

НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

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Biogenic pollution of the Unava River waterbody

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Abstract. Biogenic pollution of Ukraine's waterbodies is a systemic issue requiring continuous monitoring due to its impact on water quality and its role in driving anthropogenic eutrophication. This study aimed to assess the Unava River waterbody to determine the level of biogenic pollution and identify the predominant contamination type (nitrogen- or phosphorus-based). The findings indicate that the concentration of biogenic substances in the Unava River affects water quality, depending on its intended use and the functioning of the aquatic biota (aquatic ecosystem). Specifically, nitrite nitrogen concentrations (0.006-0.306 mgN/dm³ in 2022; 0.006-0.051 mgN/dm³ in 2024) are critical for the aquatic ecosystem. Ammonium nitrogen levels impact recreational and domestic uses (1.21-1.83 mgNH₄⁺/dm³ in 2022; 1.16-5.88 mgNH₄⁺/dm³ in 2024) as well as drinking water supply and the aquatic ecosystem as a whole (0.814-6.84 mgN/dm³ in 2022; 0.3644.56 mgN/dm³ in 2024). Phosphorus concentrations also influence the aquatic ecosystem (0.062-0.196 mgP/dm³ in 2022; 0.333-0.597 mgP/dm³ in 2024). Calculations of the degree of correlation between the variables revealed a negative (inverse) correlation between air temperature and phosphate levels ($r = -0.07$), nitrate nitrogen ($r = -0.69$), and nitrite nitrogen ($r = -0.10$). Conversely, a positive correlation was observed between water temperature and mineral nitrogen ($r_{NH_4^+} = 0.38$; $r_{NO_3^-} = 0.79$; $r_{NO_2^-} = 0.46$) as well as phosphorus ($r_{PO_4^{3-}} = 0.52$). Calculations based on the *Redfield Ratio* (RR) demonstrated that in 2022 (RR = 29.42-108.64), mineral phosphorus ions were the limiting biogenic substance, while mineral nitrogen ions were in excess, leading to predominant nitrogen pollution, potentially promoting the growth of green algae. In 2024

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($RR = 6.32-18.71$), mineral nitrogen ions became the limiting factor, whereas phosphorus ions were in excess under these conditions, resulting in predominant phosphorus pollution, which could facilitate the proliferation of cyanobacteria

Keywords: nutrients; eutrophication; water quality; nitrogen; phosphorus; Redfield Ratio

Introduction

According to research by L.V. Voitenko (2019), the primary substances contributing to biogenic pollution are phosphorus compounds (phosphate ions) and mineral nitrogen (ammonium ions, nitrate ions, and nitrite ions). In line with the Resolution of the Cabinet of Ministers of Ukraine No. 1134-r (2022), leading up to 2050, nitrogen and phosphorus compounds, along with other pollutants, are recognised as key components of both point-source and diffuse pollution in surface waters. Research conducted by V. Strokal *et al.* (2023) indicated that in Ukraine, phosphorus pollution is largely attributed (up to 80%) to point sources. These include the discharge of untreated or inadequately treated wastewater from municipal and industrial facilities, as well as the presence of cesspits in private households lacking centralised water supply and sewage systems. Conversely, diffuse sources, particularly agricultural activities, account for up to 80% of nitrogen pollution in surface waters. These activities involve the introduction of nitrogen compounds into waterbodies through water and wind erosion due to the ploughing of riparian zones, the presence of cultivated agricultural fields near waterbodies, uncontrolled storage of organic fertilisers on farms, and the application of organic and mineral fertilisers for plant nutrition. All of the aforementioned pollution sources have a detrimental effect on the quality of aquatic ecosystems. This, in turn, leads to biogenic pollution of waterbodies and, potentially, to accelerated eutrophication processes. Therefore, it is essential to monitor the quality of surface waterbodies to identify key pollution indicators and minimise their impact on aquatic ecosystems.

Researchers V.S. Kapsalis & I.K. Kalavrouziotis (2021) have highlighted that eutrophication,

driven by high concentrations of nutrients in water, is a global issue that must be addressed in all strategies for conserving river ecosystems. M. Devlin & J. Brodie (2023) investigated the input of biogenic substances into river waterbodies. Their research identified nitrogen and phosphorus compounds as the main biogenic substances entering surface waters through both diffuse (river discharges with fertiliser losses from fields, terrestrial runoff) and point sources (wastewater treatment plant discharges). The researchers emphasised in their studies that these substances have a destructive impact on the entire aquatic ecosystem.

The research of I. Micella *et al.* (2024) asserts that agriculture and urbanisation are the two primary sources of nutrients (nitrogen, phosphorus), chemical, macro- and microplastic pollution in natural waters. The authors noted that biogenic substances (nutrients) from agricultural activities frequently enter rivers through runoff from fertilised fields and via wastewater from treatment plants.

This study aimed to assess the Unava River waterbody to determine the level of biogenic pollution and to establish the ratio of phosphates to nitrates, thereby identifying the limiting nutrient and predicting the dominant type of pollution.

To achieve this aim, the study pursued the following objectives:

- evaluate the water quality of the Unava River to determine the level of biogenic pollution based on phosphate ion concentrations and mineral nitrogen levels (ammonium ions, nitrate ions, and nitrite ions);
- establish the correlation between changes in meteorological parameters (air and water temperature at the time of water sampling) and biogenic substance concentrations;

► determine the limiting biogenic substance using the *Redfield Ratio* (RR) for the Unava River ecosystem and, based on the obtained data, substantiate anthropogenic eutrophication of the Unava River waterbody.

The scientific novelty of the results lies in the fact that this is the first comparative assessment of the Unava River waterbody's quality at the point of established biogenic pollution. This includes the identification of the limiting biogenic substance using the stoichiometric *Redfield Ratio*.

Materials and Methods

Ecological investigations were conducted during 2022 and 2024. Water samples from the Unava River waterbody were collected in September 2022 and early November 2024. Water sampling was carried out following DSTU ISO 5667-6:2009 (2009). Each observation point included three water sampling locations. Sampling began at the river's mouth (1st observation point) and concluded at the point where the Unava River flows into the Irpin River (10th observation point). In total, there were 10 observation points, three of which encompassed reservoirs on the Unava River (Table 1, Fig. 1).

The Unava River aquatic ecosystem is a transformed hydro-ecosystem, altered by intensive agricultural development and urbanisation. The Unava River is located within the Kyiv and Zhytomyr regions of Ukraine. Approximately 80% of its riparian zone consists of arable land and private garden plots. Three reservoirs are situated along the Unava River (Popilnia pond farm), serving recreational needs and sport fishing. One reservoir is located within the city of Fastiv (Kyiv Region) and is used for domestic water supply, sport fishing, and recreation. Additionally, grain elevators and livestock stables are present in the riparian zones. The river is notably marshy, with shrubs and diverse vegetation along its banks (Ministry of Environmental..., 2021).

The assessment of the Unava River's water quality, to determine the level of biogenic pollution based on phosphate ion concentrations and mineral nitrogen levels (ammonium ions, nitrate ions, and nitrite ions), was conducted by comparing the actual biogenic substance concentrations from 2022 and 2024 with the regulatory (optimal) values for these indicators across different water use categories (Tables 2-3).

Table 1. Characteristics of observation points on the Unava River waterbody

Point	Location
1	Horodyshche Village, Andrushivska District, Zhytomyr Region River mouth
2	Velyki Lisivtsi Village, Popilnia District, Zhytomyr Region
3	Kvitneve Village, Popilnia District, Zhytomyr Region (Unava River reservoir)
4	Yerchyky Village, Zhytomyr District, Zhytomyr Region (Unava River reservoir)
5	Koshliaky Village, Popilnia District, Zhytomyr Region
6	Pivni Village, Fastiv District, Kyiv Region
7	Volytsia Village, Fastiv District, Kyiv Region
8	Fastiv City, Kyiv Region Fastiv Reservoir on the Unava River
9	Between Mala Ofirna and Velyka Ofirna villages
10	Vasylkiv District, Kyiv Region. Towards the Pereviz Village, between Chornohorodka and Dzvinkove villages Unava River flows into the Irpin River

Source: compiled by the authors based on the conducted research

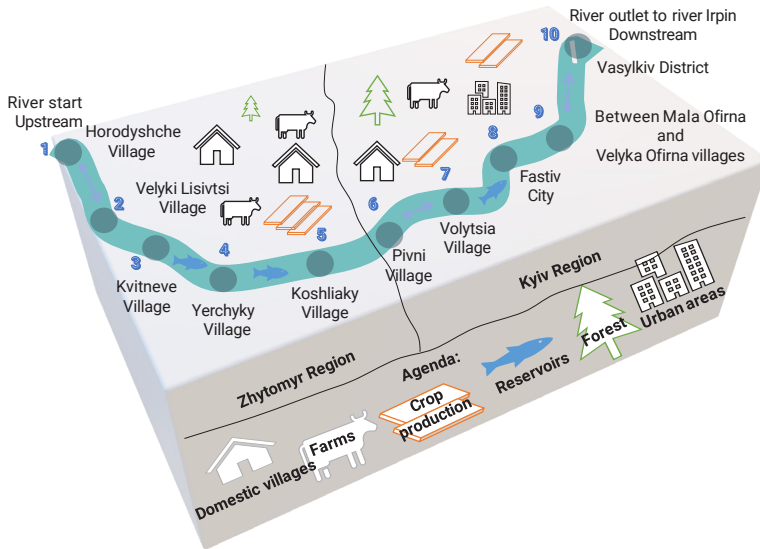


Figure 1. Projection of observation and water sampling points, including key anthropogenic sources impacting the Unava River aquatic ecosystem

