративних одиниць у межах природної зони Полісся; формування бази даних за основними таксаційними показниками (породний склад, типи лісорослинних умов, походження, вікові групи, бонітет); аналітичне узагальнення структури лісів за адміністративними одиницями. Встановлено, що переважають природні ліси (52 % площі), однак їх частка варіює за регіонами. Панівною породою є сосна звичайна, яка займає близько 63 % загальної площі. Виявлено високу мозаїчність типів лісорослинних умов із домінуванням суборів і сугрудів. У структурі переважають високобонітетні насадження (І клас і вище – 58 % площі). Виявлено певні закономірності у лісотаксаційній структурі лісів, які пов'язані зі збільшенням континентальності клімату із заходу на схід, а саме: збільшення частки штучних насаджень, зміна переважаючих вологих і сирих гігротопів на свіжі, зменшенням участі м'якголистяних порід у складі, зростання продуктивності лісів, збільшення частки пристигаючих і стиглих деревостанів. Результати дослідження можуть бути використані для оптимізації управління лісовими ресурсами, розроблення регіональних стратегій сталого лісокористування та збереження екосистемної стійкості лісів Полісся

Ключові слова: походження лісів; типи лісорослинних умов; продуктивність лісів; просторовий аналіз; ГІС

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(9), 37-48

UDC 631.354.633.1

DOI: 10.48077/scihor9.2025.37

The impact of grain combine harvester working parts on damage and quality of winter wheat seeds

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Article's History:
Received: 19.03.2025
Revised: 03.08.2025
Accepted: 27.08.2025

Abstract. The aim of the study was to improve the quality of winter wheat seeds of the Fortuna and Yuvileina varieties by reducing damage during harvesting with a combine harvester at various stages of the technological process. Based on a comprehensive approach and the interrelation of climatic and soil characteristics, theoretical calculations, mathematical models, experimental, production and laboratory studies, the influence of the working parts of drum and rotary grain harvesting threshing units on microtrauma to seeds and its impact on the development of microorganisms and, in turn, on seed quality indicators, which significantly affect crop yield. The mathematical model of a damaged spring-viscous ellipsoidal grain provided by the authors shows

Suggested Citation:
Derevianko, D., Sukmaniuk, O., Hrudovyi, R., Tsyvenkova, N., & Zayets, M. (2025). The impact of grain combine harvester working parts on damage and quality of winter wheat seeds. *Scientific Horizons*, 28(9), 37-48. doi: 10.48077/scihor9.2025.37.

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that during the impulse force of relative and absolute trajectories of motion and acceleration, Coriolis forces, inertia, friction, and friction, when the rotation speed of the drum or rotor increases, the deformation of grains weighing 0.03-0.06 g with a transverse diameter of 3-5 mm within the range of 600-700 rpm is 0.015-0.035 mm, and damage increases significantly due to a decrease in seed strength, stress and force. Microtrauma at drum speeds of 700 to 1,000 rpm increases almost 9 times, and at rotor speeds 3 times. Microtrauma of Fortuna seeds before harvesting was 4.5%, and after unloading 56.2%, and for Yuvileina seeds 5.1% and 59.3%, respectively. There was no macro-damage to the seeds of either variety before threshing, but after unloading the grain from the combine harvester's hopper, it amounted to 7.3% and 6.2%. Damage by microorganisms, in particular Fusarium in the Fortuna variety after threshing, increased to 40.1%, Helminthosporium to 24.3%, Septoria to 13.6%, Alternaria to 4.6%, and in the Yuvileina variety to 18.2; 13.0%, 11.8% and 3.9%, respectively. During the threshing process, damage, injury and microorganisms affected the quality of the seeds, in particular in the Fortuna variety, the purity at unloading was 96.2%, the number of weed seeds per 1 kg was 281, and the germination rate was 92.1%. The weight in grams was 44.0, the specific weight was 741 g/litre, the raw gluten content was 24.6, and the protein content was 14.7. Accordingly, for the Yuvileina variety, these indicators were 95.0; 170; 94.8; 44.4; 740; 23.1; 13.7. The moisture content of the grain mass after harvesting both varieties was within the range of 14.6 and 14.3%

Keywords: force; impact impulse; speed; grain; microtraumas; microorganisms; yield

INTRODUCTION

Achieving high yields of winter wheat and ensuring gross grain production in Ukraine of over 100 million tonnes will significantly improve the economic and financial capacity of the state and at the same time contribute to meeting the comprehensive food needs of the population, in particular with high-quality products of various types of bread, various baked goods, pasta, confectionery, etc. Over the past few years, gross harvests have reached more than 60 and even 70 million tonnes, with an average yield of more than 50 centners per hectare, However, in order to increase these indicators, it is necessary to improve the quality of seed material by reducing damage and microtrauma to seeds at the technological stages of harvesting, processing, transportation, storage and processing, i.e. by improving and modernising technical means.

It should be noted that some modern technological lines and agricultural machinery are metal-intensive, bulky and expensive, and the level of injury and damage to grain is high, Therefore, both in theory and in practice, it is important to scientifically substantiate the results of theoretical, experimental and production research on the impact of working parts of machines and equipment on the injury and quality of grain seeds throughout the entire technological process of their cultivation. The results of experimental and production research by D. Derevjanko *et al.* (2020) show that damage and injury during the technological process by various working parts during threshing, i.e. reapers, conveyors, threshing units, and sieves, reach 20%, and sometimes more than 40% due to the biological condition of the plant, humidity of 20-25%, weed infestation, the preparedness of units and aggregates, and the professionalism of operators. and when a grain weighing 0.005 g falls onto the surface of a working body rotating at a speed (ω) of 6 rad s^{-1}, it causes tangential deformation of the seed in the plane O, ξ η, which is 0.021 and 0.025 mm. An increase in the linear U and angular parameters Θ with a decrease in angular velocity over a certain period of time indicates damage to the seed parameters. Therefore, when the seeds pass over the surface of the combine's threshing apparatus, which rotates at a speed of 700-800 rpm and above, there is an increase in deformation and injury, which contributes to a decrease in grain quality.

External factors, including climatic and soil conditions, are important components of plant growth and development throughout the growing season and significantly affect the size and quality of the crop (Talwar *et al.*, 2023). The impact of the working parts of various technical means during the technological process of plant development reduces the germination and other quality indicators of seeds, while limited soil moisture, light, and temperatures below 15°C have a negative effect on seed germination efficiency, resulting in low crop quality and quantity. Production, experimental and laboratory studies show that the impact of working parts on seed damage during sowing sometimes reaches 20% or more, depending on the interaction of different working parts (Yu *et al.,* 2020). Studies of the impact of working body surfaces when seeds weighing 0.04-0.006 g hit the working surfaces while rotating at a speed (ω) of 6 rad s^{-1} contribute to the occurrence of deformation and the formation of cracks to a depth of 0.25-0.75 mm, and the influence of microorganisms, which reduces the quality of the grain material, and the working parts are located at an angle of 10-15°, which move the seeds and, during drying, increase seed damage. According to J. Mellmann *et al.* (2018), temperature, temperature fluctuations, light and mechanical stress, if they exceed the optimal values, for example, temperatures above 25°C or below -20°C for a long time, also have a negative impact on damage, quality and yield of grain crops.

The use of reliable, timely, accurate, cost-effective and environmentally safe methods for assessing seed quality is indicated by S. Stepanenko *et al*. (2024) point to the use of reliable, timely, accurate, cost-effective, and environmentally safe methods for assessing seed quality, as well as the creation of a structural model of the separation process and the development of a criterion equation that includes quality indicators, allowing for the assessment of grain damage under the influence of key factors such as impact force, force momentum, elasticity modulus, density, etc. The influence on the efficiency of separation and, accordingly, on the quality of the seeds obtained is highlighted in the study by V. Bredykhin *et al.* (2021) on the parameters of the pneumatic vibration and centrifugal separation process, which is critically influenced by the circular rotation frequency of the cylindrical working surface, the frequency and amplitude of its oscillation, which are within the range of $\omega = 24\text{-}25$ rad/s and $\omega = 15.0\text{-}15.6$ rad/s, and the air velocity is $V = 2$ m/s.

Scientific evidence of the impact of technical means on the quality of seeds with the lowest biological potential is provided in the studies by V. Bredykhin *et al.* (2023), which propose mathematical models of the technological processes of loading grain elevator buckets, the nonlinear dynamics of a multiphase medium on the disc spreader of a vibrating separator, and the separation of seeds by density in a pneumatic fluidised bed. Technical features of seed calibration on screens with Cassini oval-shaped holes, etc. are provided. Researchers O. Pivovarov *et al.* (2023) propose innovative methods for assessing the quality of grains of various crops and provide a description of modern laboratory equipment that allows determining the nature, moisture content, purity, vitreousness, and mass of grains and legumes from the perspective of innovative methods. The authors K. Szwedziak *et al.* (2023) indicated in their research that harvesting, transportation, and storage technologies affect seed quality, and the use of electrical engineering support allows for the detection and selection of image elements. The study describes the development of a technology for evaluating grain in storage using electrical engineering and computer technology.

In connection with the research results considered, on the basis of which it is possible to study the physical, mechanical, technological and biological characteristics of seeds and the operation of machines and technologies, it is possible to improve the operation of working parts in interaction with grain material, reduce damage and injury, and significantly improve seed quality. The aim of the study was to justify the improvement of the quality of seeds of new modern high-yielding varieties of winter wheat of Ukrainian selection by reducing its macro- and micro-injuries and damage at various stages of the harvesting process, i.e. before threshing, in the reaper, in the threshing machine, on the sieve, during the operation of the transport working parts of the LEXION 770 combine harvester.

MATERIALS AND METHODS

A LEXION 770 combine harvester (Germany) was used to harvest winter wheat (Fig. 1).

***Figure 1**. General view of the LEXION 770 combine harvester during the harvesting process of Yuvileina winter wheat*

***Source:** CLAAS (n.d.)*

This combine harvester is equipped with a high-performance, powerful and fuel-efficient engine from Mercedes-Benz, which uses an individual cylinder feed system with solenoid valves in combination with an electronic control system (Fig. 2).

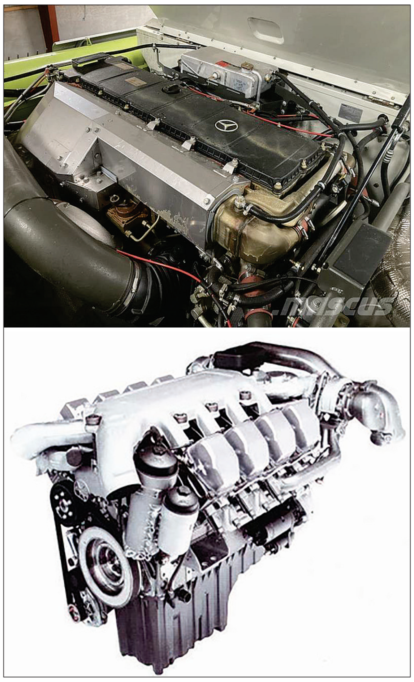

***Figure 2**. General view of the engine*

***Source:** CLAAS (n.d.)*

Features of the threshing system of this combine harvester model with a pre-accelerator, significant acceleration of grain mass movement up to 20 m/sec, and an effective separation device equipped with a multi-finger system ensure high productivity and efficiency of the machine (Fig. 3).

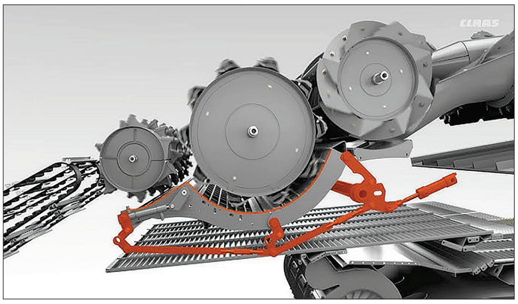

Figure 3. *Special threshing unit on MSS*
Source: *CLAAS (n.d.)*

The LEXION 770 combine harvester features the innovative MULTI CONTOUR system for efficient control of the swivel frame and adjustment of the cutting angle depending on the position of the bridge, ensuring that all process control functions are performed (Fig. 4).

Figure 4. *Innovative MULTI CONTOUR system*
Source: *CLAAS (n.d.)*

Figure 5 shows the latest equipment for more even distribution of cut mass in the combination of stalks and grain for better feeding and threshing.

Figure 5. *Equipment for uniform mass distribution*
Source: *CLAAS (n.d.)*

Theoretical research and calculations were performed by mathematical modelling of the working parts of the technical device and technological processes using the basic laws of mechanics, modern methods of computer calculations for constructing a system of differential equations, graphical definitions, integrations, transformations, etc. When compiling differential equations of relative motion of seeds on the working surface, its motion in the absolute coordinate system was considered, for which the methodology of Academician P.M. Vasylenko (1960) (1) was used. In this regard, a polar coordinate system (R, ϴ) was chosen, in which the absolute velocity is calculated from the expression:

$$V_a = \sqrt{\dot{R}^2 + R^2\theta^2}, \quad (1)$$

where $\acute{R}$ – the radial component of vector $\overline{V}_\alpha$; $R\dot{\theta}$ – the tangential component of vector $\overline{V}_\alpha$.

To differentiate the equations of seed movement, Lagrange equations of the second kind were used in accordance with the research objective of reducing seed damage and injury, to improve its quality at various stages of the threshing process on this combine harvester of modern, high-yielding varieties of winter wheat of domestic selection, for which it is necessary to substantiate and perform theoretical calculations of the influence of the working parts of the combine harvester on the deformation and injury of seeds, the impact of various types of injuries on the breaking force and maximum stress, the impact of the rotation speed of the working parts of threshing machines on the injury and quality of seeds of new, modern high-yielding varieties of winter wheat in the soil and climatic conditions of the central part of the Right-Bank Forest-Steppe of Ukraine. To this end, new designs with rubber-coated threshing apparatus beaters were improved and proposed, and laboratory equipment was manufactured to study the effect of mechanical factors on the strength, damage and microtrauma of cereal crops, in particular winter wheat. The motion of the applied mechanical system, which at the initial moment of time ($t=0$) was oriented along the Ox axis and begins to move from a state of rest, is described by Lagrange equations of the 2nd kind:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_s}\right) - \frac{\partial T}{\partial q_s} = Q_s\left(s = \overline{1,6}\right), \quad (2)$$

where T – the kinetic energy of the mechanical system; q_s – the generalised coordinate; s – the coordinate number; Q_s – the generalised force corresponding to the generalised coordinate q_s.

The kinetic energy of a mechanical system is calculated as the sum of the kinetic energies of each link in the system:

$$T = \sum_{i=1}^{4} T_i = \frac{1}{2}\sum_{i=1}^{4}\left[m_i\left(\dot{x}_i^2 + \dot{y}_i^2\right) + I_i\omega_i^2\right], \quad (3)$$

where I_i – the moment of inertia of the i-th link relative to the vertical axis passing through its centre of mass; $\omega_i = \dot{\beta}_i$ – the angular velocity of rotation of the i -th link; $\dot{x}_i, \dot{y}_i$ – the projection of the velocity vector of the centre of mass of the i -th link of the system.

The coordinates of the centre of mass of the i-th ($i=\overline{2,4}$) link can be expressed in terms of x_1, y_1, the coordinates of the centre of mass and the angles of rotation of the previous links and the given parameters:

$$\left.\begin{aligned} x_2 &= x_1-(l_1-a_1)\cos\beta_1 - a_2\cos\beta_2\,, \\ y_2 &= y_1-(l_1-a_1)\sin\beta_1 - a_2\sin\beta_2\,, \end{aligned}\right\} \quad (4)$$

$$\left.\begin{aligned} x_3 &= x_1-(l_1-a_1)\cos\beta_1 - l_2\cos\beta_2 - a_3\cos\beta_3\,, \\ y_3 &= y_1-(l_1-a_1)\sin\beta_1 - l_2\sin\beta_2 - a_3\sin\beta_3\,, \end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned} x_4 &= x_1-(l_1-a_1)\cos\beta_1 - l_2\cos\beta_2 - l_3\cos\beta_3 - a_4\cos\beta_4, \\ y_4 &= y_1-(l_1-a_1)\sin\beta_1 - l_2\sin\beta_2 - l_3\sin\beta_3 - a_4\sin\beta_4\,. \end{aligned}\right\} \quad (6)$$

Dependencies (4)–(6) can be written in general form:

$$\left.\begin{aligned} x_i &= x_1-(l_1-a_1)\cos\beta_1 - a_i\cos\beta_i - \textstyle\sum_{j=2}^{i-1} l_j\cos\beta_j, \\ y_i &= y_1-(l_1-a_1)\sin\beta_1 - a_i\sin\beta_i - \textstyle\sum_{j=2}^{i-1} l_j\sin\beta_j, \left(i=\overline{2,4}\right). \end{aligned}\right\} \quad (7)$$

Taking derivatives with respect to time from expressions (7), determine the velocities of the centres of mass of the system links:

$$\left.\begin{aligned} \dot{x}_i &= \dot{x}_1+(l_1-a_1)\beta_1\sin\beta_1 + a_i\beta_i\sin\beta_i + \textstyle\sum_{j=2}^{i-1} l_j\beta_j\sin\beta_j\,, \\ \dot{y}_i &= \dot{y}_1-(l_1-a_1)\beta_1\cos\beta_1 - a_i\beta_i\cos\beta_i - \textstyle\sum_{j=2}^{i-1} l_j\beta_j\cos\beta_j\,, \left(i=\overline{2,4}\right). \end{aligned}\right\} \quad (8)$$

Substituting (8) into (3), an expression for the kinetic energy of the system is obtained:

$$T = \tfrac{1}{2}\left[m_1(\dot{x}_1^2+\dot{y}_1^2)+I_1\dot{\beta}_1^2 + \right. \\ \left. + \textstyle\sum_{i=2}^{4}\left(m_i(\dot{x}_i^2+\dot{y}_i^2)+I_i\dot{\beta}_i^2\right)\right]. \quad (9)$$

The basis of elastic strength theory is the strength criterion, whereby the onset of a dangerous condition in a specific location under the action of stress and load causes damage to increase, i.e. the intensity coefficient reaches a critical value. Over time, the growth and accumulation of forces in the plastic deformation zone causes numerous microdamages, which is the beginning of crack formation and then destruction. The stress intensity factor k_{im} egulates the intensity and zone of plastic deformation, since strength depends on crack formation and the safety factor, i.e:

$$k_{im} = \sigma\sqrt{l\pi}, \quad (10)$$

where l – deformation distance, and σ – permissible stress.

Experimental and production studies of the impact of combine harvester working parts on macro- and micro-damage to grains of modern winter wheat varieties Fortuna and Yuvileina were conducted at the "Dnipro" agricultural enterprise in the Cherkasy region by selecting wheat samples in 2023 at various stages of the technological process during threshing. The authors determined the damage and its impact on the main quality indicators, namely purity, germination, moisture content, seed weight, nature, etc., as well as damage by microorganisms, at the regional agricultural seed laboratory. Experimental studies of plants (both cultivated and wild), including the collection of plant material, complied with institutional, national and international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

The emergence of resistance to injury and damage to seeds during threshing is associated with the action of external and internal factors that cause the displacement of organic matter from stresses and an increase in the distances between individual particles, which weakens strength and is the beginning of the formation of a rupture. This process consists of the onset of destruction, i.e. the physical characteristics of destruction and the mechanics of destruction, which have different patterns that are not yet sufficiently studied, and the correlation between microtrauma and macrodestruction is very important from the point of view of grain destruction theory and strength theory. Thus, the strength of the seed depends on the force, stress and occurrence of a crack, and its growth leads to damage and macrotrauma. Experimental studies show that force and stress affect cracks and damage and increase the stress intensity factor (Fig. 6).

Damage and injury to the embryo, seed coat, and endosperm affect seed strength, while stress, deformation, and applied force lead to micro-damage and rupture (Table 1).

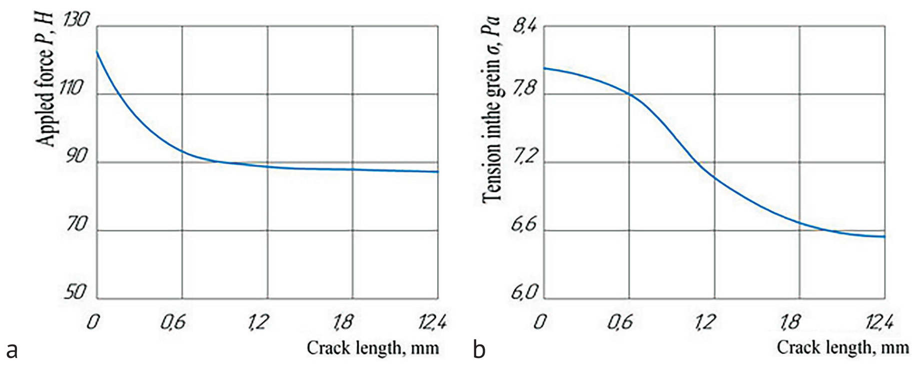

***Figure 6**. Dependence of seed destruction force (a) and stress value (b) on the degree of destruction*
***Source:** developed by the authors based on own research*

***Table 1**. Dependence of seed strength on damage*

Type of damage	Damage due to force P, N	Damage due to deformation Δl, mm	Stress value, Y, V
Cracked embryo	47.4	0.17	5.55
Damaged endosperm	79.1	0.27	7.15
Injured embryo	85.2	0.25	7.0
Damaged seed coat	96.1	0.24	7.45
Injured seed coat and embryo	105.4	0.23	7.90
Damaged seed coat of endosperm	105.2	0.25	7.95
No damage	105.5	0.29	8.55

***Source:** developed by the authors*

The results obtained, presented in Table 2 in percentage values of seed microtrauma (y_1)and damage (y_2),which depend on the increase in the rotation speed of the combine harvester's working parts (x, rpm), indicate a proportional dependence on the increase in the number of damages.