Source: compiled by the authors based on the conducted research

Table 2. Regulatory (optimal) values of key biogenic substances for potable and recreational water use, as well as for fishery waterbodies

Water quality indicator		Regulatory (optimal) values for water use from rivers													
		For waterbodies used for potable (centralised/decentralised supply), domestic, recreational, and other public needs													
		SOU	Ministry of Health of Ukraine dated 02 May 2022 No. 721		SOU 05.01-37-385:2006		DSTU 7525:2014		DSTU 4808:2007						
Unit	Category – carp	Unit	The first category (drinking)		Unit	For drinking water (tap water)	Unit	Centralised water supply	Decentralised water supply	Centralised water supply Water quality classes					
	Unit		3.5	3.5						Unit	1 – excellent	2 – good	3 – satisfactory	4 – moderate, LP	
Phosphates – PO_4^{3-}	mgP/dm^3	≤ 0.5	$mgPO_4^{3-}/dm^3$	3.5	3.5	$mgrPO_4^{3-}/dm^3$	≤ 3.5	$mgPO_4^{3-}/dm^3$	≤ 3.5	*	mgP/dm^3	< 0.3	0.3-0.5	0.6-1.0	> 1.0
Ammonium nitrogen – NH_4^+	mgN/dm^3	≤ 1.0	$mgNH_4^+/dm^3$	2.0	2.0	$mgNH_4^+/dm^3$	0.5-2.6	$mgNH_4^+/dm^3$	0.5-2.6	*	mgN/dm^3	*	0.05-0.50	0.51-2.00	> 2.00
Nitrate nitrogen – NO_3^-	mgN/dm^3	≤ 2.0	$mgNO_3^-/dm^3$	45.0	45.0	$mgNO_3^-/dm^3$	≤ 50.0	$mgNO_3^-/dm^3$	≤ 50.0	≤ 5.0	mgN/dm^3	< 5.0	5.0-7.0	7.1-10.0	> 10.0
Nitrite nitrogen – NO_2^-	mgN/dm^3	≤ 0.1	$mgNO_2^-/dm^3$	3.3	3.3	$mgNO_2^-/dm^3$	≤ 0.5	$mgNO_2^-/dm^3$	≤ 0.5	≤ 0.02	mgN/dm^3	< 0.05	0.05-0.50	0.51-1.00	> 1.00

Note: First category – centralised and decentralised potable water supply; Second category – water used for domestic needs, health resorts, recreation, and sports; LP (Limitedly potable) – water of limited suitability for use; * – indicates that the parameter should be absent in water; **FWB – fishery water body

Source: developed by the authors based on regulatory data SOU 05.01-37-385:2006 (2006), DSTU 4808:2007 (2007), Order of the Ministry of Health of Ukraine No. 400 (2010), DSTU 7525:2014 (2014), Order of the Ministry of Health of Ukraine No. 721 (2022)

Table 3. Regulatory (optimal) values for key biogenic substances for waterbody assessment (surface waters)

Methodology for ecological assessment of surface water quality by relevant categories, Approved by the Ministry of Environmental Protection No. 44 order dated 31 January

Water quality indicator	Ecological classification of surface water quality									
	Unit	Quality class	I		II		III		IV	V
		Quality category	1	2	3	4	5	6	7	
Phosphates – PO ₄ ³⁻	mgP/dm ³	<0.015	0.015-0.030	0.031-0.05	0.051-0.10	0.101-0.20	0.201-0.300	>0.30		
Ammonium nitrogen – NH ₄ ⁺	mgN/dm ³	≤0.1	0.10-0.20	0.21-0.30	0.31-0.50	0.51-1.00	1.01-2.50	>2.50		
Nitrate nitrogen – NO ₃ ⁻	mgN/dm ³	<0.20	0.20-0.30	0.31-0.50	0.51-0.70	0.71-1.00	1.00-2.50	>2.50		
Nitrite nitrogen – NO ₂ ⁻	mgN/dm ³	<0.002	0.0020.005	0.0060.01	0.011-0.02	0.021-0.05	0.051-0.10	>0.10		
		Quality class	Excellent	Very good	Good	Satisfactory	Moderate	Poor	Very poor	
			Very clean	Clean	Fairly clean	Slightly polluted	Moderately polluted	Dirty	Highly polluted	
Characteristics of water quality classes and categories Quality category General information			The waterbody is xeno- or oligosaprobic. A diverse range of organisms inhabit the water, but their numbers are low (e.g., <i>Vorticella</i> , <i>Daphnia longispina</i> , diatom alga <i>Synedra</i>). Eutrophication processes are practically absent		The waterbody is mesosaprobic. Contains numerous planktonic organisms that mineralise organic matter. Green and diatom algae may develop.		The waterbody is polysaprobic. Inhabited by numerous colourless flagellates, fungi (<i>Sewage fungus</i>), certain ciliates, saprobacteria, filamentous bacteria (<i>Sphaerotilus</i>), and others. Eutrophication processes are intensified and highly active.			

Source: developed by the authors based on the established methodology by V.D. Romanenko *et al.* (1998), V.P. Strokal & A.V. Kurovska (2024)

Given the presence of reservoirs on the Unava River, the optimal water quality values for fishing (fishery water bodies) and recreation (cultural-domestic and recreational needs) were considered. Furthermore, the city of Fastiv, located on the Unava River, relies on a reservoir within its boundaries for its water supply. Therefore, regulatory water quality values for potable and domestic needs were also taken into account. Historically, the Unava River waterbody was used for crop irrigation. During field sampling trips, irrigation channels were observed, now completely overgrown with shrubs and various vegetation. Due to active agricultural practices and the ploughing of riparian zones, the Unava River has become a low-flow river with sections containing minimal water. Consequently, optimal water quality values for irrigation were not included in this study. For fishery water bodies, the regulatory (optimal) values for the carp family were applied, as they are prevalent in the Unava River reservoirs.

The correlation between meteorological variables (air and water temperature at the time of water sampling) and biogenic substance concentrations was established by calculating the linear correlation coefficient (r). The degree of correlation can range from -1 to +1. A positive (direct) correlation indicates that high values of one variable correspond to high values of another; a negative (inverse) correlation indicates that high values of one variable correspond to low values of another. The general classification indicates that a correlation is strong (or close) when $r \geq 0.7$; moderate when $0.5 \leq r \leq 0.7$; moderate when $0.3 \leq r \leq 0.5$; weak when $0.2 \leq r \leq 0.3$; and very weak when $r < 0.2$ (Strokal & Kurovska, 2024).

The limiting biogenic substance was determined using the stoichiometric *Redfield Ratio* (*RR*) for the Unava River ecosystem, based on the analysed data from the first objective. The *Redfield Ratio* (*RR*) allowed for tracking the balance of nitrates and phosphates in the river's surface

waters (Rudenko & Dzenzerska, 2015; Bedunkova & Kaletnik, 2017). It also indicated the degree of limitation of phytoplankton production processes (Voitenko, 2019) and the excess or deficiency of nitrogen or phosphorus in the waterbody (Bedunkova & Kaletnik, 2017). Given that visible eutrophication processes were observed in the studied river during field trips, the application of the Redfield Ratio (RR) is particularly relevant. It allowed for the determination of the limiting factor influencing anthropogenic eutrophication in the Unava River waterbody. It is important to note that mineral forms of nitrogen (ammonium ions – NH_4^+ , nitrate ions – NO_3^- , nitrite ions – NO_2^-) and phosphorus in the water were used for the RR calculation.

The stoichiometric Redfield Ratio (RR) was determined using the following formula (Voitenko, 2019):

$$RR_{ot}(N/P) = 1.53 * ((1.35 * [NO_2^-] + [NO_3^-] + 3.44 * [NH_4^+]) / [PO_4^{3-}]), \quad (1)$$

where the ion concentrations are expressed in $\mu\text{g}/\text{dm}^3$. If $RR_{ot}(N/P) > 16$, the limitation of phytoplankton primary production can be attributed to mineral phosphorus (meaning that mineral phosphorus ions are the limiting biogenic substance, and mineral nitrogen ions are in excess, indicating a dominance of nitrogen pollution in the waterbody). Conversely, if $RR_{ot}(N/P) < 16$, the limitation is attributed to nitrogen (meaning that mineral nitrogen ions are the limiting biogenic substance, phosphorus ions are in excess, and consequently, phosphorus pollution is the dominant factor).

Results

The hydrological regime of the river is deteriorating annually due to anthropogenic impacts, which have led to the transport of erosion products (along with biogenic substances – nutrients) into the waterbody. This is compounded by the effects of climate change, resulting in river shallowing, and the impact of war, which has

introduced higher concentrations of toxic substances into the waterbody.

The assessment of the Unava River waterbody's quality for recreational and domestic water supply needs was conducted by considering the concentration of water quality indicators (biogenic substances) in mgPO/dm^3 , mgNO/dm^3 , or mgNH/dm^3 . For other uses and types of water consumption, such as fisheries and potable water, as well as for assessing the aquatic ecosystem itself, the comparison of water quality indicator concentrations (biogenic substances) with optimal values was performed in mgP/dm^3 or mgN/dm^3 . This is due to the units of measurement used in the regulatory standards (Tables 2-3).

It is crucial to understand the pathways through which biogenic (nutrient) substances enter waterbodies. Phosphorus and nitrogen ions can enter waterbodies via rainfall runoff through storm sewer systems and discharges of municipal and industrial wastewater (Tyagniy *et al.*, 2022). Generally, the concentration of pollutants in rainfall runoff depends on the time elapsed since the last rainfall. The longer the period without rain, the more dust, debris, and associated pollutants accumulate on streets and pavements, which are then washed into the river during rainfall (Stepova *et al.*, 2022). The biogenic salt content of nitrogen and phosphorus in rainwater is approximately 5-6 mg/dm^3 and 0.7-1.2 mg/dm^3 , respectively. Domestic wastewater contains about 50% of its nitrogen in the ammonium form, 30% as organic compounds, and 20% as nitrates and nitrites (Stepova *et al.*, 2022).

Based on analytical studies of phosphate ion concentrations in the Unava River water, it was determined that their concentration in 2022 was lower than that in the 2024 water samples (Figs. 2a, 2b). Water samples were collected during the autumn period in both years. It should be noted that, particularly in spring and autumn, silty deposits in waterbodies can release an average of 27 mg/m^2 of ammonium and 0.7 mg/m^2 of phosphorus per day (Pichura, 2021).

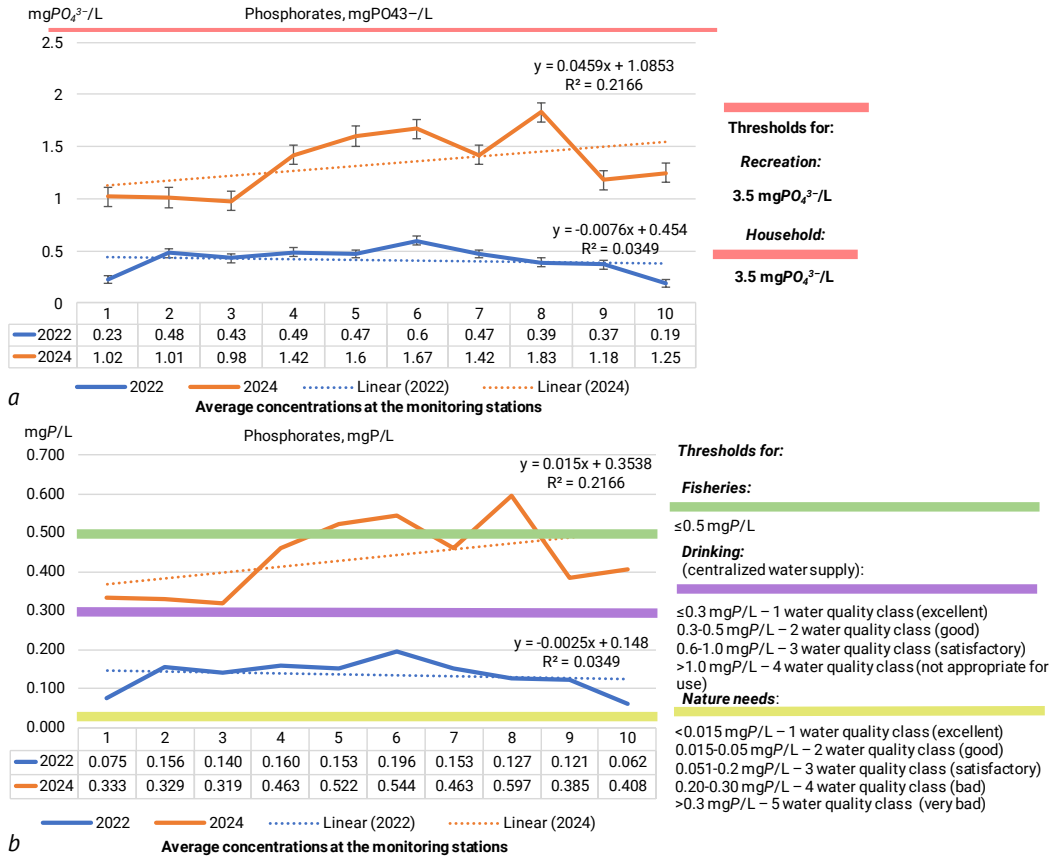


Figure 2. Weighted average concentrations of phosphate ions for 2022 and 2024

(n = 3 at each observation point) compared to the optimal PO₄³⁻ concentration values for use

Note: a – for recreational and domestic needs; b – for fishery needs, drinking needs, and the aquatic ecosystem

Source: developed by the authors based on their own analytical research results

Comparing the obtained phosphate ion concentrations in the Unava River water with optimal values for various uses reveals that, for recreational and domestic needs, the PO₄³⁻ concentration in the water was within the normal range in both 2022 and 2024 (Fig. 2a). However, for fisheries (Figure 2b), the PO₄³⁻ concentration in the water increased in 2024 by 15-35% (depending on the points), and consequently, in some observation points, the PO₄³⁻ concentration exceeds the optimal values (observation points No. 5-6, 8). When assessing the Unava River ecosystem as a whole, the PO₄³⁻ concentration at all observation points in 2022 and 2024 was outside the optimal range (the actual concentration ranged

from 0.075 to 0.597 mgP/dm³). This indicates that according to the methodology (Romanenko *et al.*, 1998), the aquatic ecosystem corresponds to quality class 3 (2022) – satisfactory quality, and quality classes 4-5 (2024) – poor and very poor water quality. For drinking water needs, all observation points in 2024 had phosphate ion concentrations exceeding the normal range, compared to the phosphate ion content in 2022 (Fig. 2b). This situation could be caused by various anthropogenic factors (point and diffuse sources) in the Unava River basin, including the input of biogenic substances by rainwater, along with the transport of these biogenic substances from ploughed agricultural areas (diffuse input)

located directly on the riverbank. Also, at observation point 8, an important factor is both storm runoff (diffuse input) and wastewater from municipal and domestic facilities in the Fastiv area

(point input).

The situation regarding nitrate ion concentrations in the studied water is less critical than that of phosphate ions (Fig. 3).

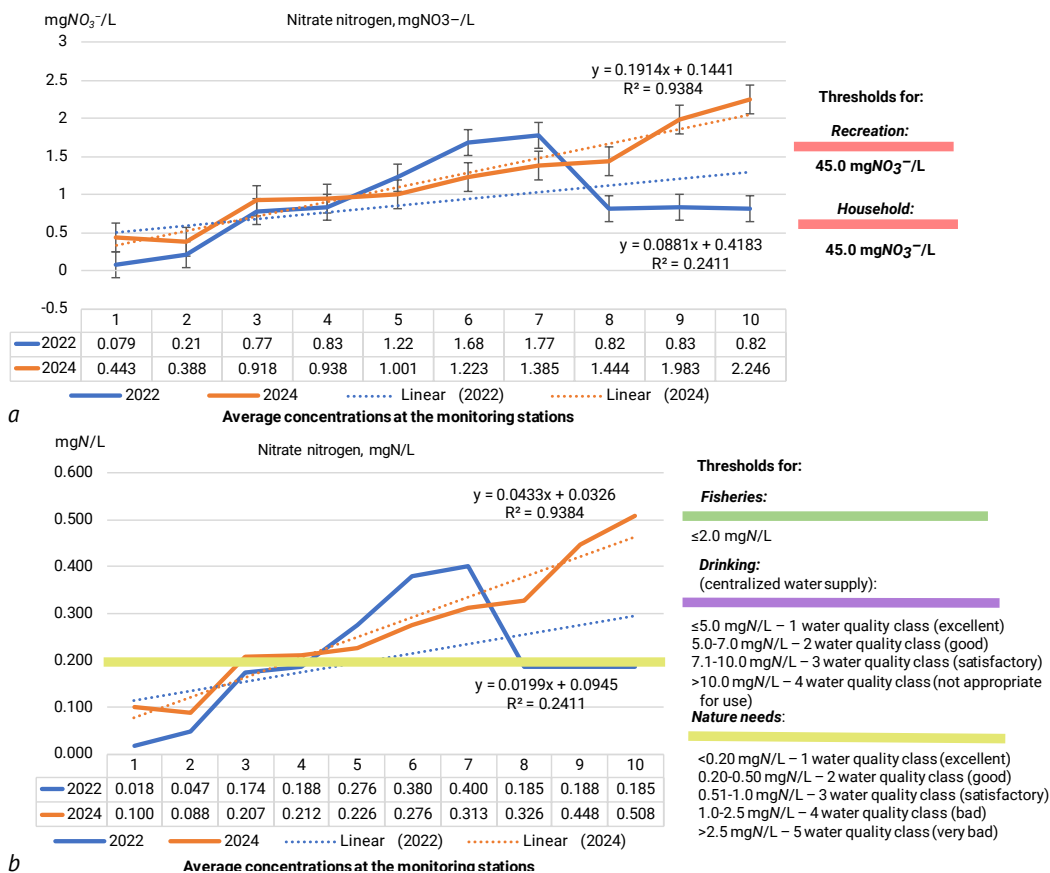


Figure 3. Weighted average concentrations of nitrate ions for 2022 and 2024

(*n* = 3 at each observation point) compared to the optimal NO₃⁻ concentration values for use

Note: a – for recreational and domestic needs; b – for fishery needs, drinking needs, and the aquatic ecosystem
Source: developed by the authors based on their own analytical research results

The Unava River exhibits optimal values for recreational (Fig. 3a), domestic, and drinking water needs (Fig. 3b), as well as for fishery water bodies (for the carp family, Fig. 3b), with actual water concentrations ranging from 0.018 to 0.4 mgN/dm³ in 2022 and 0.08 to 0.5 mgN/dm³ in 2024. When assessing the aquatic ecosystem according to the methodology (Romanenko *et al.*, 1998), observation points 3-7 (in 2022) and 3-10 (in 2024) show elevated nitrate ion concentrations in the

studied water. Accordingly, on average, the waterbody corresponds to quality class 2 (good) in 2022 and class 3 (satisfactory) in 2024. A trend of increasing nitrate ion concentrations in the Unava River is observed along the observation points. This indicates a correlation between the distance from the river's mouth (point 1), where nitrate ion concentrations are within optimal conditions for the entire aquatic ecosystem and various water use needs (observation points 1-3), and

an increase towards point 7 (Volysia Village) in 2022, and towards point 10 (confluence with the Irpin River) in 2024. This situation is indicative of active agricultural activity in the Unava River basin, particularly in the areas of these observation points. It is also worth noting that elevated nitrate ion concentrations indicate pollution that occurred in past years or seasons.