***Table 2**. Microtrauma and damage to seeds depending on the rotation speed of the working part*

Drum-type threshing machine							
x	700	800	900	920	950	970	1,000
y_2	0.8	0.84	1.45	1.51	3.35	5.40	7.05
y_1	27.0	28.15	29.50	33.15	40.40	50.15	54.25
Rotary type threshing machine							
x	700	800	900	920	950	970	1,000
y_2	0.12	0.25	0.34	0.45	0.35	1.15	3.05
y_1	29.15	34.40	36.10	39.20	42.10	46.65	47.15

***Source:** developed by the authors*

The investigation regarding the influence of force on injury and damage to the seeds according to the theorem of change in momentum during impact interactions between working parts and grains in projections on the axes of the Cartesian coordinate system, the expression will be as follows:

$$\begin{aligned} mV_{2x} - mV_{1x} &= S_x(t) \\ mV_{2y} - mV_{1y} &= S_y(t)\cdot \end{aligned} \quad (11)$$

During the passage of the grain heap between the blades of the drum apparatus, the trajectory of the grain can be presented according to the diagram (Fig. 7).

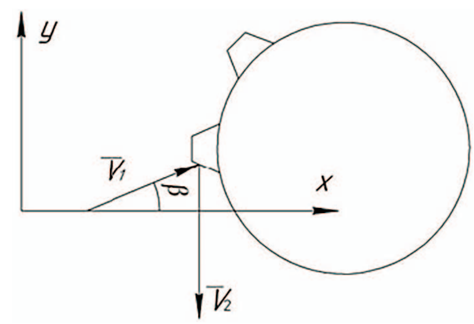

***Figure 7**. Scheme of speed dynamics*
***Source:** developed by the authors*

After performing calculations according to the dynamics diagram (Fig. 2), expression (11) took the following form:

$$0 - V_1 cos\beta = S_x/m$$
$$-V_2 - V_1 sin\beta = S_y/m, \quad (12)$$

where β – the angle of grain mass entry into the drum.

Continuing the calculation yielded:

$$\frac{S}{m} = \sqrt{V_1^2 cos^2\beta + V_2^2 + V_1^2 sin^2\beta + 2V_1 V_2 sin\beta}. \quad (13)$$

During the threshing process using a rotary combine harvester, the path of the seeds is as follows (Fig. 8).

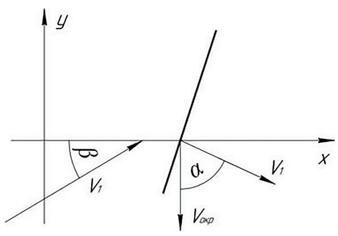

***Figure 8**. Diagram of the dynamics of movement speed*
***Source:** developed by the authors*

In this regard, the expression will be as follows:

$$V_2 sin\alpha - V_2 cos\beta = S_x/m$$
$$-2V_2 cos\alpha - V_1 sin\beta = S_y/m. \quad (14)$$

Continuing the calculation yielded:

$$\frac{S}{m} = \sqrt{V_2^2 sin^2\alpha + V_1^2 cos^2\beta - 2V_1 V_2 sin\alpha \cdot cos\beta +} \sqrt{+V_2^2 cos\alpha + V_1^2 sin^2\beta + 2V_1 V_2 sin\beta \cdot cos\alpha}. \quad (15)$$

Analysis of the calculations showed that the impact forces in the drum apparatus have advantages over the rotary one, therefore damage and injury will be more severe. Experimental studies of various threshing devices of a grain combine harvester are presented in Table 2 in the form of percentage values of microtrauma to seeds (function y_1) and damage (function y_2) depending on the rotation of the drum and rotor (rpm). An analysis of these data indicated that increasing the revolutions of both apparatuses promotes a rise in injury and damage to the grain, but the grains are more heavily injured and damaged in the drum apparatus. The data in Table 3 showed that embryo injury for the Fortuna seed variety increases from 3.7 to 6.0%, and that of the Yuvileina variety from 3.3 to 6.2%.

***Table 3**. Winter wheat seed injury during harvesting in percentages*

Farm	Variety	Research stage	Macrotrauma				
			Embryo		Total injury	No damage	Macrotrauma
			Crushed	Damaged			
PFH "Dnipro," Cherkasy Region, 2023	Fortuna	At the root	0	0	4.5	95.5	0
		During harvesting	2.1	3.7	21.5	78.5	3.1
		After threshing	3.8	4.2	41.6	58.4	4.5
		After screening	4.2	4.9	44.4	55.6	5.2
		In the bunker	4.9	5.5	53.4	46.6	6.1
		After the bunker	5.8	6.0	56.2	43.8	7.3
	Yuvileina	At the root	0	0	5.1	95.9	0
		During harvesting	2.7	3.3	21.2	78.8	2.7
		After threshing	3.8	4.4	50.3	49.7	3.8
		After screening	4.9	5.1	52.2	47.8	4.9
		In the bunker	5.6	5.9	57.6	42.4	5.6
		After the bunker	6.2	6.2	59.3	40.7	6.2

***Source:** developed by the authors*

The total number of microtraumas in Fortuna seeds increased by 51.7%, i.e. 43.8% were undamaged, while for Yuvileina seeds these figures were 54.2% and 40.7%. Macrotrauma increased to 7.3% and 6.2%, and embryo damage to 6.0% and 6.2% for both varieties, respectively. Thus, injury and damage to grains is observed in both varieties, but with a slight difference, i.e. the resistance to damage and destruction of these varieties is almost at the same level. The research data (Table 4) showed that during the harvesting of winter wheat, the purity of seeds and the amount of weeds before the cleaning system was more than 3-4 times higher, and after the combine harvester's cleaning screens, the purity remained at 96.5-95.0% and 281-270 weed seeds per 1 kg of grain mass until the end of harvesting. Germination during the technological process decreased from 95.1-97.7% to 92.1-94.8% due to the influence of contamination, injuries and damage, especially to the embryo, on which it primarily depends. Moisture content during harvesting decreased from 15.8-15.4% to 14.6-14.3% due to the separation of impurities, especially raw weed seeds, chopped straw, chaff, weed stems, and drying due to air movement, blowing, and mixing. The weight, naturalness and vitreousness of the seeds decreased at all stages of harvesting, while the amount of protein and gluten increased from 13.1% and 21.4% before harvesting to 14.7% and 24.6% after threshing, i.e. after unloading from the bunker.

***Table 4**. Influence of injury on winter wheat seed quality during harvesting*

Farm	Variety	Research stage	Purity, %	Weed seeds, pcs/kg	Germination, %	Moisture content,	Thousand grain weight, g	Test weight, g/litre	Vitreousness, %	Protein, %	Raw gluten %
PFH "Dnipro," Cherkasy Region, 2023	Fortuna	At the root	98.6	101	95.1	15.8	46.5	769	83.1	13.9	22.8
		During harvesting	97.4	188	94.5	15.1	46.4	761	81.2	14.2	23.3
		After threshing	96.8	415	93.3	15.0	45.5	757	78.1	14.4	24.1
		After screening	96.5	291	92.0	14.9	44.4	44.9	76.7	14.4	
		In the bunker	96.7	286	92.5	14.8	44.4	750	75.2	14.5	24.3
		After the bunker	96.2	281	92.1	14.6	44.0	741	74.7	14.7	24.6
	Yuvileina	At the root	98.9	103	97.7	15.4	46.1	770	66.7	13.1	21.4
		During harvesting	98.1	190	96.2	15.0	45.6	761	66.0	13.2	21.6
		After threshing	96.2	320	96.0	14.6	45.1	755	65.1	13.3	21.9
		After screening	95.8	255	95.8	14.5	44.0	753	64.2	13.4	22.0
		In the bunker	95.7	250	95.0	14.4	44.8	750	59.1	13.6	22.5
		After the bunker	95.0	170	94.8	14.3	44.4	740	58.4	13.7	23.1

***Source:** developed by the authors*

Damage by microorganisms (Table 5) during the harvesting process occurred in both varieties, but higher values were observed in the Yuvileina variety, because the damage here is also greater. The prevalence of Fusarium before harvesting was 2.8%, Helminthosporium 0.3%, Septoria 0.1%, Alternaria 0.2%, and after harvesting these figures were 42.2%, 23.4%, 14.9 and 7.7, respectively, indicating a significant increase. Thus, damage and microorganisms have a negative impact on the quality of seed material.

***Table 5**. Winter wheat seed damage by microorganisms during harvesting in percentages*

Farm	Variety	Research stage	Fusarium	Helminthosporiosis	Septoria	Alternaria	Mould fungi
1	2	3	4	5	6	7	8
PFH "Dnipro," Cherkasy Region,2023	Fortuna	At the root	2.9	0.3	0.2	0.1	-
		During harvesting	19.0	15.4	7.1	2.7	-
		After threshing	14.3	19.3	8.8	3.8	-
		After screening	28.1	18.5	10.6	4.1	-
		In the bunker	40.3	20.4	14.0	5.1	-
		After the bunker	40.1	24.3	13.6	5.6	-
1	2	3	4	5	6	7	8
PFH "Dnipro," Cherkasy Region, 2023	Yuvileina	At the root	2.9	0.3	0.1	0.2	-
		During harvesting	21.3	17.2	7.2	3.3	-
		After threshing	17.2	20.6	9.7	5.1	-
		After screening	30.5	21.1	12.4	6.0	-
		In the bunker	41.4	21.5	14.5	7.5	-
		After the bunker	42.2	23.4	14.9	7.7	-

***Source:** developed by the authors*

Thus, the results of the studies show that the working parts of drum and rotary threshing machines affect the injury and development of microorganisms, and in combination and interrelation affect such quality indicators as purity, germination, weight, naturalness, vitreousness, protein and gluten, etc. These indicators are decisive for the characterisation of seed material in terms of yield potential, as well as for the taste and nutritional properties of food, which are the basis of human energy and health. A significant contribution to the theoretical scientific research on the interaction and influence of the working parts of various machines and mechanisms was made by Ukrainian scientists P. Vasylenko (1960), P. Zaika (2006), L. Tischenko *et al.* (2011), who developed the theoretical foundations of the interaction of working bodies and materials, in particular grain, optimal operating modes of machine working bodies during harvesting and post-harvest processing, and vibrating screen separation of bulk materials.

Research by V.M. Arendarenko *et al.* (2020) on the movement of grain material on inclined surfaces of working bodies and experimental studies by T. Samoylenko *et al.* (2021) on the movement of grain material on inclined surfaces of working parts and the experimental studies of T. Samoylenko *et al.* (2021) show that the speed of material movement, the rotation of working surfaces, the angle of inclination of working bodies, and the movement and placement of grain mixtures and seeds on them, in particular taking into account their biological characteristics, moisture content, purity, and other factors, affect productivity and efficiency. Similar theoretical and experimental studies by V. Bulgakov *et al.* (2023) on the impact interaction of grains with working surfaces and their effect on seed damage and quality during technological processes of grain pile processing, transportation and other operations confirm other experimental, laboratory and production results. The results of studies by I. Strona (1974), T. Samoylenko *et al.* (2020) confirm that during the processing of grain piles after threshing, the inclination of working surfaces at an angle of 10° or more, the speed of working parts exceeding 5-7 m/s, and the rotation of working parts exceeding 600 rpm increase the damage to grain seeds. Damage to cereal seeds increases depending on their biological and physical properties.

Research data from D. Derevyanko *et al.* (2023) substantiate a series of experimental influences of working parts on damage and microtrauma to winter wheat and rye seeds during harvesting, with these indicators reaching 20% or more, and during post-harvest processing, sometimes more than 40%, and during sowing, 12-16%, which significantly affects the quality of the grains. Researchers V. Zabrodin and M. Sukhanova (2019) confirm the impact of working parts of technical equipment during seed movement on its damage, which reaches 20-22%, as well as a decrease in the germination of cereal crops, on which the quality of the future harvest fully depends. Authors J. Mellmann *et al.* (2018) investigated the impact of technological processes during the processing and drying of grain crops under different conditions with different mechanical loads, energy costs, the influence of special conditions, temperature fluctuations, light, moisture and oxidation in combination with the interaction with the working surfaces of machines and equipment, seeds are damaged, microtraumatised and their quality, especially germination, is reduced. Analytical studies on germination, growth energy, and the effect of temperature on fodder crop seeds were conducted and confirmed such an effect on these indicators by W. Chaleb *et al.* (2021) and V. Oleksiak *et al.* (2023). In addition, the authors S. Bayram *et al.* (2024) showed the negative impact of salinisation on plant growth and development, and I. Buranji *et al.* (2019) confirm a decrease in germination with an increase in soil acidity. The justification of the impact of the parameters of individual working elements of technical means during the transportation of grain materials, conducted by A. Rucins *et al.* (2024) and the assessment of the level of damage and injury to grain in the studies by O.M. Ivanov and K.V. Simonov (2021) indicate their impact on seed injury, which in turn will affect its quality.

In general, studies by various researchers indicate the relevance of studying the impact of various factors of external and internal characteristics of grain varieties, in particular different varieties of winter wheat, soil and climatic factors, especially soil fertility, moisture, acidity, soil and air temperature regimes, light and, of course, the impact of working parts of machines and equipment in interaction and interconnection on microtrauma, damage by microorganisms and seed quality, which significantly affects the yield and gross grain production in Ukraine.

CONCLUSIONS

Theoretical studies of injury and damage to seeds of modern, new, high-yielding varieties of winter wheat of domestic selection by the working parts of the foreign grain combine LEXION 770 occur due to additional forces, stress and deformation, which is a condition for the accumulation of microtraumas and the creation of mandatory causes of microtrauma and destruction. The process of the onset of injury and destruction depends on soil and climatic factors, external and internal forces, deformation, biological condition, quality, especially moisture content, mass, the presence of protein and gluten, etc. Increasing the speed of the combine's working parts from 700 to 1,000 rpm led to an increase in the number of microtraumatised seeds from 27.1% to 54.3% in the drum threshing machine, and in the rotary threshing machine, this increase was 18%. Thus, the working surfaces of the rotor have a mitigating effect on the operating mode by 9.1% compared to the drum thresher.

Experimental, production and laboratory studies show that during the technological process of harvesting, microtrauma to Fortuna seeds increased from 7.5% to 56.2%, i.e. 43.8% were undamaged, while for the Yuvileina variety, it increased from 5.1% to 59.3%, meaning that 40.7% of the seeds remained undamaged, i.e. 3.1% more seeds of this variety were damaged than the previous one, but in general, these varieties are more resistant to damage than other varieties. Damage to grains has a significant impact on seed quality indicators during the threshing process. In the Fortuna variety, purity decreased by 2.4%, moisture by 1.2%, weight by 2.5%, and specific weight by 28 g/litre, while for the Yuvileina variety, they decreased by 3.9%, 1.2%, 2.7%, and 30%, respectively. The data obtained show a slight advantage of the impact of damage on the quality of the Yuvileina variety seeds, and in general, these indicators are more positive compared to others that were previously conducted in studies.

The results of laboratory studies show that the technological process and injury significantly affect the growth of damage by microorganisms (Table 5), when before the start of harvesting the amount of Fusarium was 1.9%, Helminthosporium – 0.3%, Septoria – 0.2%, alternaria – 0.1% in the Fortuna variety, while in the Yuvileina variety these values were 2.8%, 0.3%, 0.1% and 0.2%, respectively. After unloading the seeds from the bunker, the presence of grains damaged by microorganisms in the Fortuna variety was 40.1%, 24.3%, 13.6%, and 5.6%, respectively, and in the Yuvileina variety, it was 42.2%, 23.4%, 14.9%, and 7.7%. The complex interrelationship between damage and the presence of microorganisms contributed to a significant deterioration in seed quality. Theoretical calculations, graphical dependencies, experimental and production and laboratory studies of the effect of the working parts of a grain combine harvester on modern varieties of domestic selection have a negative impact on microtrauma, damage and seed quality of both varieties of winter wheat. The drum-type working parts of grain combines have a greater negative impact than rotary ones, but all working parts have a certain negative effect on the deterioration of quality indicators. Further research should be aimed at substantiating the impact of working parts of technical equipment on seed quality, improving machine designs using modern materials, and expanding experimental and laboratory tests in various agricultural zones of Ukraine.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Вплив робочих органів зернового комбайна на пошкодження і якість насіння озимої пшениці

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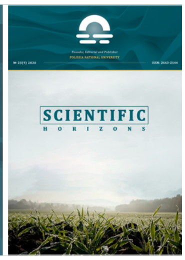
Анотація. Мета дослідження полягала в покращенні якості насіння озимої пшениці сортів Фортуна і Ювілейна шляхом зниження його пошкодження під час збирання комбайном на різних стадіях технологічного процесу. На основі комплексного підходу і взаємозв'язку кліматичних та ґрунтових особливостей, теоретичних розрахунків, математичних моделей, експериментальних, виробничих та лабораторних досліджень, показано вплив робочих органів зернозбиральних молотильних агрегатів барабанних і роторних типів на мікро травмування насіння, та його вплив на розвиток мікроорганізмів і у взаємозв'язку на якісні показники насіння, від чого суттєво залежить урожайність культури. Надана авторами математична модель пошкодженої пружино-в'язкої еліпсоїдної зернівки свідчить, що під час сили імпульсу ударів відносної і абсолютної траєкторії руху та дії прискорення, сил Коріоліса, інерції, тертя при збільшенні частоти обертання барабана або ротора при зіткненні зернівок масою 0,03-0,06 г з поперечним діаметром 3-5 мм в межах 600-700 об/хв деформація становить 0,015-0,035 мм, а пошкодження значно зростають від зниження міцності насіння, напруження та зусилля. Мікротравмування при обертах барабана від 700 до 1000 збільшується майже у 9 разів, а ротора відповідно у 3 рази. Мікротравмування насіння сорту Фортуна перед збиранням становило 4,5 %, а після вивантаження 56,2 %, а сорту Ювілейна відповідно 5,1 та 59,3 %. Макротравмування насіння перед обмолочуванням обох сортів були зовсім відсутні то після вивантаження зерна із бункера комбайна вони становили 7,3 та 6,2 %. Пошкодження мікроорганізмами, зокрема Фузаріозом у сорту Фортуна після обмолочування зросло до 40,1 %, Гельмінтоспоріозом до 24,3 %, Септоріозом до 13,6 %, Альтернаріозом до 4,6 %, а у сорту Ювілейна відповідно до 18,2; 13,0; 11,8 та 3,9 %. Під час проходження технологічного процесу обмолочування, пошкодження, травмування і мікроорганізми впливали на якість насіння, зокрема у сорту Фортуна чистота при вивантаженні становила 96,2 %, кількість насіння бур'янів у штуках на 1 кг-281, схожість 92,1 %. Маса в грамах 44,0, натура 741 г/літр, сира клейковина 24,6, а білок 14,7. Відповідно у сорту Ювілейна ці показники становили 95,0; 170; 94,8; 44,4; 740; 23,1; 13,7. Вологість зернової маси після збирання обох сортів знаходилась у межах 14,6 та 14,3 %

Ключові слова: сила; імпульс ударів; швидкість; зернівка; мікротравми; мікроорганізми; урожайність

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(9), 49-58
UDC 631.811:581.1
DOI: 10.48077/scihor9.2025.49



Balanced plant nutrition: From functional deficiency to a systematic strategy for increasing crop yields: Literature review

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Article's History:
Received: 01.04.2025
Revised: 21.07.2025
Accepted: 27.08.2025

Abstract. The aim of this study was to substantiate the functional hierarchy of nutrients and develop an applied biochemical model for optimising nutrient management in plants. The research methodology combined a comprehensive analysis of international and national scientific sources with systematisation of biochemical interactions among macro- and microelements. It was found that nutrient uptake and activation in plants follow a specific biochemical sequence, in which sulphur, boron, silicon, and calcium serve as initiating elements that activate metabolic pathways, enabling efficient nitrogen, magnesium, phosphorus, carbon, and potassium assimilation. The study analysed the physiological and biochemical mechanisms of nutrient interrelations and demonstrated that this sequential activation ensures a balance between structural development, photosynthetic activity, and stress tolerance. It was established that the efficiency of metabolic processes directly depends on the synchronisation of elemental uptake according to plant growth phases. The research generalised experimental and theoretical data on the role of calcium in transport and signalling, sulphur in protein synthesis, silicon in cell strengthening, and boron in reproductive development. Based on these findings, a functional biochemical model was developed, showing how consistent nutrient activation improves crop productivity and enhances resilience under environmental stress. The model was

Suggested Citation:
Trembitska, O., Stoliar, S., & Kropyvnytskyi, R. (2025). Balanced plant nutrition: From functional deficiency to a systematic strategy for increasing crop yields: Literature review. *Scientific Horizons*, 28(9), 49-58. doi: 10.48077/scihor9.2025.49.