Elevated concentrations of nitrite and ammonium ions indicate nitrogen pollution caused by recent anthropogenic factors. Based on the analytical results, the actual concentration of nitrite ions (NO_2^-) in the studied water at the observation points (Fig. 4a) is within optimal ranges for recreational and domestic needs (0.01-1.01 $mgNO_2^-/dm^3$ with a standard of 3.3 $mgNO_2^-/dm^3$). For fisheries (Fig. 4b), the results are within optimal ranges

for 2024 (0.06-0.051 mgN/dm^3 with a standard of 0.1 mgN/dm^3) and within acceptable ranges for 2022 (0.001-0.306 with a standard of 0.1 mgN/dm^3). For drinking water needs (Fig. 4b), the water quality at the studied observation points corresponded to quality class 1 (2024) and quality class 2 (2022). The Unava River waterbody's quality, according to the methodology (Romanenko *et al.*, 1998), was also assessed as quality class 2-3 (2024) and quality class 4-5 (2022). A trend of decreasing actual nitrite ion (NO_2^-) concentrations is observed in 2024 compared to 2022 (by 25-40%). It is important to consider that these indicators may have been influenced by temperature conditions (which were lower in 2024 than in 2022 during water sampling) and the presence of precipitation.

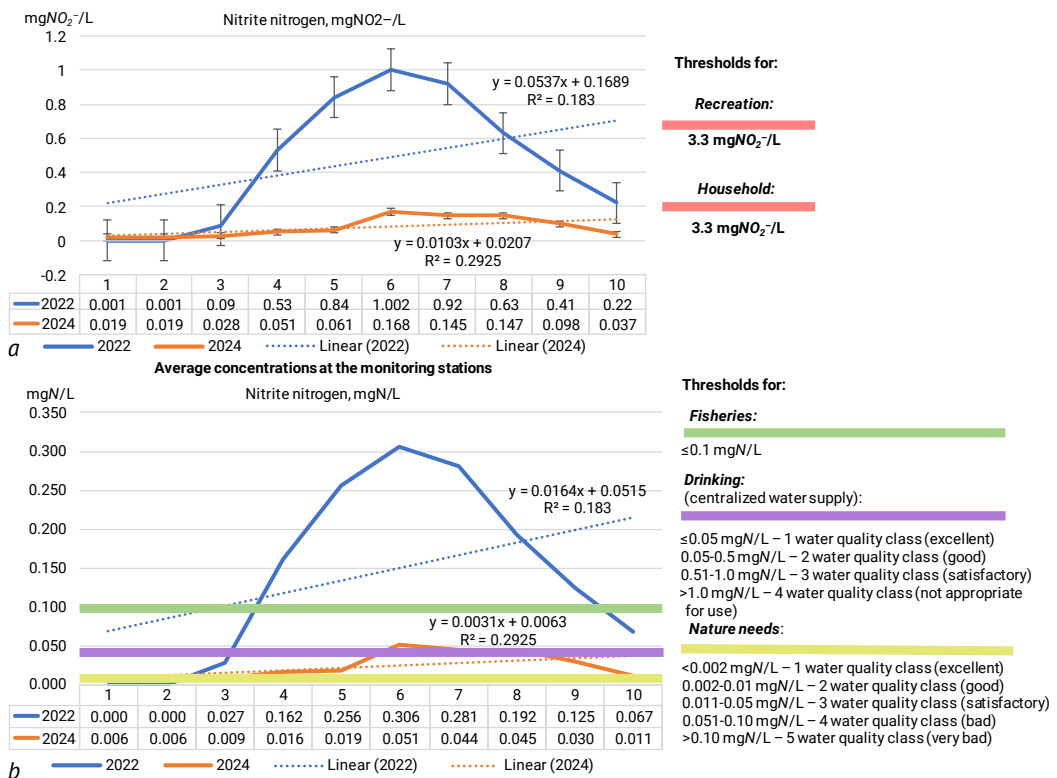


Figure 4. Weighted average concentrations of nitrite ions for 2022

and 2024 ($n=3$ at each observation point) compared to the optimal NO_2^- concentration values for use

Note: a – for recreational and domestic needs; b – for fishery needs, drinking needs, and the aquatic ecosystem

Source: developed by the authors based on their own analytical research results

The concentration of ammonium nitrogen (NH_4^+) (Fig. 5) in the water samples from 2022 and 2024 revealed the following situation:

➤ for recreational and domestic needs (Fig. 5a) – in 2024, the Unava River exhibited elevated ammonium nitrogen concentrations exceeding the standard at points 4-5 and 8-9 ($2.215.88 \text{ mgNH}_4^+/\text{dm}^3$ with a standard of $2.0 \text{ mgNH}_4^+/\text{dm}^3$). In 2022, exceedances were observed at points 28 ($2.06-8.83 \text{ mgNH}_4^+/\text{dm}^3$ with a standard of $2.0 \text{ mgNH}_4^+/\text{dm}^3$). The concentration of this indicator was lower in 2024 (25-30% lower) compared to the 2022 studies;

➤ for fishery water bodies (Fig. 5b) – The Unava River at all observation points (except point 1 – the river mouth) was characterised by elevated

ammonium nitrogen (NH_4^+) concentrations, indicating pollution at the time of water sampling and creating unfavourable conditions for aquaculture development;

➤ for drinking water needs (Fig. 5b) – The waterbody is of limited suitability for consumption, as the indicator concentration exceeds the first quality class. Specifically, in 2024, it ranged from 0.9 to $4.5 \text{ mgN}/\text{dm}^3$, and in 2022, from 0.9 to $6.8 \text{ mgN}/\text{dm}^3$, with a standard of $0.05 \text{ mgN}/\text{dm}^3$. Water with an NH_4^+ concentration $> 2.0 \text{ mgN}/\text{dm}^3$ is considered unsuitable;

➤ assessing the aquatic ecosystem based on this indicator (Fig. 5b), it can be characterised as belonging to quality classes 4-5 (poor and very poor) for both 2022 and 2024.

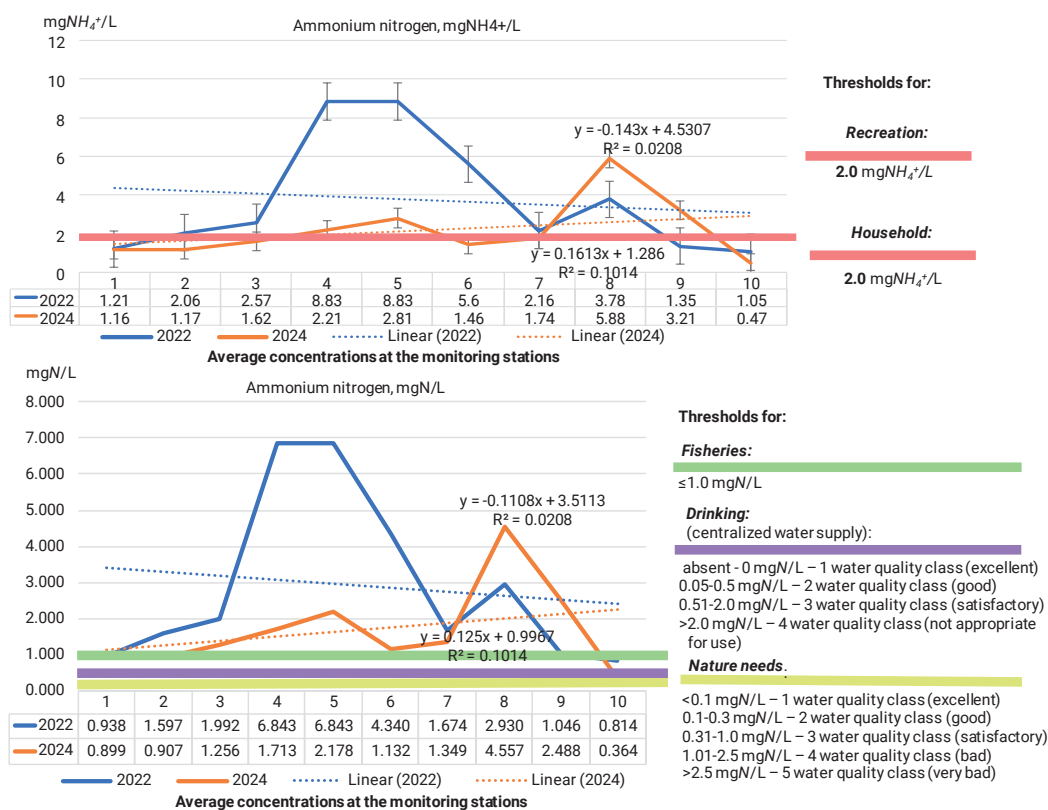


Figure 5. Weighted average ammonium nitrogen (NH_4^+) concentrations for 2022

and 2024 ($n=3$ at each observation point) compared to the optimal NH_4^+ concentration values for use

Note: a – for recreational and domestic needs; b – for fishery needs, drinking needs, and the aquatic ecosystem

Source: developed by the author based on their own analytical research results

Thus, based on the assessment of biogenic substance content in the waterbody, it can be concluded that nitrite ion and ammonium ion concentrations have the greatest impact on the aquatic ecosystem. These substances indicate pollution that occurred shortly before the water sampling period. Phosphorus loading, according to the research results, negatively affects the water quality of the Unava River, particularly for the aquatic ecosystem, while its concentration in the

studied water is optimal for recreational, domestic, and drinking needs.