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applied to analyse nutrient dynamics in Sorghum bicolor and Triticum spelta, revealing that maintaining this sequence ensures metabolic stability and sustainable soil fertility. The practical significance of the study lies in its applicability for agronomists, soil scientists, and researchers in plant physiology, as well as for agricultural enterprises seeking to improve nutrient management efficiency, optimise fertilisation strategies, and increase crop productivity under sustainable farming systems

Keywords: biochemical sequence; plant nutrition; sulphur; boron; silicon; calcium; nitrogen; photosynthesis; metabolism; agroecosystem

INTRODUCTION

The rational organisation of plant mineral nutrition is one of the central priorities of modern agriculture, as the biochemical sequence of nutrient assimilation determines both yield quality and ecosystem stability. Imbalanced application of fertilisers, without taking into account the functional order of macro- and microelements, often leads to the accumulation of nitrates, protein synthesis disruption and weakening of plant immunity. Consequently, contemporary agronomic research increasingly focuses on the interdependence and metabolic hierarchy of mineral elements that regulate photosynthesis, enzymatic activity, and antioxidant defence.

Sulfur is considered the initiating element of metabolic activation. According to R.K. Sharma *et al.* (2024), sulfur plays a fundamental role in amino acid synthesis, chlorophyll formation and oxidative stress control, and its deficiency disrupts the assimilation of nitrogen into proteins, causing metabolic imbalance. The authors emphasise that optimal sulfur supply improves both yield and the nutritional quality of crops. In turn, C. Boubakry *et al.* (2023) experimentally confirmed that the agronomic efficiency of elemental sulfur depends on particle size and soil microbial activity, which determine oxidation rates and the availability of sulfates to plants. This work substantiates the need for complex sulphur-nitrogen management strategies. Complementary findings were obtained by T. Bruulsema and R. Olson (2024), who demonstrated that sulfur management following the 4R stewardship concept – "right source, right rate, right time, and right place" – enhances crop productivity and contributes to sustainable soil fertility. These studies collectively highlight sulfur as the starting point in the biochemical sequence of nutrient activation.

Equally important is the synergistic interaction between boron and silicon. H. Sheng *et al.* (2024) established that these elements share structural and physiological roles in cell wall stability, membrane integrity and assimilate transport. Their analogy in plant nutrition reveals that silicon partially compensates for boron deficiency by maintaining turgor and mechanical strength. E. Réthoré *et al.* (2023) experimentally verified this relationship in *Brassica napus*, showing that silicon enhances tolerance to boron deficiency by stimulating the remobilisation of boron and the expression of its transporter genes. A.C. Buchelt *et al.* (2020) further proved that the inclusion of silicon in nutrient solutions mitigates nitrogen, potassium, calcium, magnesium, and sulfur deficiencies, normalising ionic balance and improving enzymatic activity. These findings position silicon as a biochemical catalyst that stabilises metabolic processes and reinforces other nutrients' functions. Calcium, traditionally perceived as a structural component, has recently been identified as a signalling regulator in nutrient transport. T. Wang *et al.* (2023) showed that calcium ions mediate the transmission of stress and nutrient uptake signals, linking cellular transport systems and metabolic feedback. O. Sahin *et al.* (2024) complemented this view by demonstrating that ecological nano-calcium derived from eggshells increases lettuce tolerance to salinity and boron toxicity, reducing oxidative stress and stabilising antioxidant enzymes. Thus, calcium serves as both a mediator and modulator in the biochemical sequence of mineral nutrition.

Another critical relationship concerns the interaction between sulfur and nitrogen. A.A. Rahman *et al.* (2025) established, through multi-site field trials on soybean, that the combined application of these elements increases the content of sulfur-containing amino acids and improves seed quality. This reinforces the hypothesis that nitrogen utilisation efficiency depends on prior sulfur activation. M.I.R. Khan *et al.* (2023) extended this concept theoretically, asserting that plant nutrition efficiency is determined not only by the quantity of elements but by their chronological participation in metabolic cycles. Such a sequence ensures homeostatic balance and resilience under environmental fluctuations.

Ukrainian research supports these findings in a regional context. V. Gamayunova and O. Sydiakina (2023) analysed the nitrogen imbalance in Ukrainian agroecosystems, noting that excessive nitrogen fertilisation without sulfur or calcium supplementation reduces soil microbiological activity and leads to nutrient leaching. L. Harbar *et al.* (2021) confirmed that fertiliser efficiency in sunflower cultivation depends on the coordination of calcium, boron and sulfur supply during the reproductive phase, which directly influences productivity. Collectively, these studies outline a coherent scientific paradigm: effective plant growth and productivity result from the biochemical sequence of nutrient interaction, not from isolated fertiliser application. The synchronised supply of sulfur, boron, silicon, calcium, nitrogen, magnesium and phosphorus forms a metabolic chain that activates enzymatic systems, enhances stress resistance and ensures sustainable yield formation. Purpose of the study – to substantiate the biochemical sequence of plant mineral nutrition and define the functional interaction of key macro- and microelements in metabolic activation.

This review is based on a systematic analysis of international and Ukrainian scientific publications from 2020 to 2025, focusing on biochemical mechanisms and functional interactions of sulfur, boron, silicon, calcium, nitrogen, magnesium, and phosphorus in plant metabolism. The methodological framework included comparative and analytical synthesis of peer-reviewed studies indexed in Scopus, Web of Science, and leading agronomic journals such as Frontiers in Plant Science, Physiologia Plantarum, Agronomy Journal, and Journal of Agriculture and Food Research. Priority was given to works combining physiological, biochemical, and agroecological approaches. The sources were critically evaluated for methodological transparency, reproducibility, and consistency of results. This integrative analysis allowed the identification of functional hierarchies among nutrients, establishing the conceptual model of a biochemical sequence of mineral nutrition as the foundation for sustainable crop production. This publication proposes a generalised model of biochemical sequence that takes into account both classical scientific approaches and empirical data from field studies. The aim is to create a structured view of the interaction of the main elements – sulphur, boron, silicon, calcium, nitrogen, magnesium, phosphorus, carbon and potassium – and their functional inclusion in plant metabolic processes. Such a model is not absolute, but it can serve as a guideline for planning crop nutrition in different agroecological conditions.

FUNCTIONAL HIERARCHY OF NUTRIENTS AND BIOCHEMICAL SEQUENCE OF ACTIVATION

In international scientific literature, particularly in the works of foreign researchers, the complexity of nutrient interactions at the level of cellular metabolism and plant anatomical and physiological responses is emphasised. Their studies highlight the importance of maintaining an optimal balance between nutrients and their mutual influence on uptake efficiency (Hernandez *et al.*, 2024). At the same time, some authors focus on the molecular-genetic mechanisms of nutrient transport as well as species-specific sensitivity to deficiencies of particular elements. A practical approach to structuring the sequence of nutrient uptake was proposed by Hugh Lovel, whose concept suggests that nutrients are incorporated into metabolic processes not simultaneously but according to the plant's functional needs at different developmental stages. This allows the design of agrotechnologies not only by growth phase but also by considering the biochemical logic of plant development. Such a model is widely applied in biological farming systems (Bruulsema & Olson, 2024). In the Ukrainian agrochemical and plant physiology research tradition, the interdependence of nutrients and their sequential activation has been actively studied, particularly within the research of specialised academic institutions. Works by scientists affiliated with the National Scientific Centre "O.N. Sokolovsky Institute for Soil Science and Agrochemistry" and the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine examine issues of calcium bioactivation, the role of silicon in enhancing tolerance to abiotic stress factors, and the physiological and biochemical mechanisms of nitrogen and phosphorus uptake. Special attention is devoted to the regional specificity of nutrient balance in the agroecosystems of the Forest-Steppe and Steppe zones of Ukraine, especially in the context of organogenesis (Trembitska *et al.*, 2020).

The study of mechanisms regulating nutrient functioning in soil and their influence on plant growth indicates the existence of a clear hierarchy or "biochemical sequence" of nutrients (Sharma *et al.*, 2024). This sequence determines which elements must act first to create favourable conditions for the efficient assimilation of subsequent nutrients. It is based on the complex interaction of chemical and biological processes in the soil that form the foundation of plant vitality. The fundamental idea of this hierarchy is that elements participating in reactions at the early stages establish the basis for soil biological activity and, consequently, for effective plant growth. Sulphur, boron, silicon, and calcium are critical initiating elements, while nitrogen, phosphorus, and potassium – despite their conventional prominence in crop nutrition – occupy the final stages of this biochemical sequence (Sheng *et al.*, 2024; Sahin *et al.*, 2024) (Fig. 1).

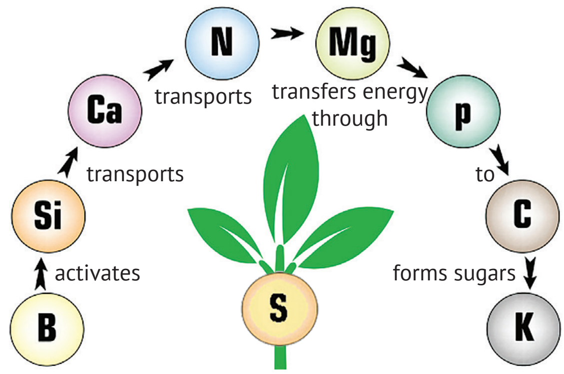

***Figure 1**. Biochemical foundation of nutrient sequence*
***Source:** developed by the authors based on H. Sheng et al. (2024) and O. Sahin et al. (2024)*

Sulphur is a key catalyst of biochemical reactions occurring on the surface of soil particles. It interacts with essential compounds of carbon, hydrogen, oxygen, and nitrogen, activating the surfaces where chemical reactions take place. However, its role extends far beyond the soil environment. In plants, sulphur is an indispensable component of amino acids such as methionine and cysteine, as well as of vitamins (biotin and thiamine) and enzymes that regulate metabolism. Sulphur participates in protein synthesis, chlorophyll formation, stimulates photosynthetic activity, and enhances nitrogen assimilation. Without sufficient sulphur, nitrogen cannot be converted into amino acids, leading to nitrate accumulation in plant tissues and impaired protein metabolism. Therefore, sulphur and nitrogen must act synergistically – sulphur opens the pathway for the full incorporation of nitrogen into biochemical chains. In this context, sulphur is not merely a nutrient but a trigger mechanism for protein synthesis (Sharma *et al.*, 2024). Furthermore, sulphur plays a crucial role in plant resistance to stress factors – it is involved in the synthesis of glutathione, one of the key cellular antioxidants that protects the plant against oxidative stress, diseases, and toxic substances. In rhizobial bacteria, sulphur is essential for the synthesis of enzymes responsible for nitrogen fixation, making it particularly critical for leguminous crops. Under sulphur deficiency, plants display symptoms similar to nitrogen shortage: chlorosis of young leaves, growth inhibition, reduced protein content, and decreased yield. However, unlike nitrogen, sulphur is poorly redistributed within the plant, so its deficiency appears primarily in young tissues (Buchelt *et al.*, 2020). Thus, sulphur is not only a structural element but a true metabolic "switch" that regulates nitrogen metabolism, energy balance, and plant defence mechanisms. Its presence is a prerequisite for proper growth, development, and the formation of high-quality yields.

Boron plays a vital role in the formation of cellular structures and tissue differentiation processes, ensuring mechanical strength and elasticity. It facilitates the effective uptake of nutrients by the root system and improves the synthesis, transport, and distribution of carbohydrates from photosynthetic organs to meristematic zones, roots, and generative organs. One of boron's important functions is its involvement in calcium uptake, the formation of the primary root system, and the development of nodules in leguminous crops. Adequate boron supply promotes the formation of generative organs, stimulates flowering, and improves fertilisation by enhancing pollen viability and germination quality. This, in turn, positively affects seed productivity and quality parameters (Vera-Maldonado *et al.*, 2024). Boron is an essential element in the plant's metabolic processes, and its deficiency leads to physiological and biochemical imbalances. Unlike many other mineral nutrients, boron cannot be remobilised within the plant – it does not move from senescing or older organs to younger tissues. Therefore, its supply must be continuous throughout the growing season, with special attention during critical growth and development phases (Réthoré *et al.*, 2023). In addition, boron increases plant resistance to phytopathogens of both fungal and bacterial origin and enhances tolerance to abiotic stresses, including extreme temperature conditions.

Silicon is also one of the most important mineral nutrients that positively influences the physiological and biochemical processes in plants. It participates in the formation of cell walls, strengthening their structure and increasing tissue mechanical stability. Accumulating in epidermal cells, silicon creates a protective barrier that reduces water loss, lowers pathogen and pest damage, and enhances tolerance to adverse environmental conditions such as drought, temperature stress, and soil salinity (Calero Hurtado *et al.*, 2019; 2020). Silicon contributes to the enhancement of photosynthetic efficiency by improving the plant's water balance, ensuring balanced uptake of macro- and microelements, and stabilising chloroplast structures. Adequate silicon supply increases the activity of enzymatic systems involved in nitrogen, phosphorus, and potassium metabolism. It also promotes root growth, stimulates the development of root hairs, improves nutrient uptake from the soil, and reduces the toxic effects of heavy metals and excessive concentrations of ions such as sodium and aluminium. Through its role in metabolic processes, silicon indirectly affects plant generative development – improving fruit and seed setting, increasing quality and storage potential. In cereals, silicon contributes to the formation of full ears, reduces stem brittleness, and minimises yield losses during ripening (de Melo Peixoto *et al.*, 2022; de Farias Guedes *et al.*, 2022).

Boron and silicon together form the basis of the plant's transport system. Boron, in combination with silicon, is responsible for the functionality of the plant's vascular system – it increases cell wall permeability and facilitates the movement of nutrients through vascular tissues. When boron or silicon are deficient, especially under hot conditions, plants wilt rapidly even with sufficient soil moisture, indicating nutrient transport failure rather than water deficit (Sheng *et al.*, 2024). Boron is also essential for maintaining sap pressure within plant tissues, influencing active growth, particularly in crops with branched venation systems (e.g., beans, tomatoes, courgettes). In contrast, crops with parallel vascular structures (e.g., cereals) tolerate boron deficiency better due to their higher silicon content (Réthoré *et al.*, 2023). Modern agricultural practices – particularly "clean farming" and the excessive use of soluble nitrogen fertilisers – can accelerate the depletion of boron and silicon reserves. This occurs because microbial activity decreases, and humus-clay complexes that retain these elements are destroyed. As a result, nutrients are easily leached, and soil biological activity declines.

Calcium is another key element, acting as a major transport agent in plant nutrition systems, working in combination with magnesium, potassium, and sodium. It provides structural stability to cells and is crucial for cell division processes, which are necessary for fruit and seed formation. Calcium plays a special role in its interaction with nitrogen for the synthesis of amino acids – the basis of the protein structure that governs enzyme and hormone function. Calcium is also a vital component of cell walls, particularly of pectic substances, where it forms calcium-pectate bonds, ensuring tissue integrity and mechanical strength. Its presence supports normal growth of meristematic tissues, especially root and shoot tips where metabolic activity is high (Wang *et al.*, 2023). In addition, calcium has a regulatory function in intracellular signal transduction, participating in stress signalling, stomatal regulation, and plant adaptation to adverse environmental conditions. Calcium also reduces cell membrane permeability, limiting pathogen invasion and thus enhancing disease resistance. Calcium deficiency, especially during active growth phases, leads to impaired development of growth points, tissue deformation, necrosis of young parts, disrupted water balance, and reduced productivity. Continuous calcium supply, particularly during critical phases of development (growth spurts and reproductive organ formation), is essential for stable growth, normal metabolism, and high-quality yields (Sahin *et al.*, 2024).

Above all, calcium interacts with nitrogen to form amino acids, which are the basis of DNA, RNA, and proteins. These nitrogen compounds, in turn, sustain the complex chemistry of enzymes and vital hormones involving all elements from sulphur and silicon to magnesium, iron, phosphorus, zinc, manganese, and copper. Most importantly, nitrogen provides amino acids in chlorophyll, which is crucial for photosynthesis – the highly efficient mechanism of energy capture (Rahman *et al.*, 2025). For instance, in maize (*Zea mays*), calcium deficiency results in incomplete kernel formation, while in soybean (*Glycine max*), adequate calcium levels prevent pod abscission. Overall, calcium is a critically important element for normal plant growth and development. It provides structural stability to cells, supports enzymatic function, participates in cell division and the formation of reproductive organs, and enhances stress and pathogen resistance. Its interaction with nitrogen underpins the synthesis of proteins and chlorophyll. Continuous calcium supply throughout the vegetation period is the key to high-quality yields.

FUNCTIONAL INTERRELATIONS OF NITROGEN, MAGNESIUM, PHOSPHORUS, CARBON AND POTASSIUM

Nitrogen: the driving factor of biochemical activity. As mentioned above, where calcium goes, nitrogen follows. Nitrogen is the foundation for amino acid formation, protein chemistry, and the replication and expression of DNA. Once nitrogen becomes active, all types of proteins, enzymes, and hormones are produced, initiating highly complex processes that involve micronutrients (Sharma *et al.*, 2024). Unfortunately, soluble nitrogen fertilisers stimulate only the final part of this process, disregarding the priority of sulphur, boron, silicon, and calcium. Such fertilisers accelerate vegetative growth, but they act similarly to stimulants, providing weak yields dependent on high weed competition, pest infestation, and disease pressure (Bruulsema & Olson, 2024). All parts of plant protein chemistry require amino acid-based nitrogen. Nitrogen lies at the intersection between chemically neutral silicon and calcium, with a large portion of amino acids being utilised for chlorophyll formation – the key to energy capture. Energy accumulation is vital, as without photosynthesis, plant life would cease to exist (Alves *et al.*, 2020). Nitrogen is not merely a growth source but a trigger for synchronising metabolic pathways that ensure full functionality of cellular structures. In agrobiological terms, nitrogen initiates the biosynthesis of nucleotides, alkaloids, vitamins, and secondary metabolites that play a critical role in plant defence mechanisms and adaptation to environmental stressors (Hernandez *et al.*, 2024).

Furthermore, nitrogen bioavailability influences the equilibrium between vegetative and generative development. Excessive nitrogen results in the overaccumulation of green biomass at the expense of fruit and seed formation. Conversely, nitrogen deficiency causes growth retardation, chlorosis, protein synthesis inhibition, and general physiological suppression. Therefore, efficient nitrogen nutrition must not rely solely on the quantity of applied compounds but should be balanced with elements that ensure full expression of its metabolic function – specifically sulphur (for amino acid synthesis), boron (for sugar transport and growth regulation), silicon (for tissue resilience), and calcium (for cellular stability). Only under such a system does nitrogen truly become the viable foundation of a productive and resilient plant organism (Boubakry *et al.*, 2023). Hence, nitrogen is a key element of protein and energy metabolism that activates the primary biochemical processes in plants. Its effectiveness, however, depends on balanced interactions with calcium, sulphur, boron, and silicon. Under such conditions, nitrogen supports not only growth but also crop resistance and productivity (Bruulsema & Olson, 2024).

Since photosynthesis requires magnesium, it ranks fifth in the biochemical sequence, preceding all other less critical microelements. Photosynthesis is not merely the accumulation of energy in chlorophyll; this energy must be transferred from chlorophyll to silicon to produce sugars from carbon dioxide and water, a process that demands phosphorus for energy transport. Without sufficient phosphorus, chlorophyll becomes unstable, leading to leaf discolouration and premature senescence (Buchelt *et al.*, 2020). If phosphorus is available, carbon is released from carbon dioxide to combine with water, producing sugars and releasing oxygen. Magnesium acts as the central atom of the chlorophyll molecule – without it, light absorption and its conversion into chemical energy would be impossible. Yet the role of magnesium extends beyond photosynthesis. It activates more than 300 enzymatic systems, including those responsible for the synthesis of nucleic acids, proteins, carbohydrates, and lipids. Magnesium maintains ribosomal stability, participates in ATP synthesis, and facilitates phosphate transport within the plant (Wang *et al.*, 2023). In addition, magnesium is essential for carbohydrate mobilisation, particularly for transporting assimilates from leaves to growing points, generative organs, and the root system. Magnesium deficiency leads to carbohydrate accumulation in leaves, premature ageing, disrupted nitrogen metabolism, and reduced overall productivity. It also exhibits antagonistic interactions with calcium and potassium, so overapplication of one without balancing magnesium can disturb ionic equilibrium and cause secondary deficiencies (Hernandez *et al.*, 2024). Thus, magnesium is indispensable for photosynthesis and general plant metabolism, as it forms part of chlorophyll and activates numerous enzymes. It enables ATP synthesis, phosphate and carbohydrate transport, and maintains the balance of nutrient elements. Its deficiency disrupts energy exchange, reduces photosynthesis, and limits plant productivity.

Phosphorus. Photosynthesis is not only the capture of light energy by chlorophyll – this energy must be converted into sugars from carbon dioxide and water, a process requiring phosphorus. Otherwise, chlorophyll "burns out", and leaves acquire a reddish hue. Phosphorus is a key element in cellular energy transfer and storage since it forms part of ATP – the main energy carrier in biochemical reactions. It allows energy captured during photosynthesis to be used for synthesising carbohydrates, proteins, nucleic acids, and other organic compounds (Wang *et al.*, 2023). Phosphorus is also an essential component of phospholipids forming cell membranes and of RNA and DNA, ensuring genetic information transfer and regulation of cell division. It participates in coenzyme and regulatory molecule synthesis, coordinating primary metabolic pathways, including nitrogen and carbohydrate metabolism. Phosphorus is particularly crucial in early plant development, stimulating root system growth, accelerating establishment, enhancing water efficiency, and improving the uptake of other nutrients. During the generative phase, phosphorus ensures full flowering, fruit set, and seed filling. Hence, phosphorus is critical for energy metabolism, synthesis of nucleic acids, proteins, carbohydrates, and cell structures. Its deficiency results in energy depletion and metabolic disturbances (Bolokhovsky *et al.*, 2024).

Carbon. When phosphorus levels are adequate, carbon participates as carbon dioxide, and energy is transferred from chlorophyll through phosphorus to bind CO_2 with water, forming sugar and releasing oxygen. Carbon is the fundamental building block of all organic molecules in plants – from simple sugars to complex proteins, lipids, nucleic acids, and cell wall structures. About 45% of plant dry matter consists of carbon, assimilated from the atmosphere as CO_2 through stomata. Using photosynthetic energy, this carbon dioxide is converted into glucose, the primary molecule for synthesising structural and storage compounds (Khan, 2025). Carbon is also a key component of cellulose, hemicellulose, and lignin – materials that form cell walls and vascular tissues. In the form of organic acids, it participates in pH buffering, mineral transport, and osmotic regulation. The accumulation of carbon compounds such as sugars and starch provides plants with energy and affects root development, stress adaptation, and yield quality. Furthermore, the carbon-to-nitrogen balance determines the growth direction – vegetative or generative – and directly influences resistance to diseases and drought (Khan *et al.*, 2023). Thus, carbon is not merely a passive element absorbed from the air but an active regulator and structural component of all vital plant processes. Its assimilation and utilisation are closely linked to the efficient functioning of the photosynthetic apparatus, phosphorus and magnesium availability, and optimal water balance. Carbon underlies organic plant life, forming structures, energy reserves, and metabolic compounds. Its assimilation through photosynthesis drives the synthesis of sugars, proteins, nucleic acids, and cell walls. The carbon balance with other nutrients defines plant growth direction, stress resistance, and yield quality.

Potassium. At this stage, sugars move into plant sap, where potassium – as an electrolyte – directs them to where they are most needed. Potassium plays a crucial role in regulating osmotic pressure, stomatal opening, and the transport of assimilates, particularly sugars, from photosynthetic leaves to growth points, roots, and reproductive organs. Through potassium, the efficient movement of nutrients through the phloem is ensured, which is particularly critical during grain filling or fruit development (Bolokhovsky *et al.*, 2024). Potassium activates more than 60 enzyme systems, including those responsible for protein synthesis, carbohydrate metabolism, and energy accumulation. Although it does not form part of organic molecules, it is indispensable for their biochemical activity. Potassium also regulates starch synthesis, water balance, and membrane integrity, enhancing resistance to mechanical stress and pathogen attack (Hernandez *et al.*, 2024). Adequate potassium levels strengthen plant tissues, improve tolerance to drought and low temperatures, and enhance resistance to fungal and bacterial diseases. It also plays a vital role in stress adaptation by maintaining turgor and reducing damage under unfavourable conditions. Thus, potassium is a critical element for sugar transport, water balance regulation, and enzymatic activity in plants. While not part of organic compounds, it ensures their effective functioning, promoting growth, energy accumulation, stress resistance, and yield formation.

APPLIED BIOCHEMICAL MODEL FOR SORGHUM BICOLOR AND TRITICUM SPELTA

All these processes unfold only when the biochemical sequence is activated by the initiating elements. To sustain this biochemical sequence, it is crucial to use mineral supplements such as gypsum, silicate rock powders, lime, and dolomite, which help restore and maintain elemental balance in the soil. In addition, organic methods of soil enrichment – such as composting with the addition of rock powders – contribute to the restoration of natural soil biology and increase fertility (Drobitko & Kachanova, 2023). Considering the interrelations of elements in plant nutrition and their functional sequence, a diagram of biochemical interactions among macro- and microelements was constructed. Using two crops – common sorghum (*Sorghum bicolor*) (Table 1) and spelt wheat (*Triticum spelta*) (Table 2) – the dynamics of nutrient incorporation into metabolic processes were illustrated, allowing observation of the stages of productivity formation and plant adaptive stability (Khan *et al.*, 2023; Bruulsema & Olson, 2024).

Table 1. *Functional role of key elements in the biochemical nutrition system of common sorghum*

Element	Function	Critical period
Sulphur (S)	Activates protein metabolism, stimulates photosynthesis, reduces nitrate accumulation	Early vegetation, tillering stage
Boron (B)	Forms the vascular system, increases pollen viability	Before stem elongation
Silicon (Si)	Strengthens cell walls, reduces moisture loss	Throughout vegetation
Calcium (Ca)	Forms cell membranes, improves nitrogen uptake	Tillering – stem elongation
Nitrogen (N)	Ensures growth and protein synthesis	Vegetation, grain filling
Magnesium (Mg)	Central atom of chlorophyll, energy metabolism	All photosynthetic phases
Phosphorus (P)	Root system growth, energy metabolism	Early development, reproductive phase
Carbon (C)	Forms organic matter, photosynthesis	Constantly
Potassium (K)	Assimilate transport, drought resistance	Grain filling, ripening

Source: *authors' data based on T. Bruulsema and R. Olson (2024), M. Khan et al. (2023)*

Table 2. *Biochemical activity of major elements during key ontogenetic phases of spelt wheat*

Element	Function	Critical period
Sulphur (S)	Stimulates protein and gluten synthesis, enhances disease resistance	Spring regrowth
Boron (B)	Ear formation, pollen fertility improvement	Stem elongation – heading
Silicon (Si)	Stem strengthening, lodging reduction	Throughout vegetation
Calcium (Ca)	Increases cell wall stability, nutrient transport	Tillering – heading
Nitrogen (N)	Growth, protein formation, ear and grain development	Spring – grain filling
Magnesium (Mg)	Chlorophyll formation, photosynthesis	Vegetation
Phosphorus (P)	Root system development, energy supply	Autumn vegetation – spring regrowth
Carbon (C)	Organogenesis, energy potential	All phases
Potassium (K)	Resistance to lodging, frost, and disease	Tillering – grain filling

Source: *authors' data based on T. Bruulsema and R. Olson (2024), M. Khan et al. (2023)*

The analysis of the biochemical nutrient sequence in *Sorghum bicolor* and *Triticum spelta* showed that the efficiency of metabolic processes in these crops directly depends on the sequential and balanced supply of macro- and microelements. A key role in initiating biochemical activity is played by sulphur, boron, silicon, and calcium, which create the prerequisites for the full assimilation of nitrogen, magnesium, phosphorus, carbon, and potassium. This sequence determines the stability of growth processes, photosynthetic activity, and crop quality. Applying this model not only enhances the efficiency of mineral nutrition but also ensures the ecologically balanced functioning of agroecosystems (Sun *et al.*, 2024).

In general, the results of the study confirmed that the effectiveness of plant growth and productivity is determined by the sequence and balance of nutrient supply. The active interaction of sulphur, boron, silicon and calcium creates conditions for the absorption of nitrogen, magnesium, phosphorus, carbon and potassium, ensuring metabolic stability and crop resilience.

CONCLUSIONS

The conducted analytical study confirmed that the functional hierarchy of nutrients and their biochemical sequence of activation form the physiological basis of effective plant growth and productivity. The research summarised both classical and modern concepts of nutrient interactions, emphasising the critical role of sulphur, boron, silicon, and calcium as initiating elements that activate metabolic pathways and prepare the biochemical environment for the effective utilisation of nitrogen, magnesium, phosphorus, carbon, and potassium. These primary elements not only initiate enzymatic and photosynthetic activity but also enhance structural integrity, transport processes, and stress resistance in plants. The analysis of the applied biochemical model for Sorghum bicolor and Triticum spelta demonstrated that the balanced and sequential uptake of macro- and microelements directly determines the metabolic stability and adaptive potential of crops. In both species, the functional order of nutrient activation ensures a synergistic relationship between energy metabolism and protein synthesis, maintaining photosynthetic efficiency and reproductive success. The implementation of this sequence in agronomic practice contributes to the optimisation of fertilisation systems, reduces nutrient losses, and supports sustainable soil fertility. The results also highlight the importance of integrating mineral and organic soil amendments such as gypsum, dolomite, silicate powders, and composts enriched with rock dusts. These materials restore the natural balance of nutrient elements, enhance soil microbial activity, and promote the development of biologically active agroecosystems. The proposed model provides a universal framework for adapting biochemical nutrient sequences to specific crop requirements and regional agroecological conditions.

Future investigations should focus on quantitative modelling of nutrient activation kinetics under varying climatic and soil conditions, as well as on identifying molecular mechanisms that regulate the biochemical synchronisation of nutrient uptake. Special attention should be given to the integration of this model into precision agriculture technologies, which would allow for dynamic adjustment of fertilisation regimes and real-time monitoring of plant physiological responses. This direction of research will ensure the practical application of biochemical nutrient hierarchy principles in the development of resilient, high-yield, and environmentally sustainable crop production systems.

ACKNOWLEDGEMENTS

None.

FUNDING

This study received no funding.

CONFLICT OF INTEREST

The authors of this study declare that there is no conflict of interest.

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Збалансоване живлення рослин: від функціонального дефіциту до системної стратегії підвищення врожайності: огляд літератури

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Анотація. Метою даного дослідження було обґрунтування функціональної ієрархії поживних речовин та розробка прикладної біохімічної моделі для оптимізації управління поживними речовинами в рослинах. Методологія дослідження поєднувала комплексний аналіз міжнародних та національних наукових джерел із систематизацією біохімічних взаємодій між макро- та мікроелементами. Було встановлено, що поглинання та активація поживних речовин у рослинах відбувається за певною біохімічною послідовністю, в якій сірка, бор, кремній і кальцій виступають ініціаторами, що активують метаболічні шляхи, забезпечуючи ефективне засвоєння азоту, магнію, фосфору, вуглецю та калію. У дослідженні проаналізовано фізіологічні та біохімічні механізми взаємозв'язків між поживними речовинами та продемонстровано, що така послідовна активація забезпечує баланс між структурним розвитком, фотосинтетичною активністю та стресостійкістю. Було встановлено, що ефективність метаболічних процесів безпосередньо залежить від синхронізації поглинання елементів відповідно до фаз росту рослин. Дослідження узагальнило експериментальні та теоретичні дані про роль кальцію в транспорті та сигналізації, сірки в синтезі білків, кремнію в зміцненні клітин та бору в репродуктивному розвитку. На основі цих висновків було розроблено функціональну біохімічну модель, яка показує, як послідовна активація поживних речовин покращує врожайність та підвищує стійкість до екологічного стресу. Модель була застосована для аналізу динаміки поживних речовин у Sorghum bicolor та Triticum spelta, що дозволило виявити, що дотримання цієї послідовності забезпечує метаболічну стабільність та стійку родючість ґрунту. Практичне значення дослідження полягає в його застосовності для агрономів, ґрунтознавців та дослідників у галузі фізіології рослин, а також для сільськогосподарських підприємств, які прагнуть підвищити ефективність управління поживними речовинами, оптимізувати стратегії удобрення та збільшити врожайність культур у рамках систем сталого землеробства

Ключові слова: біохімічна послідовність; живлення рослин; сірка; бор; кремній; кальцій; азот; фотосинтез; метаболізм; агроекосистема

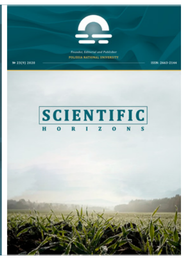
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(9), 59-71

UDC 631.811:633:674.031

DOI: 10.48077/scihor9.2025.59



Modelling plant growth dynamics using the example of paulownia (*Paulownia energy*) seedling growing

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Article's History:
Received: 13.03.2025
Revised: 19.07.2025
Accepted: 27.08.2025

Abstract. The purpose of the study was to develop and verify a nonlinear dynamic model of individual tree growth using the example of seedlings of the fast-growing *Paulownia energy* species. A set of studies on mathematical modelling of physicochemical processes accompanying the growth of seedlings was conducted, including computational and field experiments to assess the adequacy of the proposed model. It has been established that during the growing of seedlings, the rate of phytomass loss through, respiration increases proportionally with the increase in leaf area. During the period of no irrigation, along with the loss of mass due to evaporation of moisture from the soil, a 1.3 time increase in seedling mass was recorded. An increase in the phytomass of the seedling by 63% was established solely due to respiration and the intake of assimilates, and without considering the mass of the pot. The high correlation coefficient ($R^2 = 0.99$) confirmed the high accuracy of the obtained experimental data. Therefore, to maintain stable growth, it is necessary to

Suggested Citation:
Kulman, S., Vyshnevskyi, A., Horbachova, O., & Mazurchuk, S. (2025). Modelling plant growth dynamics using the example of paulownia (*Paulownia energy*) seedling growing. *Scientific Horizons*, 28(9), 59-71. doi: 10.48077/scihor9.2025.59.

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ensure continuous micro-irrigation and active photosynthesis. The developed three-stage nonlinear kinetic model in qualitative terms reliably reflects the process of seedling growth (the correlation coefficient exceeds 90%). This facilitates its use as a basic model for predicting growth rates. It has been confirmed that accurate determination of the kinetic parameters of the process is necessary to ensure quantitative compliance. Based on research of the fast-growing species of paulownia (*Paulownia energy*), a nonlinear dynamic model of tree growth was created. The results obtained provide a reliable opportunity (at the level of $R^2 = 0.99$) to predict the rate of seedlings growing and determine the optimal conditions for their growth

Keywords: paulownia; kinetic model; seedling growth; dynamic phase variables; phytomass increase; integral curves

INTRODUCTION

Contemporary approaches to forest modelling consider numerous factors, including climatic conditions, biological processes, and anthropogenic impacts, which contributes to a more complete picture of tree growth and stand productivity. These approaches rely not only on empirical observations but also on data-driven simulation techniques that integrate remote sensing, machine learning algorithms, and physiological modelling. By incorporating variables such as soil moisture dynamics, temperature fluctuations, light availability, CO_2 concentrations, and disturbance regimes, contemporary forest models enable researchers to assess ecosystem responses under both current and projected environmental scenarios. Furthermore, the inclusion of anthropogenic drivers—such as land use change, forest management practices, and pollution – allows for a more accurate representation of real-world dynamics, enhancing the predictive capacity of models in both natural and managed forest systems.

Researchers M. Blumstein *et al.* (2023) investigated how nonstructural carbohydrate (NSC) reserves in trees vary globally in response to climatic gradients. The study found that temperature and moisture availability are key drivers influencing NSC storage patterns, with significant implications for tree resilience and forest productivity under climate change. T.A.M. Pugh *et al.* (2020) analysed the sources of uncertainty in global forest carbon turnover using a multimodel approach. Their findings highlighted substantial variability stemming from model assumptions about mortality rates, carbon residence times, and climate sensitivity, emphasising the need for harmonised datasets and improved model structures. K. Merganicova *et al.* (2019) focused on modelling forest carbon allocation dynamics under projected climate change conditions. They demonstrated that changes in temperature and precipitation regimes alter allocation patterns between above- and belowground biomass, underscoring the importance of incorporating flexible allocation schemes in dynamic vegetation models.

There are several basic principles for creating mathematical models in biology. One of the main modelling methods is the ordering of balance relations (usually in the form of conservation laws). In dynamic models, balance relations are typically written as systems of differential equations that relate the rates of process flow. This is often done according to Liebig's principle of limiting factors. H.A. Echavarria-Heras *et al.* (2021) in their research argued that the intensity of the output process at each point in time is determined by the minimum component of the input process, that is, the component that prevents others from having their effect. The number of factors influencing the functioning of an ecological system is extremely large, and when creating a model, it is necessary to select the main ones (Mengel, 2019). For example, the development of phytoplankton in seas and lakes is never limited by the carbon content of the water, but is very frequently inhibited by a lack of nitrogen or phosphorus. Therefore, according to A. Cabon & W.R.L. Anderegg (2023), the model must primarily consider the dynamics of nitrogen or phosphorus concentrations, and the concentration of carbon (at least at the first stages of model formulation) should be neglected.

R. Peters *et al.* (2014) determined that such relationships exist between body weight, its surface area, and volume. The use of allometric relationships allows significantly reducing the number of independent model variables. At the same time, dynamic ecophysiological models of whole-tree growth provide an opportunity to combine existing knowledge about physiological and ecophysiological processes and phenomena into a single system. This allows identifying bottlenecks, quantitative discrepancies, and unresolved issues for further ecophysiological research. The decisive factor in dynamic modelling of tree stand growth, according to M.V. Fonti *et al.* (2022), is how much the growth models of an individual tree can be improved and refined. Therefore, the creation of a tree growth model is a central component in most modern forest ecosystem research programmes. Existing tree growth models have considered empirical growth equations in detail. Dynamic modelling of tree growth, which began in the late 1960s, has been addressed in reviews without much separation between tree and stand models. However, it would be more correct to select from the models for comparison those parts (submodels) that describe the same phenomena (Petter *et al.*, 2021).

The purpose of the study was to create and test a nonlinear dynamic model of an individual tree growth using the example of seedlings of the fast-growing species of *Paulownia energy*. To achieve the goal, the task was set to conduct a set of studies on mathematical modelling of physicochemical processes occurring during the growth of seedlings, including computational and full-scale experiments to assess the adequacy of the created model.

MATERIALS AND METHODS

Growth dynamics were investigated on paulownia seedlings (*Paulownia energy*) – 5 pcs – (Fig. 1), which were provided by the company Paulownia energy Ukraine (Lutsk). The samples were in pots during the experiment, the plant height was 120 mm. Before the start of the study, empty pots (containers) and separately, the moist substrate used to grow the experimental seedling were weighed. This helped to obtain the net weight of the samples at each measurement stage by subtracting the previously determined weights of the container and substrate. This procedure ensured the minimisation of the influence of extraneous factors on the weight indicators of the samples under study. The experiment was conducted in laboratory conditions, environmental parameters were as follows: temperature t = 25°C, air humidity φ = 60%, controlled ventilation. Light sandy-clay, well-drained soil, pH = 6, was used. Soil moisture was constantly monitored with moderate watering. Illumination of 20/7 for test specimens was provided using a fluorescent lamp. The biomass calculation method was weighing. The duration of the experiment was 43 days. Such pot-based experimental setup allowed maintaining optimal and stable environmental conditions for paulownia growth.

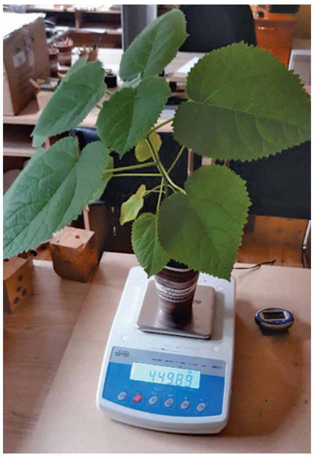

Figure 1. *Preparation of samples*
Source: *photo by the authors*

In contrast to open-field conditions where seedlings may be exposed to sharp temperature fluctuations (e.g. heatwaves or frosts), pot cultivation provided thermal buffering that reduced stress. Additionally, controlled irrigation in pots ensured consistent moisture levels, unlike field conditions, where water availability depends on unpredictable rainfall, groundwater fluctuations, and evaporation rates. This controlled setting minimised risks of overwatering or drought and prevents air humidity swings that would otherwise affect plant transpiration. The study was conducted in accordance with the Convention on Biological Diversity (1992).

A computational experiment was conducted using parametric analysis of the constructed mathematical model. The total weight of the plant, which includes the weight of leaves, trunk, roots, and pot with soil, was taken as a phase variable during the modelling. The model described the growth of an individual tree, during which there was a constant change in the total weight of the plant over time. In this case, the change in total weight was determined by the basic kinetic equation, which reflected the law of conservation of mass:

$$dW(t) = dW^{+}(t) - dW^{-}(t), \tag{1}$$

where $dW^{+}(t)$ – increase in total weight due to photosynthesis and assimilates (input), over time $d(t)$, kg; $dW(t) = dW^{+}(t) - dW^{-}(t)$ – reduction in total weight due to plant respiration and soil evaporation over time (losses) $d(t)$, kg.