During the 2024 research, a correlation between changes in meteorological parameters (water and air temperature measured at the time of water sampling at the observation points) and biogenic substances was established (Tables 4 and 5). This allowed for confirming the hypothesis that biogenic substance concentrations are significantly dependent on temperature conditions.

Table 4. Initial data for calculating the correlation dependency

Indicator/ Point	Concentration of biogenic substances in the studied water				t_{Air} , °C	t_{Water} , °C
	Phosphates, $mgPO_4^{3-}/dm^3$	Ammonium nitrogen, $mgNH_4^+/dm^3$	Nitrate nitrogen, $mgNO_3^-/dm^3$	Nitrite nitrogen, $mgNO_2^-/dm^3$		
1	1.02	1.16	0.443	0.019	6.0	11.4
2	1.01	1.17	0.388	0.019	6.0	10.4
3	0.98	1.62	0.918	0.028	7.0	10.8
4	1.42	2.21	0.938	0.051	6.0	10.9
5	1.6	2.81	1.001	0.061	6.0	11.6
6	1.67	1.46	1.223	0.168	6.0	12.1
7	1.42	1.74	1.385	0.145	6.0	12.0
8	1.83	5.88	1.444	0.147	6.0	13.9
9	1.18	3.21	1.983	0.098	5.0	12.2
10	1.25	0.47	2.246	0.037	5.0	14.0

Source: developed by the authors based on their own analytical research results

Table 5. Dependency of biogenic substances in the water on air and water temperature

Indicator	Coefficient of linear correlation r		Justification
	t_{Air} , °C	t_{Water} , °C	
Phosphates, $mgPO_4^{3-}/dm^3$	-0.07	0.52	Medium correlation with t_{Water} ; inverse correlation with t_{Air}
Ammonium nitrogen, $mgNH_4^+/dm^3$	0.01	0.38	Weak correlation with t_{Water} ; very weak correlation with t_{Air}
Nitrate nitrogen, $mgNO_3^-/dm^3$	-0.69	0.79	Strong correlation with t_{Water} ; inverse correlation with t_{Air}
Nitrite nitrogen, $mgNO_2^-/dm^3$	-0.10	0.46	Medium correlation with t_{Water} ; inverse correlation with t_{Air}

Source: developed by the authors based on their own analytical research results

The correlation between meteorological variables (air and water temperature at the time of water sampling) and biogenic substances was established by calculating the linear correlation coefficient (r). Calculations revealed a negative (inverse) correlation between air temperature and phosphate, nitrate nitrogen, and nitrite nitrogen

levels. Conversely, a positive correlation was found between water temperature and all biogenic indicators. The inverse (negative) correlation may be attributed to the intensification of various microbiological processes during temperature increases or decreases. The direct (positive) correlation with water temperature is justified because

elevated water temperatures stimulate microbiological processes within the waterbody, which can significantly influence nitrogen and phosphorus concentrations. This is particularly evident in the nitrate nitrogen indicator, which exhibits a strong correlation with water temperature (Table 5).

Based on the objectives outlined above, the stoichiometric Redfield Ratio (RR) for the Unava River ecosystem was calculated (Fig. 6) to determine the limiting factor, which demonstrates the dominant type of pollution (mineral phosphorus or mineral nitrogen).

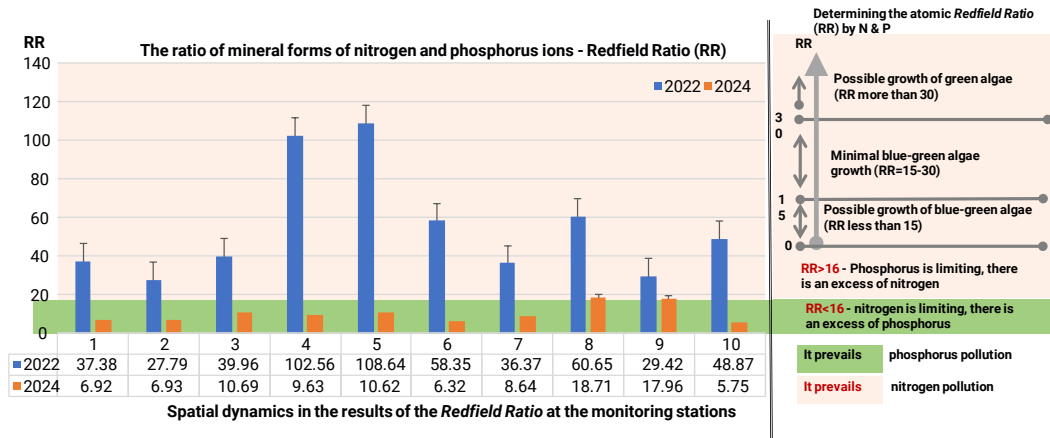


Figure 6. Calculation of the stoichiometric Redfield Ratio (RR) based on nitrogen and phosphorus ion forms in the Unava River, showing the changes across the 2022 and 2024 study period
Source: developed by the authors based on their own analytical research results

According to the calculated RR , the dominant type of pollution in 2022 was nitrogen. As the RR during this period ranged from 29.42 to 108.64, this indicated that mineral phosphorus ions were the limiting biogenic substance, while mineral nitrogen ions were in excess. This signifies that nitrogen pollution was dominant in the waterbody, potentially favouring the growth of green algae.

The 2024 results differ significantly. The RR during this period ranged from 6.92 to 18.71, indicating that mineral nitrogen was the limiting factor, and phosphorus ions were in excess. Consequently, this indicates a shift towards dominant phosphorus pollution in the water. Under these conditions, blue-green algae may proliferate in the waterbody. This is consistent with the previously described analysis of biogenic substances. In particular, based on the assessment of phosphate ions in the studied water, the waterbody was classified as quality class 3 (satisfactory) in 2022 and quality class 5 (very poor) in 2024. This

indicates a substantial increase in phosphate ion concentrations compared to 2022.

Therefore, anthropogenic eutrophication of the Unava River waterbody has been actively occurring and continues to do so. Biogenic substances play a significant role in intensifying these processes, as evidenced by the biogenic substance levels in the studied water for 2022 and 2024.

Overall, the Unava River is experiencing shallowing in most of its length and is overgrown with shrubs. There is a considerable amount of unauthorised waste along the riverbanks. Throughout the Unava River basin, there are ploughed agricultural lands, animal stables, and active fishing in the Unava River reservoirs. There is also significant siltation at the bottom of the Fastiv reservoir (observation point 8).

Discussion

It is important to note that this study focuses on biogenic pollution of the waterbody by nutrients,

specifically mineral compounds of nitrogen and phosphorus. The presence of these compounds in high concentrations leads to reduced oxygen saturation in the waterbody, the proliferation of bluegreen algae, for which these nutrients are a primary food source, and, as a final result in this chain, the intensification of anthropogenic eutrophication processes. Consequently, anthropogenic eutrophication of waterbodies deteriorates the ecological state of the waterbody itself, disrupts selfregulation and self-restoration processes within the aquatic ecosystem, leads to fish hypoxia, and worsens conditions for recreational needs.

The results of this study allow for the examination of biogenic pollution in surface waterbodies (rivers) by establishing the dominant type of pollution based on biogenic substances (nitrogen, phosphorus) using the stoichiometric Redfield Ratio. This is a key distinction from previous research by other authors. The use of this approach enables the prediction of pollution sources in waterbodies, both point and diffuse, and provides a basis for assessing the degree of their impact on the aquatic ecosystem. The significance of studying point and diffuse pollution sources in Ukrainian rivers is substantiated by the research of V.P. Strokal & A.V. Kurovska (2024). In their study, the authors elucidate the nature of nitrate pollution in the Dnipro River basin and demonstrate that nitrate pollution in rivers is closely linked to both diffuse and point pollution sources. The research of V.P. Strokal & A.V. Kurovska (2024) revealed that high concentrations of nitrogen compounds (nitrite, nitrate, and ammonium) in surface waters result from diffuse pollution. This type of pollution manifests through the introduction of nitrogen ions into waterbodies from ploughed agricultural fields (due to wind and water erosion, soil runoff enriched with nitrogen ions enters the waterbody) and ploughed riparian zones through the creation of additional arable land (leading to the direct input of nutrients from soils into waterbodies). A previous study by Strokal *et al.* (2023) confirms that phosphorus compounds, entering waterbodies

through wastewater discharges from municipal and industrial facilities, constitute a significant portion of point source pollution in surface waters (rivers). In this context, urbanisation acts as the main pollution driver. Therefore, the current study adopts the previously outlined pollution types and predicts their occurrence in rivers.