Considering the physicochemical processes accompanying growth, it can be written:

$$dW^{+}(t) = dW^{+}_{ph}(t) + dW^{+}_{ass}(t), \tag{2}$$

where $dW^{+}_{ph}(t)$ – increase in phytomass due to photosynthesis, kg; $dW^{+}_{ass}(t)$ – increase in phytomass due to the assimilation of substances coming from the soil, kg;

$$dW^{-}(t) = dW^{-}_{br}(t) + dW^{-}_{ll} + dW^{-}_{ev}(t), \tag{3}$$

where $dW^{-}_{br}(t)$ – reduction of phytomass due to respiration (breath), kg; $dW^{-}_{ll}(t)$ – reduction in phytomass due to precipitation (leaflitter), kg; $dW^{-}_{ev}(t)$ – reduction in phytomass due to evaporation of moisture from the pot soil (evaporation), kg.

As an initial hypothesis, it can be accepted that the rate of increase in phytomass and the rate of decrease in phytomass are proportional to the amount of phytomass. This hypothesis is well confirmed in many cases of modelling the dynamics of the living beings' population development or other complex dynamic systems. Following this hypothesis, it is possible to write:

$$\frac{dW^{+}(t)}{dt} = k_1 \cdot W(t), \tag{4}$$

$$\frac{dW^{-}(t)}{dt} = k_2 \cdot W(t), \tag{5}$$

$$\frac{dW(t)}{dt} = k_3 \cdot W^{+}(t) - k_4 \cdot W^{-}(t). \tag{6}$$

In this case, the initial conditions for conducting the experiment will be the following restrictions:

$$t = 0: W(t) = W0;\ W^{+}(t) = 0;\ W^{-}(t) = 0, \tag{7}$$

where $k_1(t)$ – rate of increase in phytomass due to photosynthesis and assimilates, kg/s; $k_2(t)$ – rate of phytomass loss due to respiration, precipitation, and soil drying, kg/s; $k_3(t)$ – rate of change in phytomass due to photosynthesis and assimilates, kg/s; $k_4(t)$ – rate of change in phytomass due to respiration, precipitation, and soil drying, kg/s.

In the general case, the rates of change of phytomass cannot be constant values. They depend on many factors that affect growth. These are temperature, solar radiation level, humidity, etc. All of these values were constant. However, in the first approximation, in order to obtain a qualitative image of the kinetics of the process and to have the possibility of qualitative analysis of the integral curves, it was necessary to take them as constant. In order to better understand the development trend, it was better to use dimensionless quantities, because they were the most informative and were not tied to reference systems. In order to be able to compare and study the growth kinetics of several seedlings observed simultaneously, which have different initial weights, it was necessary to introduce new dimensionless values of phytomass measurements, namely, dimensionless phytomass:

$$CB(t) = \frac{W(t)}{W0}. \tag{8}$$

Then, considering the initial conditions (7), it is possible to write them in the form:

$$t = 0 : CB(0) = 1;\ CA(t) = 0;\ CC(t) = 0. \tag{9}$$

Nonlinear dynamic model in the form of a system of nonlinear differential equations:

$$\left\{\begin{aligned} \frac{dCA(t)}{dt} &= k_1(t)CB(t) \\ \frac{dCB(t)}{dt} &= k_3(t)\,CA(t) - k_4CC(t) \\ \frac{dCC(t)}{dt} &= k_2(t)\,CB(t) \end{aligned}\right\}, \tag{10}$$

where $CA(t)$ – increase in the total phytomass of the tree due to photosynthesis and assimilates over time; $CB(t)$ – change in the total phytomass of a growing tree over time; $CC(t)$ – decrease in total phytomass due to respiration over time; $k_1(t)$ – rate of increase in phytomass due to photosynthesis; $k_2(t)$ – rate of phytomass reduction due to respiration; $k_3(t)$ – rate of change in phytomass due to photosynthesis; $k_4(t)$ – rate of change in phytomass due to respiration.

Having solved this system of differential equations (10) under the initial conditions (9), the following values of the change in phase variables over time (integral curves) were obtained:

$$CA(t) := (-2)\cdot k_1 \cdot \frac{CB(0)}{2\cdot k_3\cdot k_1 - 2\cdot k_4\cdot k_2}\cdot [(-k_3)\cdot k_1 + k_4\cdot k_2]^{\frac{1}{2}}\cdot sin\left[[(-k_3)\cdot k_1 + k_4\cdot k_2]^{\frac{1}{2}}\cdot t\right], \tag{11}$$

$$CB(t) := CB(0)\cdot cos\left[[(-k_3)\cdot k_1 + k_4\cdot 2]^{\frac{1}{2}}\cdot t\right], \tag{12}$$

$$CC(t) := (-2)\cdot k_2 \cdot \frac{CB(0)}{2\cdot k_3\cdot k_1 - 2\cdot k_4\cdot k_2}\cdot [(-k_3)\cdot k_1 + k_4\cdot k_2]^{\frac{1}{2}}\cdot sin\left[[(-k_3)\cdot k_1 + k_4\cdot k_2]^{\frac{1}{2}}\cdot t\right]. \tag{13}$$

During the field experiment, periodic measurements of the phytomass of seedlings were made along with the pots. In this way, the total weight and its change over time were recorded. Weight measurements were carried out on electronic scales from RADWAG with an accuracy of 0.01 g. In order to determine the amount of seedling respiration at each measurement, parallel measurements of shrinkage were made of the same pot with soil, but without the seedling.

RESULTS AND DISCUSSION

Considering that the system parameters are the rates of change in phytomass, changes in the growth process depend on the ratio of the rates of processes. The values of dynamic phase variables at time are assumed $t = 0 : CB(0) = 1;\ CA(t) = 1;\ CC(t) = 1$. The kinetic diagram also shows the values of the model parameters k_1, k_2, k_3, and k_4, which in this case are variable values and change over time depending on the external and internal conditions of the growth process. Figure 2a shows the kinetic scheme of the model under certain initial conditions $k_1(t) = a$, $k_2(t) = b$, $k_3(t) = c$, $k_4(t) = d$.

The integral curves shown in Figure 2b indicate a constant increase in all phase variable models. Since the arrival of phytomass CA is greater than its consumption CC, the total phytomass CB is also constantly increasing. However, if the model parameters are changed, a corresponding change in the velocities of the phase variables can be seen, that is, the growth rate of the plant. Thus, knowing the values of the parameters from experience, it is possible to predict the growth rate of phytomass. In the initial period, the model shows a growth rate of total phytomass CB less than the rate of its decrease CC. This area is shown in Figure 3.

The results obtained provided that all parameters are equal to each other are presented in Figure 4.

Analysing the integral curves, it can come to the disappointing conclusion that in the case of phytomass growth, there is no CB, since CA = CC. Computational experiment under the condition (condition 2) shown in Figure 5.

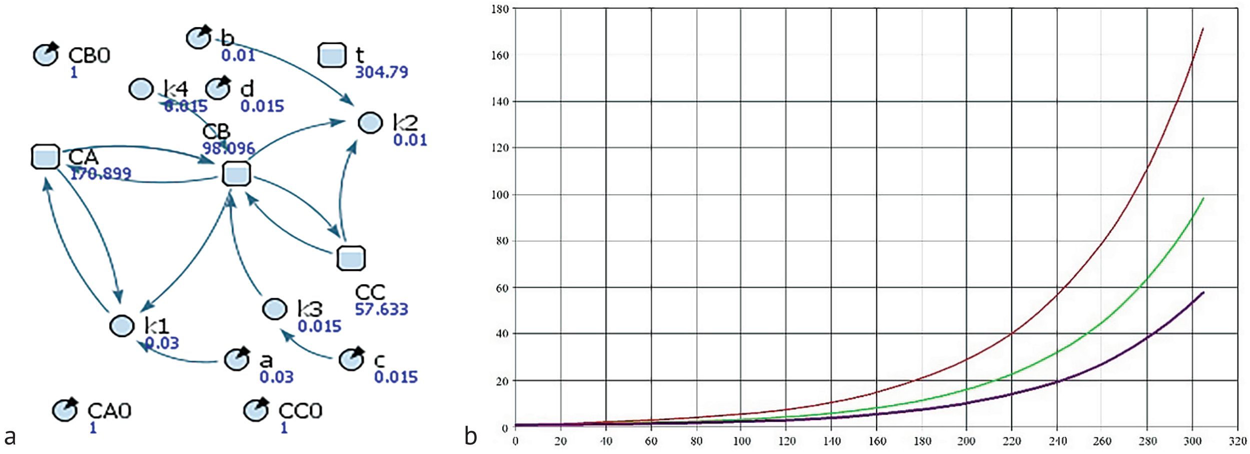

***Figure 2**. Integral curves at the model time point 304.79 s*

***Note:** a – kinetic scheme of the model; b – general curves of changes in dynamic phase variables in time (—— dCA(t)/dt = -k_1·CB; —— dCB(t)/dt = k_3·CA-k_4·CC; —— dCC(t) = k_2·CB)*

***Source:** compiled by the authors*

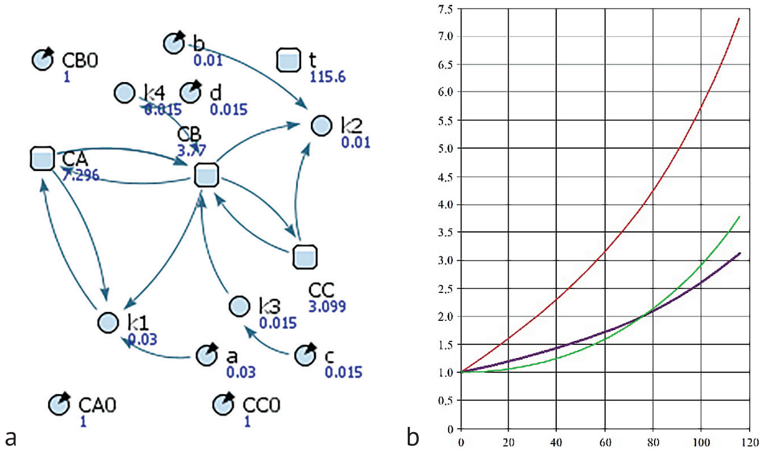

***Figure 3**. Initial section of the computational experiment*

***Note:** a – kinetic scheme of the model; b – curves of changes of dynamic phase variables (—— dCA(t)/dt = -k_1·CB; —— dCB(t)/dt = k_3·CA-k_4·CC; —— dCC(t) = k_2·CB)*

***Source:** compiled by the authors*

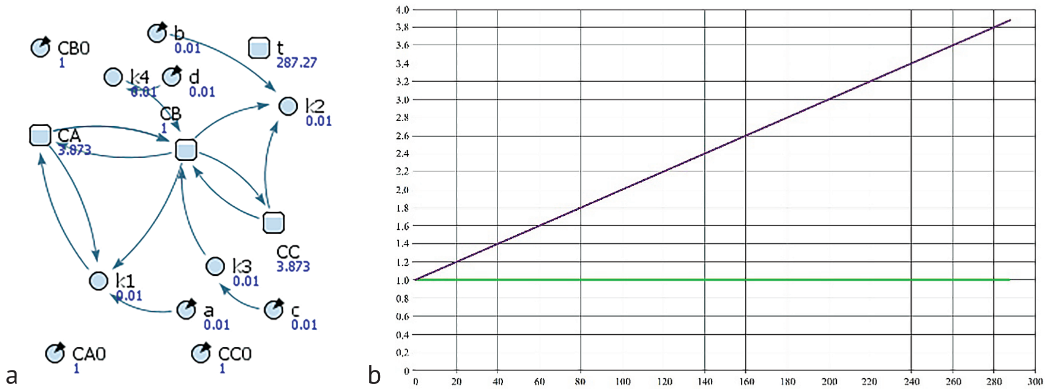

***Figure 4**. Integral curves with the same value of all model parameters*

***Note:** a – kinetic scheme of the model; b – curves of changes of dynamic phase variables (—— dCA(t)/dt = -k_1·CB; —— dCB(t)/dt = k_3·CA-k_4·CC; —— dCC(t) = k_2·CB)*

***Source:** compiled by the authors*

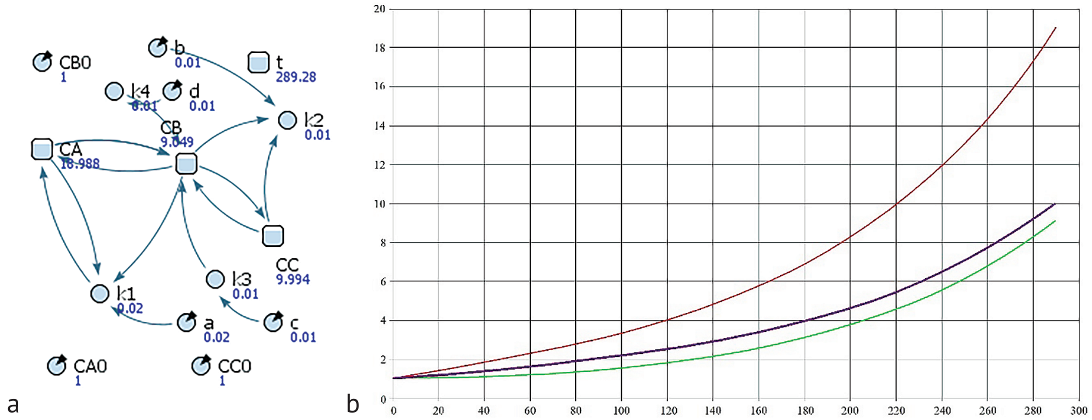

Figure 5*. Integral curves of phytomass increase (condition 2)*
Note: *a – kinetic scheme of the model; b – curves of changes in dynamic phase variables (—— $dCA(t)/dt=-k_1 \cdot CB$; —— $dCB(t)/dt=k_3 \cdot CA-k_4 \cdot CC$; —— $dCC(t)=k_2 \cdot CB$)*
Source: *compiled by the authors*

Analysis of this experiment indicates that an increase in phytomass (*CA*) leads to an increase in total weight (*CB*). The next stage is the study of conditions (condition 3). The results are shown in Figure 6. In this case, due to the high rate of phytomass reduction (*CC*), there is a decrease in total phytomass (CB). Checking the conditions (condition 4) (Fig. 7). A rather paradoxical result – all the curves merged into one integral curve. However, the rates of change of all phase variables are equal to each other (*CA* = *CB* = *CC*). Final computational experiment, checking the conditions (condition 5) (Fig. 8).

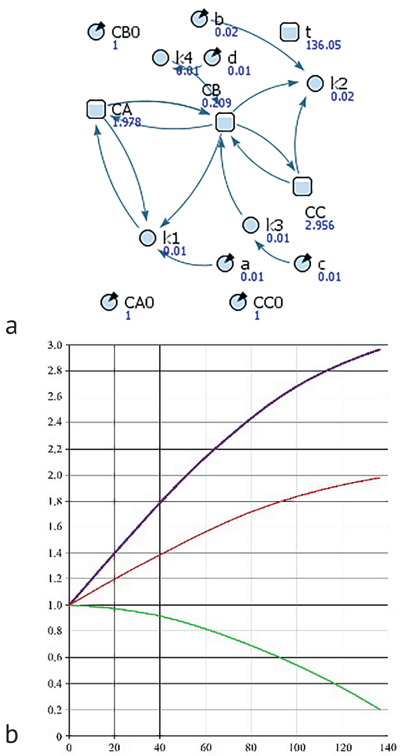

Figure 6*. Integral curves of phytomass increase (condition 3)*
Note: *a – kinetic scheme of the model; b – curves of changes in dynamic phase variables (—— $dCA(t)/dt=-k_1 \cdot CB$; —— $dCB(t)/dt=k_3 \cdot CA-k_4 \cdot CC$; —— $dCC(t)=k_2 \cdot CB$)*
Source: *compiled by the authors*

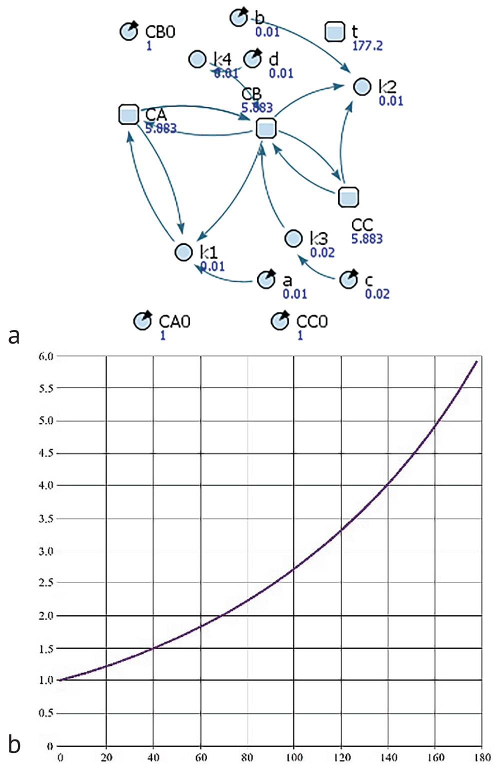

Figure 7*. Integral curves of phytomass increase (condition 4)*
Note: *a – kinetic scheme of the model; b – curves of changes in dynamic phase variables (—— $dCA(t)/dt=-k_1 \cdot CB$; —— $dCB(t)/dt=k_3 \cdot CA-k_4 \cdot CC$; —— $dCC(t)=k_2 \cdot CB$)*
Source: *compiled by the authors*

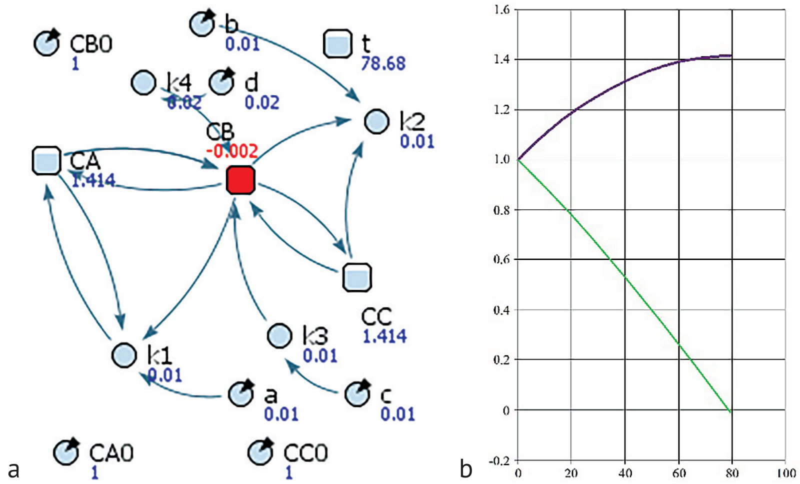

***Figure 8**. Integral curves of phytomass increase (condition 5)*
***Note:** a – kinetic scheme of the model; b – curves of changes in dynamic phase variables (—— $dCA(t)/dt=-k_1 \cdot CB$; —— $dCB(t)/dt=k_3 \cdot CA-k_4 \cdot CC$; —— $dCC(t)=k_2 \cdot CB$)*
***Source:** compiled by the authors*

It is quite an expected result, at which the rates of arrival (CA) and expenditure (CC) of phytomass are equal, therefore, there is a decrease in total phytomass (CB). Since photosynthesis rates and phytomass loss due to respiration depend on cyclical changes in weather conditions, dynamic variables also change accordingly. However, the total phytomass of the tree periodically increases. Since this model considers a limited number of variable factors and growth parameters, it may not be entirely adequate. It shows good resilience and the general growth trend of the tree. Therefore, it can be accepted as a basic kinetic model of growth.

Based on the results of the computational experiment, it can be concluded that the proposed model of seedling growth kinetics can be used for qualitative description and optimisation of growth conditions. However, to be confident in a high-quality growth rate forecast, it is necessary to test this model for adequacy, by conducting a full-scale experiment and comparing its results with the modelling results. For this purpose, a full-scale experiment was conducted. Figure 9 presents a listing of part of the results of the measurements, which indicates the dates of the measurements and the weight of the seedlings.

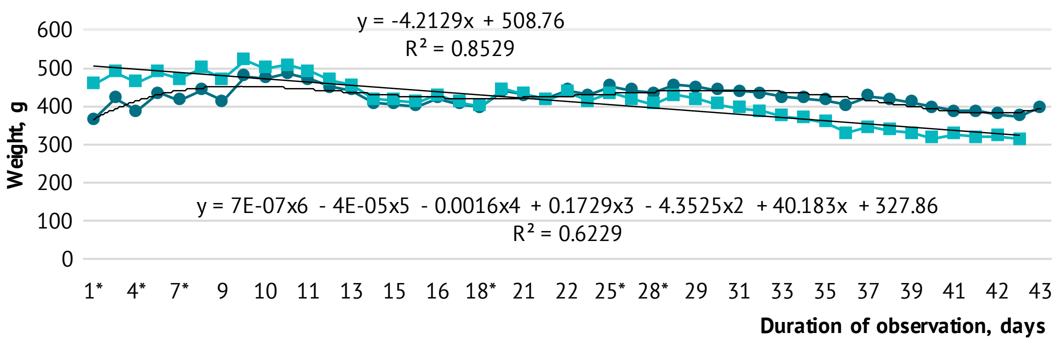

***Figure 9**. Dynamics of changes in the total weight of experimental seedlings*
***Note:** "*" indicates the dates of watering seedlings*
***Source:** compiled by the authors*

Throughout the entire experiment, constant growth of seedlings was visually observed. Simultaneously, the area of leaves also increased. However, as can be seen from the curves presented in Figure 9, the increase in total weight occurs only at the time of irrigation due to additional moisture. When analysing the curve of change in total weight in the initial period, it was noticed that the total weight changes slightly or tends to decrease. Based on these observations, a hypothesis was developed that during the process of phytomass growth due to assimilates and photosynthesis, phytomass simultaneously, decreases due to an increase in respiration intensity. However, the rate of uptake of assimilates from the soil remains practically unchanged.

To test this hypothesis, it is necessary to compare how the total weight of the seedling with the soil and pot changes. Moreover, it is necessary to consider the evaporation losses of the soil itself during the growth process, that is, to exclude this value from the total weight. In order to determine what part of the change in total phytomass is accounted for by soil evaporation, two more pots were prepared with the same soil, but without seedlings. Their watering and weight measurement were carried out in parallel, simultaneously with the seedlings. In order to increase the purity of the experiment by reducing the number of variable factors, watering was not carried out for 6 days for both seedlings and pots without seedlings. The results of measurements of the total weight of pots without watering with seedlings are presented in Figure 10.

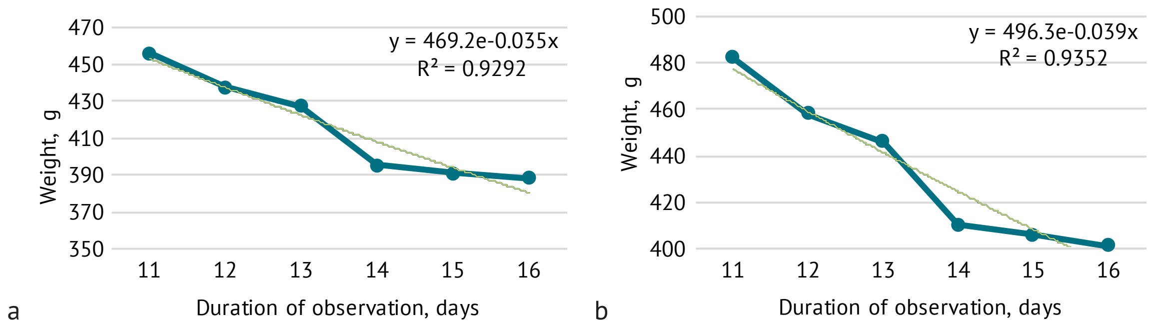

***Figure 10**. Results of measurements of the total weight of samples in the period between watering*
***Note:** a – pot with a seedling; b – pot without a seedling*
***Source:** compiled by the authors*

As can be seen from the results shown in Figure 10, there was a gradual decrease in the weight of pots with and without seedlings. It was noted that the pot without a seedling lost 30 % more weight compared to the seedling during the period without watering. The reliability of the obtained dependence is evidenced by the high correlation coefficient $R^2 = 0.9292$ and $R^2 = 0.9352$, respectively. Figure 11 presents combined graphs of changes in the weight of pots with seedlings and without seedlings in units of dimensionless weight.

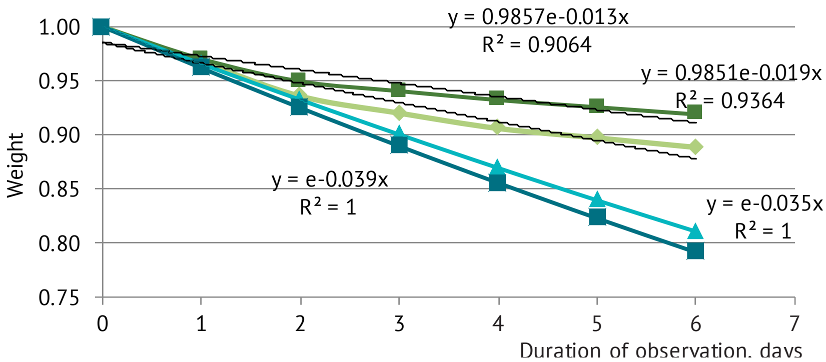

***Figure 11**. Weight changes of pots with seedlings (lower curves) and without seedlings (upper curves) in units of dimensionless weight*
***Source:** compiled by the authors*

In order to exclude the effect of soil drying in pots with seedlings, it is necessary to subtract the values of the change in the total weight of the pots. The results of this operation are presented in Figure 12, which shows the summary graphs of changes in phytomass only due to respiration and the intake of assimilates. In this study, during plant growth modelling, the moment of planting (beginning of observation) means time $x = 0$, that is, growth is not yet observed, and the value of phytomass (variable y) may be close to zero (Fig. 12a). Since the exponential function does not assume zero values (it must always be positive), it is more correct to start observations from $x = 1$, that is, from the first fixed phase of active growth (Fig. 12b).

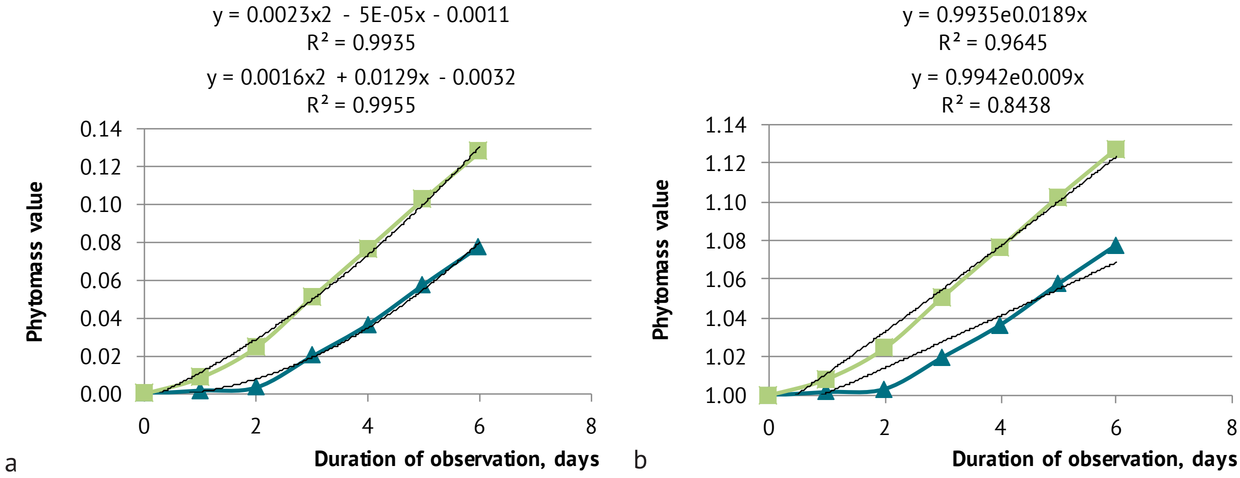

***Figure 12**. Changes in phytomass only due to respiration and the intake of assimilate*
***Note:** a – under real conditions; b – under conditions of a shifted coordinate system*
***Source:** compiled by the authors*

As a result, a correct mathematical model was obtained that corresponds to the biological reality of the seedling growth process and confirms stability during logarithmic analysis and model verification. It is clearly visible that in the first two days the changes are insignificant, and from the third day onwards, a sharp increase in phytomass can be observed. Since the rate of photosynthesis and the loss of phytomass due to respiration depend on cyclical changes in weather conditions (Fig. 7), this directly affects the change in the dynamic parameters of tree growth. After all, temperature fluctuations, light levels, humidity, and other environmental factors determine the intensity of metabolic processes in plants. This is confirmed by the results of H.A. Jabri *et al.* (2021), who noticed the reflection of seasonal and daily environmental variations on biomass productivity. Although fluctuations in metabolic activity can lead to a temporary decrease in organic matter accumulation (Liu *et al.*, 2019), the overall trend in woody phytomass development remains positive. This indicates stable growth of plantations in the long term. However, this model partially considers variable factors and growth parameters, which does not allow it to be completely accurate for all environmental conditions. However, due to its ability to reflect general patterns and adapt to major environmental changes, the model demonstrates high robustness in predicting wood growth trends. This allows it to be used as a basic kinetic model, which can serve as the basis for further improvement and expansion, considering additional biotic and abiotic factors.

Analysing the graphical dependences of changes in the total weight of seedlings (Fig. 9), it can be noted that its increase occurs mainly at the moments of watering, which is conditioned by the saturation of the substrate with additional moisture. This phenomenon is explained by the fact that water is the main component of the total weight of the plant, especially in the initial periods of vegetation, when the root system actively absorbs moisture. In their comparative study of Scots pine growth, V. Lovynska *et al.* (2021) also recorded a significant weight increase of seedlings directly after irrigation, particularly in the early vegetation stages. Their results confirmed that water availability is a decisive factor influencing biomass accumulation and that rapid moisture uptake plays a critical role in shaping the growth dynamics of seedlings in different ecological zones.

A detailed study of the dynamics of weight changes in the initial stages of development indicates relative stability or even a slight decrease in total weight. R. Silvestro *et al.* (2023) consider that this may be due to adaptive processes occurring in plants in response to changing environmental conditions. This is clearly visible at the stage of transition from using internal reserves to actively attracting external resources. However, regardless of minor fluctuations in total weight, a steady trend towards an increase in the phytomass of seedlings was recorded. This was confirmed by the gradual growth of vegetative organs, such as the stem and leaf blade. The intensive increase in leaf area is evidence of the activation of photosynthetic processes, which contributes to the synthesis of organic compounds and, accordingly, the further development of biomass.

Based on the results obtained (Fig. 12), it can be stated that during the growth of seedlings, the respiration intensity continuously increases, obeying quadratic or exponential laws. This is conditioned by acceleration in metabolism in the plant, which is accompanied by an increase in energy expenditure to support life processes. P. Fransson *et al.* (2025) demonstrated that under resource-limited conditions, such as nitrogen and water shortage, plants tend to redistribute energy flow to maintain vital physiological activities, even at the cost of reduced structural biomass accumulation.

Their eco-physiological model confirmed that respiration intensity can dominate over photosynthesis under stress, leading to changes in net carbon gain. However, there is a tendency for the respiration rate to significantly exceed the increase in phytomass caused by the assimilation of organic matter through photosynthesis. An increase in respiration rates causes a relative decrease in the total phytomass of the seedling, since part of the stored assimilates is spent on energy provision for physiological processes, rather than on the formation of new structural components. This highlights the important role of the balance between the level of photosynthetic activity and the intensity of respiration in determining the overall growth and productivity of the plant. R.M. Gifford (2003) argued that many productivity models underestimate the cost of respiration, especially under dynamic environmental conditions, which can lead to overestimations of net primary productivity. He also emphasised the need for integrating realistic respiration dynamics into plant growth models, particularly for fast-growing species. Thus, the absolute growth of a seedling directly depends on the rate of intake of assimilates, the efficiency of the photosynthetic apparatus, and the plant's ability to regulate metabolism in response to external conditions.

Comparative analysis of the breathing curves obtained in the field experiment (Fig. 12) with similar data during computational modelling (Fig. 2b), curve CC(t)) showed their qualitative correspondence. In both cases, an exponential growth of phase variables was recorded, which indicates the reliability and adequacy of the developed mathematical model. Its ability to qualitatively describe the dynamics of physiological changes allows it to be used to predict the growth and development of seedlings under various environmental conditions. This is important for optimising agrotechnical measures and planning forestry operations.

Nowadays, there is significant interest in growing fast-growing tree species with a short life cycle. The main purpose of creating such plantations is to obtain wood fibres and biomass, which are widely used in industry. Moreover, these species have significant potential for the production of finished wood products, which opens up additional prospects for their application. Paulownia is one of the most promising fast-growing species, the area of its plantations in Ukraine is growing rapidly. However, currently, information on the physical and mechanical properties of this wood remains insufficiently studied (Barbu *et al.*, 2023), which causes certain difficulties in determining possible areas of its use in the woodworking industry (Tsapko *et al.*, 2022). It is also important to assess and predict the condition of a product manufactured from this wood under different loading conditions (Kulman *et al.*, 2021; Bkarbu *et al.*, 2023), which will determine its durability. S. Kulman *et al.* (2021) proposed a kinetic approach for long-term strength prediction of wood-based composites and demonstrated the relevance of time-dependent stress factors, which could also be applied to fast-growing hardwoods such as paulownia. M.C. Barbu *et al.* (2023) showed that the mechanical characteristics of paulownia wood significantly varied along the stem height and across radial sections, which required a differentiated approach in selecting material for structural and non-structural applications. C. Huber *et al.* (2023) confirmed this variability and emphasised that paulownia's low density and fast maturity made it suitable for thermal modification and use in lightweight construction, although not all material met mechanical stability standards.

However, despite the successes achieved, both challenges and new opportunities remain for further improvement of the models. The model can be significantly refined by determining the values of the rate constants of the processes occurring, which in general have a thermal activation character according to the Arrhenius type (Kulman *et al.*, 2019). S. Kulman *et al.* (2019) demonstrated that variations in temperature and moisture affected the modulus of elasticity and rupture of particleboards, suggesting the possibility of adapting these parameters for paulownia-based products. In addition, these may be other values, which generally depend on environmental parameters, such as absolute temperature T, humidity W %, solar radiation level R, time of the vegetative or other period t. If the period of daily fluctuations of these quantities is considered, then the rate constants can be represented, for example, in this form . Such integration of dynamic environmental effects into the models allowed for more precise prediction of product behaviour and contributed to enhancing the ecological and practical relevance of forestry strategies. This development process allows not only optimising forestry practices, but also opens up prospects for innovative research in the field of ecology and nature management.

Thus, the conducted modelling enabled the identification of key relationships between the physiological parameters of paulownia seedling growth and environmental conditions. The results confirmed that photosynthetic activity, water availability, and respiration intensity significantly influence the rate of phytomass accumulation. The proposed kinetic model can be applied as a tool for predicting plant growth under variable irrigation and light conditions. Overall, the study provides a foundation for evidence-based approaches to the cultivation of fast-growing tree species, which is highly relevant in the context of sustainable forestry and the bioeconomy.

CONCLUSIONS

During the growth of a seedling, especially at the time of intensive increment in phytomass due to an increase in the area of its leaves, the rate of decrease in phytomass using respiration increases proportionally. Therefore, it is very important to maintain a constant supply of moisture (increase in phytomass) by ensuring continuous micro-irrigation and constant photosynthesis. During the period without watering, along with weight loss due to drying of the soil, an increase in the weight of the seedling by 20 g was recorded. Weight gain was accompanied by an increase in leaf size. If the weight of the pot was subtracted, a 1.63 time increase in phytomass was determined only due to respiration and the intake of assimilates. A correlation coefficient above $R^2 = 0.99$ indicates high accuracy of the experiment.

Comparing weight loss, it was found that the average weight loss rate of pots without seedlings was 0.0115 g/day, and with seedlings it was 2.8 times faster – 0.0325 g/day. That is, the presence of seedlings significantly accelerates weight loss, which is direct evidence of transpiration. This confirms that biological processes are the dominant factor in moisture loss compared to physical evaporation from the soil surface alone. Based on both experiments, the qualitative adequacy of the model was recorded. The exponential growth of phase variables in both cases confirms that the developed model adequately reproduces the overall dynamics of the studied biological processes. The proposed nonlinear kinetic three-stage model in a qualitative form adequately describes the process of seedling growth (correlation coefficient more than 90%) and therefore, can be used as a basic kinetic model for predicting growth rate. For this model to adequately describe the growth process quantitatively, accurate knowledge of the kinetic parameters of the model is necessary. Using this model allows predicting the growth rate of seedlings and creating optimal development conditions for them. Further development of this approach, considering additional factors, will not only optimise forest management methods, but also open up new opportunities for innovative ecological research, ease of monitoring, and effective modelling of forest ecosystem development.

ACKNOWLEDGEMENTS

This study was undertaken within the framework of the project "Research into the physical and mechanical properties of wood and wood composites in order to ensure the possibility of their modification and increase in service life with long-term strength and creep" (on the basis of Academic cooperation framework agreement concluded according to § 269 subs. 2 of the Commercial Code No. 513/1991 Coll. and Law No. 131/2002 Coll, on Higher Education, as amended by later Slovak regulations), contracts No. APVV-17-0583, APVV-18-0378 and APVV-19-0269. Authors also thanks to the Slovak Research and Development Agency for its support.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Моделювання динаміки росту рослин на прикладі зростання саджанців павловнії (*Paulownia energy*)

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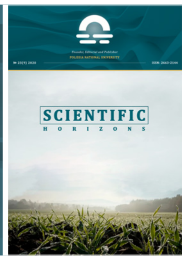
Анотація. Метою дослідження була розробка та верифікація нелінійної динамічної моделі росту окремого дерева на прикладі саджанців швидкорослої породи *Paulownia energy*. Проведено комплекс досліджень із математичного моделювання фізико-хімічних процесів, що супроводжують ріст саджанців, включаючи обчислювальні та натурні експерименти з оцінки адекватності запропонованої моделі. Встановлено, що у процесі розвитку саджанців швидкість втрати фітомаси через дихання пропорційно зростає разом зі збільшенням площі листя. У період відсутності поливу, поряд із втратою маси через випаровування вологи з ґрунту, було зафіксовано збільшення маси саджанця в 1,3 рази. Зафіксовано збільшення фітомаси саджанця на 63 % виключно внаслідок дихання та надходження асимілятів та без врахування маси горщика. Високий коефіцієнт кореляції ($R^2 = 0,99$) підтвердив високу точність отриманих експериментальних даних. Тому для підтримання стабільного приросту необхідне забезпечення безперервного мікрополиву та активного фотосинтезу. Розроблена трьохстадійна нелінійна кінетична модель у якісному вираженні достовірно відображає процес зростання саджанців (коефіцієнт кореляції перевищує 90 %). Це сприяє використанню її як базової моделі для прогнозування швидкості росту. Підтверджено, що для забезпечення кількісної відповідності необхідне точне визначення кінетичних параметрів процесу. На основі дослідження швидкорослої породи павловнії (*Paulownia energy*) створено нелінійну динамічну модель росту дерев. Отримані результати забезпечують вірогідну можливість (на рівні $R^2 = 0,99$) прогнозувати темпи розвитку саджанців та визначати оптимальні умови для їхнього росту

Ключові слова: павловнія; кінетична модель; ріст саджанців; динамічні фазові змінні; збільшення фітомаси; інтегральні криві

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(9), 72-84

UDC 633.11:631.82.015.3:631.559(477.41) DOI: 10.48077/scihor9.2025.72



Features of foliar fertilisation of facultative wheat

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Article's History:
Received: 20.05.2025
Revised: 01.08.2025
Accepted: 27.08.2025

Abstract. The purpose of the study was to evaluate the effect of foliar fertilisation systems and seed treatment on the productivity and physiological development of the facultative wheat variety Zymoyarka under the soil and climatic conditions of the Polissia region. The research was conducted in 2025 on the experimental field of Polissia National University using a randomised block design with four fertilisation variants. The methodology included pre-sowing seed treatment with GROS Korenerist,

Suggested Citation:
Zhuravel, S., Kravchuk, M., Zhuravel, S., Kyianychenko, M., Ruban, N., & Shershunov, V. (2025). Features of foliar fertilisation of facultative wheat. *Scientific Horizons*, 28(9), 72-84. doi: 10.48077/scihor9.2025.72.

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foliar applications of ECOLINE Phosphite (K), ECOLINE Boron (organic), and POLYACTIVE Boost, biometric and phenological observations, laboratory assessment of grain quality, and statistical analysis by ANOVA and correlation methods. It was established that the combined application of GROS Korenerist and ECOLINE Phosphite (K) significantly increased yield to 3.46 t/ha (+40.6% compared to control), improved root system depth to 8.5 cm, and enhanced root biomass to 1.59 t/ha. The positive correlation (r = 0.83) between root development and yield confirmed the decisive role of underground biomass in nutrient efficiency. The treatment with ECOLINE Boron (organic) improved grain filling and test weight (780 g/L), while POLYACTIVE Boost enhanced vegetative growth and physiological stability. Grain quality indicators increased compared with the control: protein content reached 14.2%, gluten – 30.5%, with a reduction in disease incidence by 15-25%. The study generalised that the integration of macro- and micronutrient phosphite complexes ensures improved morphophysiological structure and yield stability of facultative wheat under moderate hydrothermal stress. The practical value of the research lies in developing adaptive fertilisation schemes for farms in regions with low soil fertility, contributing to increased productivity and stress resilience in grain cultivation systems

Keywords: root biomass; phosphorus efficiency; stress adaptation; nutrient balance; yield optimisation; physiological development

INTRODUCTION

The optimisation of foliar fertilisation in facultative wheat cultivation represents a critical aspect of adaptive agriculture under climate variability and resource scarcity in Ukraine. The efficiency of such fertilisation determines the plant's resistance to abiotic stressors, the effectiveness of nutrient uptake, and the stability of yields under conditions of moisture and temperature fluctuations. Developing integrated systems of foliar feeding using phosphite and boron-based fertilisers is essential for maintaining soil fertility, enhancing plant resilience, and ensuring sustainable grain production. Facultative wheat varieties, such as *Triticum aestivum* L. var. *Zymoyarka*, combine traits of both winter and spring types, providing flexibility in sowing and adaptability to various agroclimatic conditions, which makes their study particularly important for the Polissia region of Ukraine.