Numerous scientific studies underscore the importance of researching and assessing biogenic pollution in rivers. Scientists A.K. Tiwari & D.B. Pal (2022) have demonstrated that the primary drivers of eutrophication in river systems are high concentrations of biogenic substances (nutrients) in the water. Their research indicates that along with the discharge of untreated industrial, urban, and agricultural runoff into waterbodies, large amounts of carbon, nitrogen, phosphorus, and many other pollutants are introduced. They also state that eutrophication is a natural process that enhances the growth of aquatic plants, such as algae, which in turn use excessive amounts of inorganic nutrients like nitrogen and phosphorus for their growth. The authors emphasised that eutrophication resulting from increased algal growth in a waterbody can lead to the formation of so-called “dead zones”, the death of aquatic animals, and the loss of the aquatic ecosystem.

The study of S. Bae & D. Seo (2021) analysed the impact of hydrodynamic changes in a large river on algal growth, which leads to eutrophication. They demonstrated that the response to algal blooms in water depends on the season, and this factor should be considered in research. The authors of the current article agree with their view that the season is an important factor in studying eutrophication processes in waterbodies. Consequently, the concentration of biogenic substances in water will also vary depending on the season. Temperature regimes (air and water temperature) and the amount of precipitation received during different seasons are key indicators that influence the concentration of biogenic substances in water. Therefore, one of the objectives of this article was to determine the correlation between nitrogen and phosphorus concentrations and air and

water temperature. Future research should include additional monitoring studies for each season to establish the dominant type of pollution based on biogenic substances (nitrogen, phosphorus) in more detail, using the stoichiometric Redfield Ratio, and to determine whether these types differ depending on the season.

The scientific research of A. Ural-Janssen *et al.* (2024) indicates that the export of nitrogen (N) and phosphorus (P) compounds by rivers, as key indicators of coastal water eutrophication in Europe, will increase by 13-28% due to global climate change and technological advancements. Using the MARINA-Nutrients model, they calculated that to prevent future coastal eutrophication in European waterbodies, it is necessary to reduce nitrogen (N) compound inputs by up to 47% and phosphorus (P) compound inputs by up to 77%.

The results of scientists A.K. Sahu *et al.* (2024) confirmed that water resource pollution significantly affects drinking water quality and access, particularly for rural populations lacking centralised water supplies. They noted that, unlike groundwater, surface water sources such as small rivers, ponds, and lakes are most susceptible to elevated nutrient levels, which serve as food sources for eutrophic aquatic organisms (such as cyanobacteria). However, they argued that despite the toxic effects of cyanobacteria in water, they play a significant role as primary producers, nitrogen fixers, and organisms with high nutritional value. Complete eradication of cyanobacteria could disrupt the functioning of the aquatic ecosystem, especially in small rivers and ponds. Therefore, when researching small rivers (like the Unava River), particular attention must be paid to determining biogenic substance concentrations in the water and controlling eutrophication processes.

The research of E. Soana *et al.* (2024) indicates that the problem of waterbody eutrophication results from the presence of significant amounts of biogenic substances in the water and requires continuous monitoring. The scientists noted that all rivers worldwide suffer from nitrate pollution. Climate change exacerbates this

problem for rivers, creating unexpected ecological consequences for aquatic ecosystems. This study examined nitrogen and phosphorus export in a seasonal pattern, along with correlations with water temperature. The research showed that despite the constant input of diffuse and point sources, a noticeable decrease (-20%) in nitrogen export, primarily in the form of nitrates, was recorded compared to the 1990s. However, the study did not show significant changes in phosphorus export. This indicates an increase in the proportion of point sources in river pollution.

The scientific article of I. Micella *et al.* (2024) confirmed that diffuse pollution sources contribute 95-100% of nitrogen (from agriculture) and macroplastics (from improper waste management), while point sources (wastewater) account for 40-95% of phosphorus and microplastics in global seas. Their research demonstrates riverine export of pollutants to seas, noting that the discharge of untreated wastewater and improper waste management are primary factors influencing the accumulation of biogenic substances in river waters. Additionally, the study of I. Zahoor & A. Mushtaq (2023) indicates that agricultural activities release chemicals and nutrients, such as phosphates and nitrates, into the water, leading to nutrient and chemical pollution. Accordingly, the authors emphasise the importance of controlling diffuse pollution sources.

The current research partially aligns with the studies of scientists V.I. Pichura & L.O. Potravka (2021), who assessed the ecological state of the Dnipro River, considering biogenic substances. Their study highlighted that a pressing issue for the Dnipro River cascade reservoirs is the deterioration of water properties due to eutrophication, which causes biological pollution of waterbodies, driven by the accumulation of biogenic compounds in the water mass. These scientists also examined other types of river pollution. For instance, the problem of anthropogenic pollution in the transboundary Siverskyi Donets River is addressed in the article of E.V. Vorobiev *et al.* (2021). They examined this type of

pollution based on the composition of inorganic compounds (nitrates, nitrites, sulphates, chlorides, phosphates). Their research results showed that this type of river pollution occurs through both natural and anthropogenic pathways. It was also shown that nitrate pollution of the river occurs outside Ukraine, i.e., it is transboundary, while phosphate pollution occurs within Ukraine due to mine water discharges from the mining industry.

Additionally, the current research partially coincides with the concept of O.V. Stepova *et al.* (2022), who analysed diffuse pollution by biogenic elements (phosphorus, nitrogen) in the Vorskla River in Poltava. They analysed the main sources of biogenic substances entering the Vorskla River, establishing that rainwater entering the river contained elevated concentrations of biogenic substances and caused river pollution.

Scientists are paying particular attention to military activity as a source of pollution, which significantly affects the contamination of environmental components, including water resources. For example, the research of M. Matkivskyi & T. Taras (2024) shows that as a result of military actions in the Kharkiv Region, all rivers have high concentrations of ammonium nitrogen (exceeding the maximum permissible concentration (MPC) by 2 to 4 times) and correspondingly low levels of dissolved oxygen in the water (below the optimal level by 2 times). O.O. Dmitrieva *et al.* (2023) noted that military actions significantly intensify anthropogenic eutrophication processes.

In researching biogenic pollution in the Unava River, the ideas of the aforementioned scientists were considered to substantiate the problem of eutrophication and the pollution sources that cause the appearance of biogenic substances in the water. To establish the dominant type of pollution source, the stoichiometric Redfield Ratio method was used, which, in the authors' view, is appropriate and complements the aspects of assessing rivers at the time of biogenic pollution in waterbodies.

It is worth noting that in 2020, residents of Fastiv appealed to the mayor of the Fastiv City

Council, Kyiv Region, with a request to designate the Unava River valley as an ecological disaster zone (petition No. HOO.1495.8 dated 16 July 2020). However, they received a response from the mayor stating that there were no grounds for this decision. The residents of Fastiv were concerned about the rapid shallowing of the river, which was turning into a swamp, and they noted that the river was becoming increasingly overgrown with reeds and algae each year.

Within the framework of the Program for Comprehensive Restoration of the Kyiv Region for 2023-2027, approved by the decision of the Kyiv Regional Council on 17 October 2023, No. 726-21-VIII, the Strategy for the Development of the Kyiv Region for 2021-2027, approved by the decision of the Kyiv Regional Council on 19 December 2019, 2019, No. 789-32-VII, was developed. As part of this strategy, in 2023, the project "Cleaning of the Channel, Restoration and Maintenance of the Hydrological Regime and Sanitary Condition of the Unava River" (project identifier DREAM-UA-041223-9528D395) was developed. This project aimed to restore the natural channel of the Unava River by eliminating unauthorised obstructions, clearing the channel from siltation, improving the hydrobiological regime and rehabilitating the river, and creating favourable conditions for the existence of flora, fauna, ichthyofauna, and biodiversity. This project is currently in the implementation stage.

Conclusions

In this study, according to the first objective, it was established that the concentration of biogenic substances (nutrients) in the Unava River water affects water quality depending on its intended use and the functioning of aquatic biota (aquatic ecosystem). Specifically, nitrite nitrogen concentrations (0.006-0.306 mgN/dm³ in 2022, 0.006-0.051 mgN/dm³ in 2024, assessed as quality classes 3 to 5) are critical for the aquatic ecosystem; ammonium nitrogen concentrations are critical for recreational and domestic needs (1.21-1.83 mgNH₄⁺/dm³ in 2022, 1.16-5.88 mgNH₄⁺/dm³

in 2024, with a standard of $2.0 \text{ mgNH}_4^+/\text{dm}^3$), for drinking water needs, and for the aquatic ecosystem as a whole ($0.814\text{--}6.84 \text{ mgN}/\text{dm}^3$ in 2022, $0.364\text{--}4.56 \text{ mgN}/\text{dm}^3$ in 2024, assessing the waterbody as quality classes 3 and 4 for drinking water, and quality classes 4-5 for the aquatic ecosystem); phosphorus concentrations are critical for the aquatic ecosystem ($0.062\text{--}0.196 \text{ mgP}/\text{dm}^3$ in 2022, $0.333\text{--}0.597 \text{ mgP}/\text{dm}^3$ in 2024, assessing the waterbody as quality classes 2-3 in 2022 and quality class 5 in 2024).

Based on the calculations of the correlation degree between variables (second objective), a negative (inverse) correlation was established between air temperature and phosphate ($r = -0.07$), nitrate nitrogen ($r = -0.69$), and nitrite nitrogen ($r = -0.10$) levels. Correspondingly, a positive correlation was found between water temperature and mineral nitrogen ($r\text{NH}_4^+ = 0.38$; $r\text{NO}_3^- = 0.79$; $r\text{NO}_2^- = 0.46$) and phosphorus ($r\text{PO}_4^{3-} = 0.52$).