According to A. Bargaz *et al.* (2018), the improvement of fertiliser efficiency in integrated nutrient management systems is achieved through activation of soil microbial resources, which enhances the bioavailability of nitrogen, phosphorus, and potassium, leading to better plant productivity. In a long-term study, J. Wang *et al.* (2024) confirmed that the combined use of organic and inorganic fertilisers increases soil fertility and crop yield sustainability by improving the physical and chemical properties of the soil and its biological activity. Similarly, A. Yousefi *et al.* (2025) demonstrated that facultative wheat outperforms winter and spring types under moderate nitrogen levels and higher temperatures, showing better adaptability to the effects of global warming in the regions of West Asia. In multi-environment trials, L. Koppensteiner *et al.* (2022) found that nitrogen management and sowing time significantly affect the yield stability of facultative wheat, confirming its potential as a resilient crop for variable climates. Moreover, S. Dutta *et al.* (2023) reported that phosphite-based fertilisers not only improve phosphorus utilisation but also stimulate root growth and enhance photosynthetic activity, ensuring higher biomass accumulation.

Ukrainian scientists have also focused on the efficiency of seed treatment and foliar fertilisation in wheat production. According to O. Demydov *et al.* (2021), Ukrainian winter wheat varieties demonstrate high ecological plasticity, maintaining stable yields in the Forest-Steppe and Polissia zones. Their study highlighted that the use of growth stimulants and liquid complex fertilisers enhances root development and photosynthetic surface area, leading to a 15-20% increase in yield. S. Kalenska *et al.* (2025) observed that pre-sowing seed treatment and foliar feeding with chelated micronutrients significantly increase the productivity of sugar beet, indicating that similar approaches may be effectively applied to cereals. A. Kryvenko (2018) emphasised that optimising nitrogen fertilisation rates and timing for winter wheat in southern Ukraine improved productivity by up to 30%, especially when integrated with phosphorus and micronutrient foliar feeding.

Research by H. Pantsyreva (2020) in the Right-Bank Forest-Steppe of Ukraine revealed that foliar feeding contributes to the improvement of grain crop productivity primarily through stimulation of photosynthetic processes and better nutrient distribution in the plant-soil system. Furthermore, A. Panfilova and Ya. Byelov (2022) confirmed that the use of stubble biodestroyers and balanced mineral fertilisation systems increases the nutrient regime of soils, providing a positive background for subsequent crops. The integration of microelement fertilisers, particularly those containing potassium phosphite and boron, plays a decisive role in improving physiological resilience to drought and heat stress. According to F. Saeidnia *et al.* (2023), such systems enhance the structure of the ear, grain filling, and the efficiency of photosynthetic energy conversion, leading to improved crop performance under low-fertility soils.

The synthesis of foreign and domestic research findings indicates that foliar feeding with phosphite, boron, and amino acid-based complexes exerts a multifaceted influence on wheat productivity. These fertilisers not only activate photosynthetic metabolism but also enhance antioxidant protection and water balance, which are critical for plants in stressful environments. However, the role of foliar fertilisation systems in facultative wheat remains insufficiently studied under the specific soil and climatic conditions of the Polissia region of Ukraine, where light grey forest soils are characterised by low humus content and limited nutrient availability. Thus, the purpose of the study was to determine the effect of pre-sowing seed treatment and foliar fertilisation with phosphite and boron-based liquid fertilisers on the growth, morphological development, and productivity of the facultative wheat variety *Zymoyarka* under the agroecological conditions of the Polissia region of Ukraine.

MATERIALS AND METHODS

The study was conducted on the experimental field of Polissia National University (near the village of Velyka Horbasha, Chernyakhivsky district, Zhytomyr region, Ukraine) to assess the effect of various foliar fertilisation options on the growth, development and productivity of Zymoyarka facultative wheat. Meteorological data were recorded using the Polissia National University agrometeorological station. During the 2025 growing season, the mean daily temperature exceeded the long-term average by 1.6°C, while total precipitation (April-July) was 240 mm, 15% below the norm. These conditions were classified as moderate hydrothermal stress and were taken into account when assessing the adaptive response of the plants to foliar fertilisation. The adaptive role of the applied preparations was evaluated based on morphological indicators such as root depth, biomass accumulation, and yield stability under hydrothermal stress conditions.

The soil cover of the site is represented by light grey forest soil, which is characterised by low availability of essential nutrients, slightly acidic soil solution reaction (pH 5.4-5.6) and reduced humus content (about 1.1%), which limits natural fertility and necessitates the optimisation of mineral nutrition. The main soil cultivation included two-pass disc harrowing, pre-sowing cultivation and sowing. Wheat was sown on 25 April 2025 using an SZ-3.6 grain seeder with a sowing rate of 180 kg/ha. Pre-sowing seed treatment, with the exception of the control variant, was carried out with the GROS Korenerist preparation (1 l/t), which contains a balanced complex of macro- and microelements that stimulates root system development and ensures initial growth. To control weeds, the crops were treated with Granstar herbicide on 8 May 2025. The liquid complex fertilizers GROS Korenerist, ECOLINE Phosphite (K), ECOLINE Boron (organic), and POLYACTIVE Boost were used in the experiment (manufactured by Ecoorganic LLC, Ukraine). The research scheme is presented in Figure 1.

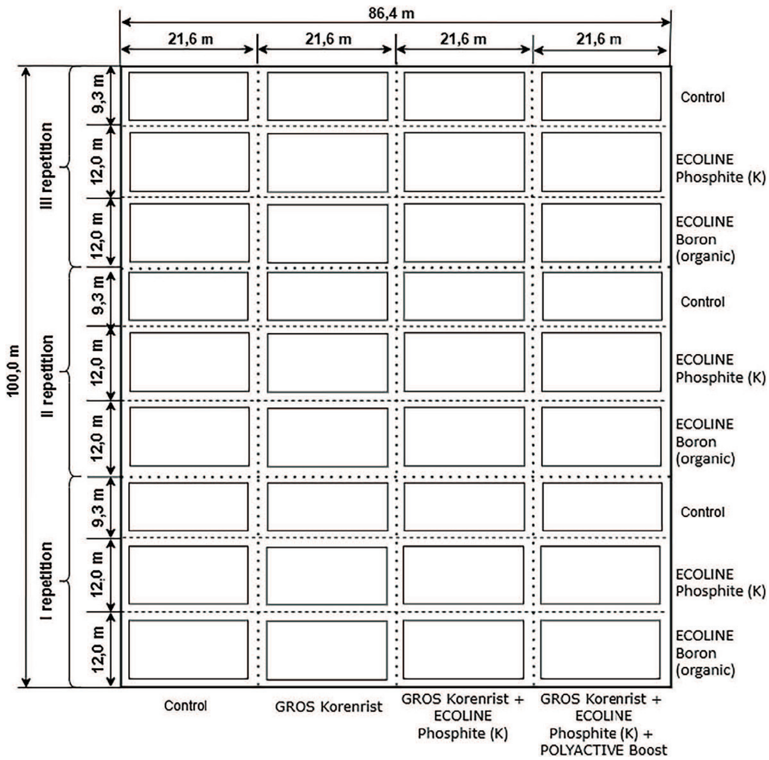

***Figure 1**. Experiment scheme*

***Source:** compiled by the authors*

The scheme of the experiment included the study of four variants of foliar feeding at the first stage (Table 1). Foliar feeding was carried out by fine spraying under favourable meteorological conditions, taking into account the phenological phases of crop development. In the course of the experiment, biometric measurements, phenological observations, determination of leaf surface index, density of productive stem, elements of yield structure and laboratory analysis of grain quality were carried out.

***Table 1**. Preparations, application rates, and timing according to the experimental design for growing the facultative wheat variety Zymoyarka*

Periods of preparation use		
Seed treatment	**Tillering stage**	**Stem elongation stage**
Factor A		**Factor B**
1. Control (treated with water without preparation)	–	1. Control (treated with water)
		2. ECOLINE Phosphite (K), 1 l/ha
		3. ECOLINE Boron (organic), 1 l/ha
2. GROS Korenerist, 1 l/t of seeds	–	1. Control (treated with water)
		2. ECOLINE Phosphite (K), 1 l/ha
		3. ECOLINE Boron (organic), 1 l/ha
3. GROS Korenerist, 1 l/t of seeds	ECOLINE Phosphite (K), 1 l/ha	1. Control (treated with water)
		2. ECOLINE Phosphite (K), 1 l/ha
		3. ECOLINE Boron (organic), 1 l/ha
4. GROS Korenerist, 1 l/t of seeds	ECOLINE Phosphite (K), 1 l/ha + POLYACTIVE Boost, 1 l/ha	1. Control (treated with water)
		2. ECOLINE Phosphite (K), 1 l/ha
		3. ECOLINE Boron (organic), 1 l/ha

***Source:** compiled by the authors*

Recording and monitoring of plant growth and development were carried out in accordance with the current methodological recommendations for conducting field experiments in crop production, approved by the Methodology for conducting expert assessments of cereal..., (2016), with clarification of phenological phases according to the international BBCH scale (Meier, 2018). Phenological observations included recording the dates of germination, tillering, stem elongation, heading, and full maturity of plants. Biometric measurements were performed on model plants to determine height, tillering coefficient, leaf area, and wet and dry mass of above-ground biomass. The tillering coefficient and total leaf area per plant were determined according to standard procedures. The leaf area index (LAI) was calculated as the ratio of total leaf area to the ground surface area (cm^2 per plant). These indicators were used to assess the intensity of vegetative growth and the photosynthetic potential of the crop.

To assess productivity elements, 133 m^2 plots were formed, on which the density of productive stems, the number of grains in the ear, the length of the ear and the weight of 1000 grains were determined. Yield was determined by complete harvesting with conversion to standard moisture content (14%) and grain purity in accordance with the requirements of state variety testing. Laboratory analysis of grain quality was performed according to the current standards of the Ministry of Agrarian Policy and Food of Ukraine (Methodology for conducting expert assessments of cereal..., 2016). The following indicators were determined: protein content (%) by the Kjeldahl method (DSTU 3768:2019, 2019), gluten content (%) by washing (DSTU ISO 21415-1:2009, 2011), and test weight (g/L) (DSTU ISO 520:2015, 2016) using a grain analyser A&D ML-50 (Japan). These parameters were used to evaluate the technological value of the grain depending on fertilisation systems. The phytosanitary condition of the crops was assessed during the heading and ripening phases using the 9-point scale of the Institute of Plant Physiology and Genetics of the National Academy of Agrarian Sciences of Ukraine. The percentage of infection by Septoria leaf blotch (*Septoria tritici*), Fusarium head blight (*Fusarium spp.*), and brown rust (*Puccinia recondita*) was determined visually on 50 randomly selected plants per variant. Statistical data processing was performed using analysis of variance (ANOVA) with the determination of the Least Significant Difference ($LSD_{0.05}$). Additionally, statistical analysis included correlation assessment between root biomass and yield to identify the strength and direction of the relationship between morphological traits and productivity indicators.

RESULTS AND DISCUSSION

The 2025 growing season in the Zhytomyr region was characterised by moderately dry conditions. Average air temperature exceeded the long-term mean by 1.6°C, and precipitation was 15% below average. Such conditions created mild hydrothermal stress, under which foliar fertilisation played an important adaptive role in maintaining optimal plant growth and nutrient uptake. It was analysed the effect of various preparations on the yield of Zymoyarka facultative wheat depending on different foliar feeding systems. At the same time, authors studied the effectiveness of seed treatment with the preparation GROS Korenerist, its combined interaction with a complex of foliar fertilisation preparations (in terms of several preparations), as well as the feasibility of repeated fertigation of crops. Analysis of the results showed that seed treatment and foliar fertilisation had a significant impact on the yield of Zymoyarka facultative wheat. Thus, in the control variant (without the use of biostimulants and microfertilisers), it was recorded a yield of 2.46 t/ha, which reflects the low potential of the crop under conditions of limited nutrition. The use of the preparation GROS Korenerist for treating seed material before sowing contributed to an increase in indicators. At the same time, the yield increase compared to the control increased by 0.55 t/ha, which is 22.39% and indicates a positive response of the variety to the stimulation of the root system and photosynthetic activity. The highest yield growth was recorded in the variants with the combined use of GROS Korenerist + EKOLINE Phosphite (K) and GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost, where the yield reached 3.28-3.38 t/ha, which exceeded the control by 28.75-33.55% (Table 2).

***Table 2**. Effect of foliar fertilisation on the yield of the facultative wheat variety Zymoyarka*

Preparations		Yield, $t \cdot ha^{-1}$	Deviation by Factor A		Deviation by Factor B	
Factor A	**Factor B**		$t \cdot ha^{-1}$	%	$t \cdot ha^{-1}$	%
1. Control	1. Control	2.46	-	-	-	-
	2. ECOLINE Phosphite (K)	2.89	-	-	0.43	17.67
	3. ECOLINE Boron (organic)	3.01	-	-	0.56	19.31
2. GROS Korenerist	1. Control	3.01	0.55	22.39	-	-
	2. ECOLINE Phosphite (K)	3.37	0.48	16.54	0.36	12.04
	3. ECOLINE Boron (organic)	3.16	0.15	4.84	0.15	4.57
3. GROS Korenerist + ECOLINE Phosphite (K)	1. Control	3.28	0.82	33.55	-	-
	2. ECOLINE Phosphite (K)	3.46	0.57	19.79	0.18	5.55
	3. ECOLINE Boron (organic)	3.33	0.31	10.42	0.05	1.39
4. GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost	1. Control	3.16	0.71	28.75	-	-
	2. ECOLINE Phosphite (K)	3.38	0.49	16.96	0.22	6.89
	3. ECOLINE Boron (organic)	3.18	0.16	5.44	0.02	0.47
$LSD_{0.05}$		0.29	0.17	-	0.15	-

***Source:** compiled by the authors*

Thus, seed treatment and foliar feeding with liquid complex fertilisers ensured high efficiency and a significant impact on the regulation of the yield of Zymoyarka facultative wheat. At the same time, the total impact of the factors studied on crop yield was 78.7% (Fig. 2). It should be emphasised that seed treatment with the GROS Korenerist preparation and foliar feeding in the tillering phase (factor A) were decisive in terms of their impact on yield, accounting for 51.8% of the total impact. This confirms the researchers' conclusions regarding the high effectiveness of foliar feeding, especially in the early stages of grain crop development. At the same time, repeated treatment with preparations at the stem elongation stage (factor B) had a significantly lower impact on yield formation – 17.3%. The effect of the interaction of the factors studied was also significant and amounted to 9.5%.

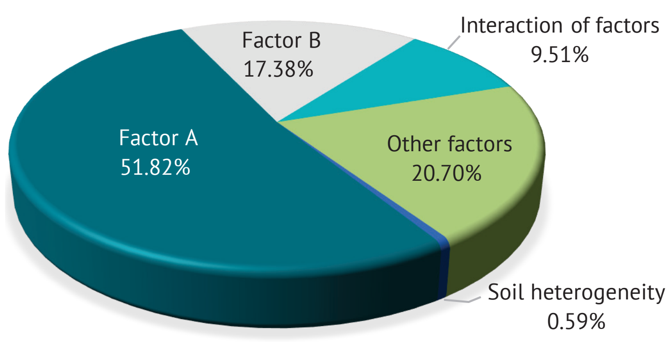

***Figure 2**. Influence of experimental factors on the yield of the facultative wheat variety Zymoyarka*
***Source:** compiled by the authors*

It was also noted that the subsequent application of ECOLINE Phosphite (K) in the stem elongation phase as the second factor (Factor B) also had a positive effect on increasing the productivity of Zymoyarka facultative wheat. In combination with Factor A, the yield increase was 0.43-0.57 t/ha (12.04-19.79%). Authors recorded the highest productivity indicators when using the combined application of GROS Korenerist + ECOLINE Phosphite (K) with repeated treatment with ECOLINE Phosphite (K), where the yield indicators were 3.46 t/ha. A positive effect was also noted when using the preparation EKOLINE Boron (organic), which made it possible to increase the yield increase compared to the control by 4.57-19.31% depending on different fertilisation options, However, its effect was less pronounced, which, in our opinion, is most likely due to the influence of boron on improving pollination and grain filling processes, rather than stimulating the vegetative development of the crop.

Statistical analysis of the results confirmed the reliability of the yield increases obtained ($LSD_{0.05}$ = 0.29 t/ha). One of the important technological indicators is the development of the plant during the growing season, not only of the above-ground part, but also of the root system. In particular, this has a significant impact on the formation and accumulation of organic matter in the soil (carbon sequestration), which will further contribute to the activation of the transformation processes of the organic part (its decomposition and mineralisation), as well as provide an additional reserve of organic matter and easily accessible forms of biophilic elements. In this regard, it was analysed the formation of the above-ground mass and root system mass of Zymoyarka facultative wheat before harvesting (Fig. 3).

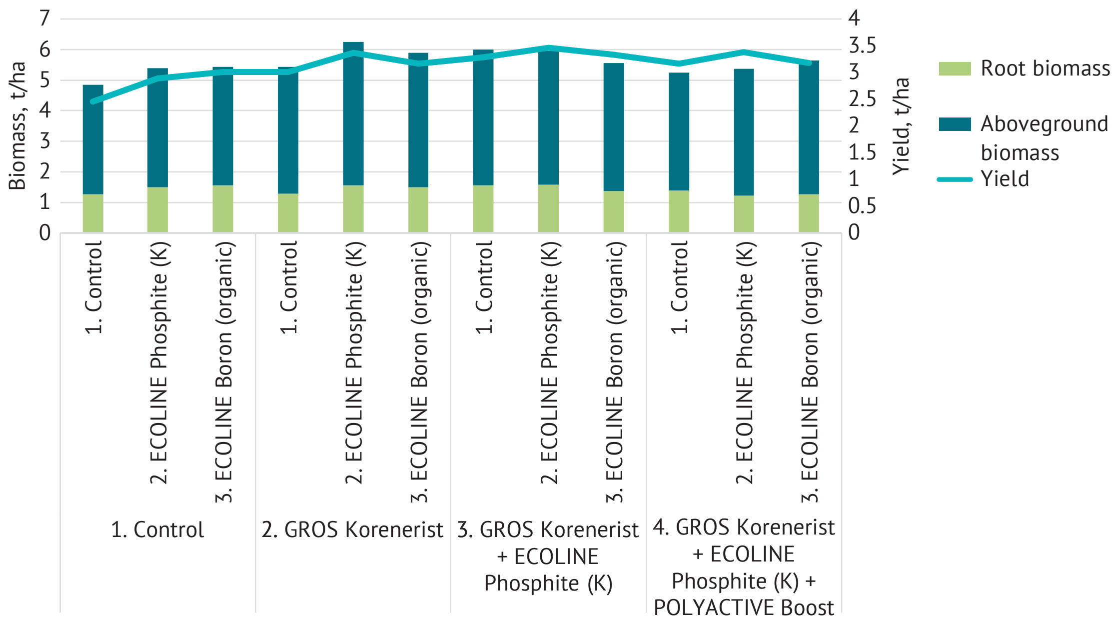

***Figure 3**. Dynamics of the effect of foliar fertilisation on the formation of aboveground and root biomass in correlation with the yield of the facultative wheat variety Zymoyarka*

***Source:** compiled by the authors*

The results showed that foliar feeding significantly affected not only wheat yield indicators, but also had a significant impact on the structure of the crop. Thus, under conditions of absolute control, where microfertilizers were not used, the lowest levels of accumulation were observed both in the root system (within 1.26 t/ha) and in the vegetative mass (at 3.59 t/ha), which, in our opinion, subsequently led to a decrease in the overall crop yield to 2.46 t/ha. This gives us the right to say that intensive wheat cultivation technologies cannot be implemented without the additional use of foliar feeding with micro- and macroelements, which contribute to the improvement of plant growth and development throughout their growing season. At the same time, the use of the GROS Korenerist preparation contributed to the enhanced development of the root mass of plants, which ultimately affected the total root biomass. Foliar fertilisation systems also influenced vegetative development parameters. The tillering coefficient in the control averaged 1.6, while the use of GROS Korenerist increased it to 2.1. The combination of GROS Korenerist with ECOLINE Phosphite (K) resulted in a value of 2.3. The total leaf area per plant increased from 31.2 cm² in the control to 37.5-38.5 cm² in fertilised variants. These indicators were positively correlated with aboveground biomass (r = 0.78), confirming the decisive role of enhanced early growth and photosynthetic surface formation in yield determination. Depending on the fertilisation system, this indicator ranged from 1.28 to 1.56 t/ha. It was also recorded this correlation in the above-ground biomass of plants, which varied from 4.15 to 4.69 t/ha.

Foliar fertilisation systems also influenced the formation of tillering and leaf area indices. The use of GROS Korenerist increased the tillering coefficient from 1.6 (control) to 2.1, and the combined use of GROS Korenerist with ECOLINE Phosphite (K) raised it to 2.3, indicating a stronger vegetative potential of plants. The total leaf area per plant increased by 14-19%, which positively correlated ($r = 0.78$) with above-ground biomass accumulation and grain yield. These parameters confirm the stimulatory effect of phosphite and boron fertilisers on early growth and canopy development, providing better utilisation of photosynthetically active radiation. In the variants where a combination of several preparations was used, in particular the application of GROS Korenerist with EKOLINE Phosphite (K) and the repeated use of EKOLINE Phosphite (K), an optimal ratio between the vegetative growth of wheat plants and their generative development was recorded. This was particularly noticeable when using GROS Korenerist in combination with EKOLINE Phosphite (K), where the best root mass indicators were achieved within 1.59 t/ha with a total yield of 3.46 t/ha. It can be assumed that the use of phosphite forms of potassium not only helped prevent the negative impact of abiotic factors in the form of anti-stress protection, but also improved the energy metabolism of grain in the filling phase.