The results of the third objective, which involved calculating the *Redfield Ratio* (RR), established that in the 2022 research period

($RR = 29.42\text{--}108.64$), the limiting biogenic substance was mineral phosphorus ions, while mineral nitrogen ions were in excess, indicating dominant nitrogen pollution in the waterbody, potentially leading to the growth of green algae. In 2024 ($RR = 6.32\text{--}18.71$), the limiting factor was mineral nitrogen ions, and phosphorus ions were in excess, indicating dominant phosphorus pollution in the water, potentially leading to the development of blue-green algae.

Future research directions involve assessing the water quality of the Unava River based on heavy metal concentrations and general hydrochemical indicators, which will allow for a more accurate conclusion regarding the ecological state of the Unava River and determine its suitability for specific water use needs.

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None.

Conflict of Interest

None.

References

- [1] Bae, S., & Seo, D. (2021). Changes in algal bloom dynamics in a regulated large river in response to eutrophic status. *Ecological Modelling*, 454, article number 109590. doi: [10.1016/j.ecolmodel.2021.109590](https://doi.org/10.1016/j.ecolmodel.2021.109590).
- [2] Bedunkova, O.O. & Kaletnik K.V. (2017). [The limiting element of anthropogenic eutrophication of the small river Zamchysko](#). *Student Bulletin of the National University of Water Management and Environmental Management*, 2(8), 42-45.
- [3] Devlin, M., & Brodie, J. (2023). Nutrients and eutrophication. In *Marine pollution – monitoring, management and mitigation* (pp. 75-100). Cham: Springer Nature Switzerland. doi: [10.1007/978-3-031-10127-4_4](https://doi.org/10.1007/978-3-031-10127-4_4).
- [4] Dmitrieva, O.O., Tsapko, N.S., Koldoba, I.V., Lysov, B.V., & Teliura, N.O. (2023). Environmental monitoring of eutrophication process in water bodies across Ukraine. *Scientific and practical journal "Ecological Sciences"*, 3(48), 143-147. doi: [10.32846/2306-9716/2023.eco.3-48.23](https://doi.org/10.32846/2306-9716/2023.eco.3-48.23).
- [5] DSTU 4808:2007. (2007). *Sources of the centralized drinking water supplying. The hygienic, ecological requirements to water quality and the rules of selection*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=53159.
- [6] DSTU 7525:2014. (2014). *Drinking water. Requirements and control methods of quality*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=61154.
- [7] DSTU ISO 5667-6:2009. (2009). *Water quality. sampling part 6. Guidance on sampling of rivers and streams*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=64511.

- [8] Kapsalis, V.C., & Kalavrouziotis, I.K. (2021). Eutrophication – a worldwide water quality issue. In *Chemical lake restoration: Technologies, innovations and economic perspectives* (pp.1-21). Cham: Springer. doi:10.1007/978-3-030-76380-0_1.
- [9] Matkivskiy, M., & Taras, T. (2024). Pollution of the atmosphere, soil and water resources as a result of the Russian-Ukrainian war. *Ecological Safety & Balanced Use of Resources*, 15(1), 87-99. doi: 10.69628/esbur/1.2024.87.
- [10] Micella, I., Kroeze, C., Bak, M.P., & Strokal, M. (2024). Causes of coastal waters pollution with nutrients, chemicals and plastics worldwide. *Marine Pollution Bulletin*, 198, article number 115902. doi: 10.1016/j.marpolbul.2023.115902.
- [11] Ministry of Environmental Protection and Natural Resources of Ukraine. (2021). *National Report on the State of the Environment in Ukraine in 2021*. Retrieved from <https://mepr.gov.ua/wp-content/uploads/2023/01/Natsdopovid-2021-n.pdf>.
- [12] Order of the Ministry of Health of Ukraine No. 400 “On Approval of the State Sanitary Norms and Rules ‘Hygienic Requirements for Drinking Water Intended for Human Consumption’”. (2010, May). Retrieved from <https://zakon.rada.gov.ua/laws/show/z0452-10#Text>.
- [13] Order of the Ministry of Health of Ukraine No. 721 “Hygienic standards for water quality of water bodies to drinking, household and other needs of the population”. (2022, May). Retrieved from <https://zakon.rada.gov.ua/laws/show/z0524-22#Text>.
- [14] Pichura, V.I., & Potravka, L.O. (2021). Ecological condition of the Dnipro River Basin and improvement of the mechanism of organization of nature use on the water catchment territory. *Scientific Journal “Water Bioresources and Aquaculture”*, 1(9), 170-200. doi: 10.32851/wba.2021.1.14.
- [15] Resolution of the Cabinet of Ministers of Ukraine No. 1134-r “Water Strategy of Ukraine”. (2022, December). Retrieved from <https://zakon.rada.gov.ua/laws/show/1134-2022-%D1%80#Text>.
- [16] Romanenko, V.D., Zhukynsky, V.M., & Oksiyuk, O.P. (1998). *Methodology for ecological assessment of surface water quality by relevant categories*. Kyiv: SYMVOL-T.
- [17] Rudenko, S.S., & Dzenzerska, O.M. (2015). [The dependence of the Redfield Ratio from the phase of water regime of river ecosystems](#). *Biological Systems*, 7(2), 184-194.
- [18] Sahu, A.K., Mir, S., Nayak, B., & Baitharu, I. (2024). Sustainable management of eutrophication and problems associated with the algal toxin in ponds and lakes of rural areas. In *Water resources management for rural development* (pp. 155-170). Amsterdam: Elsevier. doi: 10.1016/B978-0-443-18778-0.00021-0.
- [19] Soana, E., Gervasio, M.P., Granata, T., Colombo, D., & Castaldelli, G. (2024). Climate change impacts on eutrophication in the Po River (Italy): Temperature-mediated reduction in nitrogen export but no effect on phosphorus. *Journal of Environmental Sciences*, 143, 148-163. doi: 10.1016/j.jes.2023.07.008.
- [20] SOU 05.01-37-385:2006. (2007). *Water of fishery enterprises. General requirements and standards*. Retrieved from <https://f.eruditor.link/file/3178429/>.
- [21] Stepova, O.V., Gakh, T.O., & Tyagniy, L.M. (2022). [Diffuse pollution with biogenic elements \(nitrogen, phosphorus\) of the Vorskla River in Poltava](#). In *Environmental safety: Problems and solutions: Materials of the XVIII international scientific and practical conference* (pp. 291-297). Kharkiv: “Ukrainian Research Institute of Environmental Problems”.
- [22] Strokal, V., Kurovska, A., & Strokal, M. (2023). More river pollution from untreated urban waste due to the Russian-Ukrainian war: A perspective view. *Journal of Integrative Environmental Sciences*, 20(1), article number 2281920. doi: 10.1080/1943815X.2023.2281920.

- [23] Strokal, V.P., & Kurovska, A.V. (2024). [*Integrated assessment of the ecological state of water of the Kyiv Reservoir*](#). Kyiv: Publishing Center of NUBiP of Ukraine.
- [24] Tiwari, A.K., & Pal, D.B. (2022). Nutrients contamination and eutrophication in the river ecosystem. In *Ecological significance of river ecosystems* (pp. 203-216). Amsterdam: Elsevier. doi: [10.1016/B978-0-323-85045-2.00001-7](https://doi.org/10.1016/B978-0-323-85045-2.00001-7).
- [25] Tyagniy, L., Stepova, O., & Gakh, T. (2022). [*Sources of pollution by biogenic substances \(nitrogen, phosphorus\) of the Vorskla River and its tributary the Kolomak River within the city of Poltava*](#). In *Environment recovery and reconstruction: War context: Materials of the international scientific-practical conference* (pp. 107-108). Poltava: National University "Poltava Polytechnic named after Yuriy Kondratyuk".
- [26] Ural-Janssen, A., Kroeze, C., Meers, E., & Strokal, M. (2024). Large reductions in nutrient losses needed to avoid future coastal eutrophication across Europe. *Marine Environmental Research*, 197, article number 106446. doi: [10.1016/j.marenvres.2024.106446](https://doi.org/10.1016/j.marenvres.2024.106446).
- [27] Voitenko, L.V. (2019). *Chemistry with the basics of biogeochemistry*. Kyiv: Publishing "House Scientific Capital".
- [28] Vorobiev, E.V., Usova, E.V., & Orkhova, Y.V. (2021). Analysis of sources of anthropogenic pollution of the transboundary river, the Serevsky Donets, based on the dynamics of the anion composition (nitrites, nitrates, sulfates, chlorides, phosphates) in 2007-2016. *IOP Conference Series: Earth and Environmental Science*, 720, article number 012059. doi: [10.1088/1755-1315/720/1/012059/meta](https://doi.org/10.1088/1755-1315/720/1/012059/meta).
- [29] Zahoor, I., & Mushtaq, A. (2023). [*Water pollution from agricultural activities: A critical global review*](#). *International Journal of Chemical and Biochemical Sciences*, 23(1), 164-176.