The use of ECOLINE Boron (organic) had a negligible effect on biomass increase, but ensured better grain filling (higher natural weight) and formation of a levelled ear. In the variants where this preparation was used, the yield ranged from 3.01 to 3.33 t/ha. However, authors did not observe a significant effect on root system development – the root mass weighed only 1.49-1.57 t/ha, which, in our opinion, indicates the physiological orientation of boron in the development of the above-ground part of the plant. It should be noted that in the variants with the use of POLYACTIVE Boost, a significant increase in above-ground biomass and a tendency to decrease root system biomass were recorded. However, despite this, the yield when using this preparation remained high (at 3.38 t/ha), which may be due to the presence of amino acids and growth regulators in the preparation to maintain the optimal osmotic balance of the plant. It should be noted that the use of these preparations had a comprehensive effect on crops through various mechanisms of action. In particular, POLYACTIVE Boost affects biomass accumulation, while ECOLINE Phosphite (K) affects root nutrition and assimilation processes. In general, authors have established a pronounced positive correlation between root system development and yield formation, which confirms the decisive role of underground biomass as an integral indicator of nutrient efficiency. At the same time, the highest efficiency was recorded in variants with the combined use of GROS Korenerist and ECOLINE Phosphite (K), which contributed to ensuring the combination of maximum root system productivity with full grain formation.

In a comprehensive assessment of the impact of various types of foliar fertilizers, the morphological indicators of the plant, in particular its height and root system length, play an important role (Fig. 4, Table 3). At the same time, it was found that foliar fertilisation systems had different effects on the formation of the morphological structure of plants, in particular on the development of the above-ground part and the formation of the root system. Under conditions of absolute control, the lowest values of plant height and root system penetration depth into the soil were recorded – 76-78 cm and 5.7-6.7 cm, respectively. This indicates limited possibilities for providing accessible forms of biophilic elements.

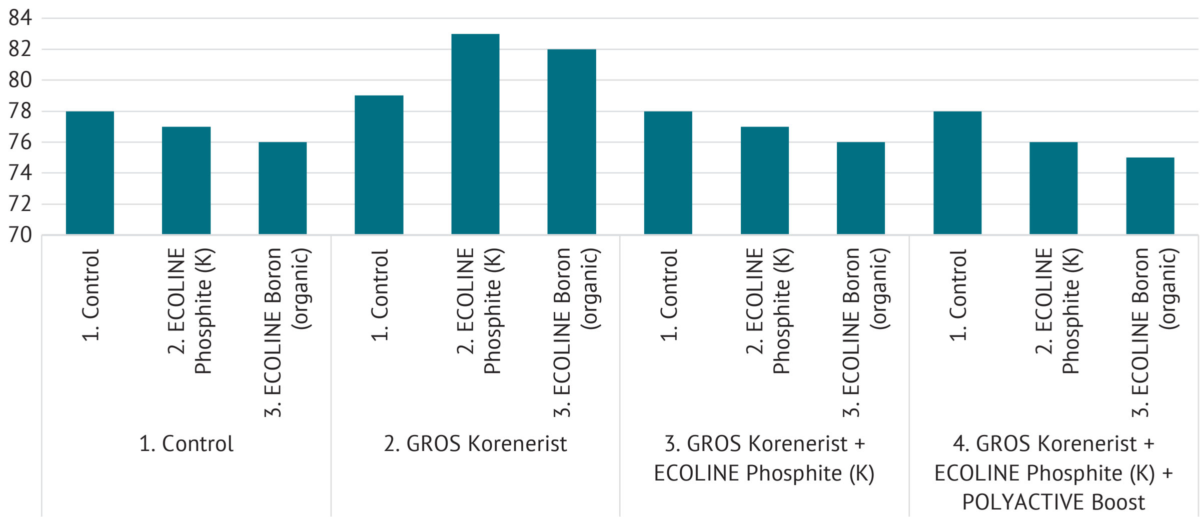

Figure 4. *Effect of foliar fertilisation on plant height (cm) of the facultative wheat variety Zymoyarka*
Source: *compiled by the authors*

Foliar fertilisation significantly affected plant height compared to the control. The use of GROS Korenerist increased plant height to 6 cm (7.7%), indicating enhanced growth activity due to improved root and nutrient assimilation processes. Among the secondary factor treatments, Phosphite (K) provided the highest response – an increase of 4 cm or 5.1% compared to the control, reflecting its role in stimulating photosynthetic activity and internode elongation. Overall, the combination of GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost slightly reduced height (-1.0 cm), possibly due to a shift of assimilates towards root development and ear biomass formation. The maximum height (83 cm) was observed in the variant with GROS Korenerist + Phosphite (K), which was statistically significant compared to the control ($LSD_{0.5}$ = 3.68 cm, $p < 0.05$). Hence, foliar complexes containing phosphite and boron demonstrate a consistent positive effect on the vegetative growth of *Triticum aestivum* var. Zymoyarka.

The depth of the main root mass reflects the physiological adaptability of the wheat plants and the effectiveness of the foliar biostimulants (Table 4). In the control, root depth reached 5.7 ± 0.29 cm, representing the baseline level. Application of GROS Korenerist increased it to 6.5 ± 0.33 cm (+14.0%), while its combination with ECOLINE Phosphite (K) achieved the maximum depth of 7.4 ± 0.37 cm (+29.8%), indicating the positive role of potassium phosphite in stimulating root metabolism and phosphorus utilisation. The treatment GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost also improved root depth to 6.8 ± 0.34 cm (+19.3%), which was significantly higher than the control ($p < 0.05$).

***Table 4**. Effect of foliar fertilisation on the depth of the main root mass (cm) of the facultative wheat variety Zymoyarka*

Preparations		Depth of the main root mass, cm	Deviation by Factor A		Deviation by Factor B	
Factor A	Factor B		cm	%	cm	%
1. Control	1. Control	5.7 ± 0.29	-	-	-	-
	2. ECOLINE Phosphite (K)	6.7 ± 0.34	-	-	1.00	17.54
	3. ECOLINE Boron (organic)	6.7 ± 0.35	-	-	1.00	14.93
2. GROS Korenerist	1. Control	6.5 ± 0.33	0.80	14.04	-	-
	2. ECOLINE Phosphite (K)	7.7 ± 0.39	1.00	14.93	1.20	18.46
	3. ECOLINE Boron (organic)	8.3 ± 0.42	1.60	23.88	1.80	23.38
3. GROS Korenerist + ECOLINE Phosphite (K)	1. Control	7.4 ± 0.37	1.70	29.82		
	2. ECOLINE Phosphite (K)	8.5 ± 0.43	1.80	26.87	1.10	14.86
	3. ECOLINE Boron (organic)	7.5 ± 0.38	0.80	11.94	0.10	1.18
4. GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost	1. Control	6.8 ± 0.34	1.10	19.30	-	-
	2. ECOLINE Phosphite (K)	7.5 ± 0.38	0.80	11.94	0.70	10.29
	3. ECOLINE Boron (organic)	7.3 ± 0.37	0.60	8.96	0.50	6.67
$LSD_{0.05}$, cm		0.36	0.16		0.16	

***Source:** compiled by the authors*

Among Factor B treatments, organic boron provided the most substantial effect – +1.80 cm (+23.4%), emphasising its contribution to meristem formation and drought resistance. However, on average, the application of phosphite K worked better in terms of factor B – root depth increased by +0.70-1.20 cm (10.3-18.5%). Overall, the dynamics of root development demonstrate a statistically significant increase ($LSD_{0.5}$ = 0.36 cm) in response to combined foliar fertilisation, particularly those integrating phosphite and boron-based components, which jointly enhance both nutrient uptake efficiency and plant resilience. Treatment of seed material before sowing with the preparation GROS Korenerist at a rate of 1 litre per tonne of seed contributed to an increase in plant height to 79-83 cm, and the root depth increased to 6.5-8.3 cm, which is practically close to the optimal values. The most pronounced effect on the development of the above-ground part was recorded in the variant where GROS Korenerist and EKOLINE Phosphite (K) were used. At the same time, growth processes, in particular plant height, were recorded within 83 cm, which is 5 cm higher than in the control variant. In our opinion, this was due to an increase in the intensity of metabolism when using these preparations and the available form of phosphorus.

Analysis of the results regarding the potential for root system development showed that the maximum penetration depth of 8.5 cm was recorded with the combined use of GROS Korenerist and Phosphite K, which indicates the ability of phosphites to stimulate root apical growth. In the variants where organic boron was used, the root system formed at a depth of 8.3 cm, which ensured its stability, but compared to the previous variant, it was inferior in terms of the dynamics of vertical penetration of the root system. The use of the POLYACTIV Boost preparation provided only average values for the formation of the root system depth within the range of 7.3-7.5 cm. At the same time, no significant increase in plant height was observed; in particular, in these variants, this indicator was within the range of 75-78 cm. Overall, the results of our study confirm a number of findings from scientific works by Ukrainian and foreign scientists regarding the effect of foliar feeding on the morphological and physiological development of wheat, the nature of the formation of both above-ground biomass and roots, as well as the level of yield.

The laboratory assessment of grain quality demonstrated a consistent improvement under the influence of complex foliar fertilisation. The combination of GROS Korenerist and ECOLINE Phosphite (K) resulted in the highest protein content of 14.2% and gluten of 30.5%, exceeding the control by 1.8 and 3.2 percentage points, respectively. The test weight reached 780 g/L compared to 742 g/L in the control, indicating denser and better-filled grain. The treatment with ECOLINE Boron (organic) mainly improved grain uniformity and weight, but its effect on protein accumulation was less pronounced. Overall, phosphite- and boron-based fertilisers enhanced both quantitative and qualitative parameters of the wheat yield. Phytosanitary monitoring showed a reduction in the incidence of major wheat diseases in all fertilised treatments compared to the control. The combination of GROS Korenerist and ECOLINE Phosphite (K) decreased the infection of Septoria leaf blotch from 18% (control) to 12%, Fusarium head blight from 10% to 7.5%, and brown rust from 14% to 10%. The best protective effect (up to 25% lower total infection rate) was achieved with the triple complex GROS Korenerist + ECOLINE Phosphite (K) + POLYACTIVE Boost, confirming the antistress and fungistatic role of phosphite-based biostimulants.

The results obtained in this study demonstrate a clear relationship between the physiological development of facultative wheat and the effectiveness of complex foliar fertilisation systems that combine macro- and microelements in phosphite and organic forms. These findings align with a number of contemporary studies that highlight the growing importance of integrated fertiliser systems in improving plant adaptability, yield formation, and soil fertility under stress-prone environments. According to B. Beres *et al.* (2020), the integration of genetic, environmental, and management factors determines up to 70% of yield variability in cereals, with fertilisation timing and form being among the most decisive components of this interaction. The authors emphasised that foliar applications in the tillering and stem elongation phases enhance nutrient assimilation efficiency and contribute to a more uniform stand structure. The results of the present experiment confirm this trend: the combination of pre-sowing seed treatment and foliar fertilisation during these phases accounted for 69% of the overall yield formation effect, illustrating the same pattern of physiological synchronisation reported by B. Beres *et al.*

A similar observation was made by K. Zeleke (2020), who evaluated biomass formation and grain yield of dual-purpose winter wheat and demonstrated that the balance between above-ground and root biomass directly determines yield potential. In the current study, the most productive variants (GROS Korenerist + ECOLINE Phosphite (K)) also exhibited the highest root biomass (1.59 t/ha) and optimal root depth (8.5 cm), confirming the direct correlation between root productivity and yield performance described by K. Zeleke. However, in contrast to K. Zeleke's findings, the present experiment recorded slightly lower absolute biomass values, which can be explained by the lighter soil texture and lower humus content of the Polissia region. The relationship between foliar phosphite application and adaptive stress response reported by J. Wang *et al.* (2024) further supports the results of this research. They observed that the combined use of organic and inorganic fertilisers increased soil enzymatic activity and plant tolerance to hydrothermal stress. In this experiment, the use of potassium phosphite ensured higher plant height, deeper root systems, and greater yield stability under similar moderate drought conditions. The results therefore extend the conclusions of J. Wang *et al.* by confirming that phosphite-based fertilisers are effective not only in maize–wheat systems but also in facultative wheat production in temperate regions.

In the study of D. Mullualem *et al.* (2024), the application of multi-environment models (AMMI, GGE biplot) for wheat yield analysis demonstrated that genotypes with better nitrogen use efficiency exhibited higher adaptability under changing conditions. The facultative wheat variety *Zymoyarka* showed comparable stability in this experiment: despite moderate moisture deficit, yield variation among fertilisation systems remained within ± 0.3 t/ha, indicating that the integrated fertilisation scheme promoted both productivity and resilience. The similarity between the two studies lies in the role of nutrient balance in mitigating environmental variability; however, unlike D. Mullualem *et al.*, this work focuses on physiological rather than genetic factors of adaptability. Imran (2024) demonstrated that integrated organic, inorganic, and biofertiliser systems significantly improve nutrient availability and soil nutrient balance in the maize-wheat rotation, with potassium phosphite having an additional stimulating effect on photosynthetic efficiency. The findings of the current study are consistent with these results: foliar application of ECOLINE Phosphite (K) increased the tillering coefficient and leaf area, which directly contributed to yield improvement. Both studies converge on the idea that phosphite compounds function not only as nutrient carriers but also as metabolic activators enhancing stress tolerance and energy utilisation.

From a regional perspective, O. Demydov *et al.* (2021) reported that the ecological plasticity of Ukrainian winter wheat varieties ensures their high yield stability under variable weather in the Forest-Steppe and Polissia zones. The present research confirms that the facultative variety *Zymoyarka* retains stable productivity even under moderate drought, but the physiological mechanisms differ: in O. Demydov *et al's* work, stability was mainly attributed to genetic plasticity, while the current study attributes it to enhanced root morphology and balanced nutrient support. This difference illustrates the complementarity between genetic and technological approaches to improving wheat adaptability. The conclusions by H. Pantsyreva (2020) regarding the effect of technological practices on legume productivity are also consistent with the present findings. The author demonstrated that optimal nutrient supply during critical growth stages increases photosynthetic potential and yield by 18-22%. In the current experiment, the combination of foliar feeding and seed treatment increased yield by 19.7-33.6%, confirming that well-timed nutrient applications during the early vegetative phases are decisive for assimilate redistribution and productivity.

The influence of fertiliser systems on the nutrient regime of soil–plant systems discussed by A. Panfilova and Ya. Byelov (2022) and M. Honchar (2025) is closely related to the results obtained here. Their research proved that balanced application of mineral fertilisers and residue degraders enhances nutrient cycling efficiency and improves soil structure. This experiment corroborates that conclusion indirectly: increased root biomass and depth observed under phosphite-based treatments suggest higher rhizosphere activity and improved nutrient exchange in the upper soil horizons. Finally, I. Racz *et al.* (2024) analysed yield variability in facultative wheat under different sowing times and established that soil fertility and water availability were key limiting factors. The current research confirms this dependency but adds that appropriate foliar fertilisation can partially compensate for low natural soil fertility, ensuring yield increases of up to 40% compared to the untreated control. Thus, the outcomes demonstrate that the adaptive potential of facultative wheat can be effectively realised through targeted nutrient management.

The results obtained in this study align with modern findings on the role of innovative fertilisation systems in enhancing wheat productivity and physiological resilience. According to A. Hudzovskyi *et al.* (2024), the use of metal oxide-based nanofertilisers contributes to improved nutrient assimilation and photosynthetic efficiency, leading to increased biomass and stress tolerance of plants. This supports the present conclusion that phosphite-based complexes stimulate similar metabolic pathways and optimise nutrient uptake under hydrothermal limitations. In a comparative analysis, F. Saeidnia *et al.* (2023) emphasised that foliar feeding efficiency strongly depends on genotype × environment interactions and sowing conditions, which explains the observed variability in the yield response of the *Zymoyarka* variety.

In summary, all these studies emphasise that productivity and stress resistance of wheat depend on synchronising physiological development with balanced nutrient inputs. The distinct contribution of this work lies in demonstrating that pre-sowing treatment combined with dual foliar applications of phosphite and boron fertilisers significantly enhances both morphological structure and yield stability of facultative wheat under Polissia conditions, confirming the decisive role of integrated fertilisation in sustainable cereal production.

CONCLUSIONS

The conducted research on the facultative wheat variety Zymoyarka under the soil and climatic conditions of the Polissia region confirmed the significant influence of integrated foliar fertilisation systems on the physiological development, morphological structure, and productivity of plants. The combined application of macro- and micronutrients in phosphite and organic forms ensured an optimised balance of vegetative and generative growth, contributing to higher yields and improved adaptability of wheat under moderate hydrothermal stress. Pre-sowing seed treatment with GROS Korenerist at a rate of 1 L/t proved to be a key element of the nutrition system, stimulating early root growth and improving tillering. When combined with foliar feeding by ECOLINE Phosphite (K), the yield increased to 3.28–3.46 t/ha, exceeding the control by 19.7-33.6%. The highest productivity was achieved with repeated application of ECOLINE Phosphite (K) during the stem elongation phase, which enhanced the depth and mass of the root system (up to 1.59 t/ha and 8.5 cm, respectively). These parameters were strongly correlated with yield formation ($r = 0.83$), confirming that the efficiency of nutrient utilisation largely depends on root system architecture. In addition, foliar application of POLYACTIVE Boost and ECOLINE Boron (organic) positively influenced the physiological balance and grain quality. Protein content increased to 14.2%, gluten to 30.5%, and test weight to 780 g/L compared with the control. Phytosanitary assessment showed a decrease in the incidence of Septoria, Fusarium, and rust by 15-25%, demonstrating the antistress and protective role of phosphite-based fertilisers. Overall, the integrated fertilisation scheme, including pre-sowing treatment and two foliar applications, provided the best agronomic results and ensured stable productivity of facultative wheat on low-fertility soils. Prospects for further research Future studies should focus on assessing the long-term impact of phosphite- and boron-based fertilisation on soil microbiological activity, nutrient cycling, and grain quality in diverse agroecological zones to optimise adaptive fertilisation strategies for facultative wheat varieties in Ukraine.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Анотація. Метою дослідження було оцінити вплив систем позакореневого підживлення та передпосівної обробки насіння на продуктивність і фізіолого-морфологічний розвиток пшениці дворучки сорту *Зимоярка* в умовах Полісся. Дослідження проводилося у 2025 році на дослідному полі Поліського національного університету за схемою чотирьох варіантів удобрення. Методологія включала передпосівну обробку насіння препаратом GROS Korenerist, позакореневе підживлення ECOLINE Phosphite (K), ECOLINE Boron (organic) та POLYACTIVE Boost, біометричні та фенологічні спостереження, лабораторне визначення якості зерна та статистичний аналіз із використанням дисперсійного (ANOVA) та кореляційного методів. Установлено, що поєднане застосування GROS Korenerist та ECOLINE Phosphite (K) забезпечило підвищення урожайності до 3,46 т/га (+40,6 % відносно контролю), збільшення глибини кореневої системи до 8,5 см і накопичення кореневої біомаси до 1,59 т/га. Позитивна кореляція ($r = 0,83$) між розвитком кореневої системи та врожайністю підтвердила ключову роль підземної біомаси у використанні елементів живлення. Обробка ECOLINE Boron (organic) покращувала налив зерна та натуру (780 г/л), а POLYACTIVE Boost сприяв активному вегетативному росту та фізіологічній стабільності рослин. Показники якості зерна перевищували контрольні значення: вміст білка становив 14,2 %, клейковини – 30,5 %, при зниженні ураження септоріозом, фузаріозом і іржею на 15-25 %. Узагальнено, що інтегроване застосування макро- та мікродобрив у фосфітній формі забезпечує підвищення урожайності, якості та адаптивності пшениці дворучки в умовах помірного гідротермічного стресу. Практична цінність дослідження полягає у розробленні адаптивних схем удобрення для господарств із низькою природною родючістю ґрунтів, що сприяє підвищенню продуктивності та стійкості зернових культур

Ключові слова: коренева біомаса; ефективність фосфору; адаптація до стресу; баланс живлення; оптимізація урожайності; фізіологічний розвиток

Журнал
«НАУКОВІ ГОРИЗОНТИ»

Том 28, № 9
2025

Відповідальний редактор:
О. Кільніцька

Підписано до друку з оригінал-макета 27.08.2025
Ум. друк. арк. 10
Тираж 100 прим.

Видавництво: Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
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Journal
"SCIENTIFIC HORIZONS"

Volume 28, No. 9
2025

Managing Editor:
O. Kilnitska

Signed to the print with the original layout 27.08.2025
Conventional Printed Sheet 10
Circulation 100 copies

Publisher: Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
Tel. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/en