Біогенне забруднення водойми річки Унава

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Анотація. Біогенне забруднення водойм України є системною проблемою, яка потребує постійного моніторингу через його вплив на якість води та стимулювання антропогенної евтрофікації. Мета дослідження передбачала провести оцінювання водойми р. Унава для визначення рівня забруднення водойми біогенними речовинами та обґрунтування переважаючого типу забруднення (азотне/фосфорне). В ході дослідження визначено, що концентрація біогенних речовин у воді р. Унава впливає на якісний стан води залежно від потреб її використання та функціонування водної біоти (водна екосистема). Зокрема, концентрація азоту нітритного ($0,006\text{--}0,306\text{ мгN/дм}^3$ за 2022 р., $0,006\text{--}0,051\text{ мгN/дм}^3$) у воді є критичною для водної екосистеми; азоту амонійного – для рекреаційних, господарсько-побутових потреб ($1,21\text{--}1,83\text{ мгNH}_4^+/\text{дм}^3$ за 2022 р., $1,16\text{--}5,88\text{ мгNH}_4^+/\text{дм}^3$ за 2024 р.) для питних цілей й водної екосистеми в цілому ($0,814\text{--}6,84\text{ мгN/дм}^3$ за 2022 р., $0,364\text{--}4,56\text{ мгN/дм}^3$ за 2024 р.); фосфору – водної екосистеми ($0,062\text{--}0,196\text{ мгP/дм}^3$ за 2022 р., $0,333\text{--}0,597\text{ мгP/дм}^3$). За розрахунками ступеня кореляційного зв'язку між ознаками встановлено негативну кореляцію (обернену) між температурою повітря та показниками фосфатів ($r = -0,07$), азоту нітратного ($r = -0,69$) та азоту нітритного ($r = -0,10$). Відповідно, позитивну кореляцію виявлено між температурою води та мінеральним азотом ($r\text{NH}_4^+ = 0,38$; $r\text{NO}_3^- = 0,79$; $r\text{NO}_2^- = 0,46$) і фосфором ($r\text{PO}_4^{3-} = 0,52$). Проведені обчислення за співвідношенням Редфілда (Redfield Ratio – RR) дозволили обґрунтувати, що у 2022 році досліджень ($RR = 29,42\text{--}108,64$) лімітуючою біогенною речовиною були іони мінерального фосфору, а іони мінерального азоту знаходилися в надлишку, переважаючим стало азотне забруднення водойми з можливим ростом зелених водоростей. У 2024 році ($RR = 6,32\text{--}18,71$) – лімітуючою ознакою були іони мінерального азоту, а іони фосфору в цих умовах перебували у надлишку, переважаючим стало фосфорне забруднення води з можливим розвитком синьо-зелених водоростей

Ключові слова: поживні речовини; евтрофікація; якість води; азот; фосфор; співвідношення Редфілда



Mathematical model of the process of converting waste oils into diesel biofuel

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Abstract. The growing demand for renewable energy sources encourages the development of technologies for the production of biodiesel from waste, but the high content of free fatty acids in raw materials complicates transesterification, reduces fuel yield, and increases the need for purification. The purpose of the study was to develop and validate a mathematical model of the process of transesterification of used oils into diesel biofuels to optimise technological parameters. The rationalised model described in detail the patterns of triglyceride transformation in the presence of alcohol and a catalyst. It allowed tracking changes in the concentrations of reaction intermediates, in particular, diglycerides, monoglycerides, biodiesel, and glycerol, which is critical for predicting the effectiveness of the process. Stable values of the speed of the transesterification process are indicated using the Arrhenius equation, which helped to estimate the effect of temperature and the ratio of reactants on the overall kinetics of the reaction. As part of the study, numerical modelling and correlation of the model were carried out by systematising the results with the data obtained during the research and obtained from the results of the analysis of literature sources. Catalytic and non-catalytic variants of the process were analysed, which determined the most effective reaction conditions. The simulation results confirmed that an increase in temperature values to 60°C leads to an increase in the yield of diesel biofuels, so excessive heating above the boiling point of methanol causes its evaporation, which leads to a decrease in the efficiency of the process and the loss of raw materials. Optimal technological parameters that ensure the maximum yield of biodiesel with minimal material and energy costs were determined. The proposed mathematical model can be used in industrial settings to optimise the biofuel production process, helping to increase the efficiency of recycling

Keywords: kinetic model; free fatty acids; parameter optimisation; temperature regime; biofuel yield; energy efficiency

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Introduction

The crisis in the field of energy resources has affected almost all world countries, and it has not spared Ukraine, the high cost of mineral diesel fuel, usually due to the pricing policy for oils, fats, and reagents, which can account for up to 75% of the main production costs. Moreover, the use of alternative sources of raw materials, such as animal fats (beef fat, pork fat), used vegetable oils and waste from food and processing enterprises, in particular fat residues, is a promising approach to reducing production costs and environmental burden. These wastes are often disposed of by incineration, which is accompanied by additional economic and environmental costs. Attracting these resources to biodiesel production is an effective means of increasing the level of economic efficiency and minimising the negative impact on the environment (Aghbashlo *et al.*, 2021).

The problem of processing used oils into diesel biofuels is relevant from the standpoint of energy sustainability and reducing environmental pollution. Numerous studies have been carried out on various aspects of this process, in particular, the study of chemical reactions, optimisation of technological parameters, and the use of mathematical models for modelling and predicting processing results. Transesterification is the main method of converting fats and oils into biodiesel. Mathematical models have been developed to optimise the process and predict the yield of biodiesel depending on the oil quality and reaction conditions. A.S. Elgharbawy *et al.* (2021) and S. Vickram *et al.* (2023) presented models that include thermodynamic aspects of the reaction and the mechanism of interaction between oil molecules and methanol in the presence of various catalysts. The researchers noted that for waste oils that may have a high acid content, it is necessary consider account the altered kinetic parameters of the reaction. This model allows significantly increasing the efficiency of the process, reducing the cost of raw materials.

Studying the effect of temperature and catalyst selection on the efficiency of the transesterification process is an important part of developing optimal conditions for waste oil processing. H. Hosseinzadeh-Bandbafha *et al.* (2022) investigated the effect of different temperature regimes on the reaction rate using different alkaline and acid catalysts. They concluded that raising the temperature to optimal values (60-70°C) significantly improves the yield of biodiesel, but higher temperatures can lead to the development of by-products, which negatively affects the quality of biofuels. In addition, the use of non-standard catalysts, such as calcium salts, can reduce the cost of production and improve the selectivity of the reaction.

The cost-effectiveness of producing biodiesel from waste oils depends not only on the yield of biofuels, but also on the cost of energy and raw materials. M.U.H. Suzihaque *et al.* (2023) and K. Tucki *et al.* (2020) investigated the energy efficiency of various technological processes for processing oils into biofuels. They built a mathematical model that considers the energy costs of heating the oil, the cost of the catalyst and other components, and the energy value of the resulting biofuels. They note that the cost of producing biodiesel from waste oils may be significantly lower than from primary oils, but to achieve maximum economic effect, it is important to optimise energy costs and the choice of processing technology.

To improve the quality of diesel biofuels, it is important to consider hydrogenation processes that reduce the percentage of unsaturated bonds, which increases the resistance of biofuels to oxidation and ensures stable operation of engines. P. Maheshwari *et al.* (2022) proposed a mathematical model for the waste oil hydrogenation process based on the use of platinum and nickel-based catalysts. The researchers proved that the optimal conditions for the hydrogenation process include a temperature of 150-200°C and a pressure of 3-5 MPa, which allows achieving high oil conversion and reduce the level of unpleasant odours in the product.

Innovative approaches to waste oil processing include the use of bioengineering to improve the transesterification process. G.M. Mathew *et al.* (2021) considered the possibility of using microorganisms for the biological transformation of oils, which can help to reduce the need for chemical reagents and increase the efficiency of the process. In particular, it has been shown that some bacterial strains can speed up the esterification process by reducing temperature and reaction time, which, in turn, reduces energy costs and improves the environmental friendliness of the technology. This opens up new prospects for the sustainable development of bioenergy and reducing the impact of production on the environment.

A separate important part of the study is to consider the kinetics of the process of producing biodiesel from waste oils, since knowledge of the kinetic characteristics allows fine-tuning the process and improving its efficiency. H. Esmaeili (2022) developed kinetic equations for the transesterification process using waste oils, in particular, under conditions of high acidic oil values. The researcher noted that with a high content of free fatty acids in oil, it is important to use a multi-stage model, where the first stage includes acid neutralisation, and the second – direct transesterification.

An important aspect of the research is also the issue of environmental safety of the waste oil processing process. M.K. Pasha *et al.* (2021) considered possible negative environmental consequences of the use of waste oils in bioenergy technologies, in particular, the development of toxic by-products in the production of diesel biofuels. The researchers stressed the need to develop environmentally friendly technologies and implement effective systems for cleaning raw materials and waste from biofuel production.

More and more attention is being paid to combining conventional waste oil processing with renewable energy sources to reduce the cost of energy support for biodiesel production. C.T. Pinheiro *et al.* (2021) described the use of solar and wind energy to provide thermal power

processes in biodiesel production, which can significantly reduce CO₂ emissions and improve the economic efficiency of the process. They presented a mathematical model for integrating these energy sources into the overall technological process, which reduces energy costs and increases the purity of the final product.

The search for effective catalysts is an important area of research in waste oil processing. M.S. Gad *et al.* (2023) investigated the effect of inorganic catalysts such as metal oxides (calcium oxide, magnesium oxide) on the transesterification process. They have proven that these catalysts provide high efficiency at low temperatures and are cost-effective, making the process more affordable for industrial use. In addition, a mathematical model was constructed to optimise the catalyst concentration and temperature regime to achieve maximum biofuel yield.

The purpose of the study was to develop and verify a mathematical model for the re-esterification of waste oils into diesel biofuels to optimise technological parameters, increase product yield, and minimise energy and material costs.

Materials and Methods

This study used waste vegetable oils and animal fats (beef fat, pork fat) as the main raw materials for the synthesis of diesel biofuels. During the process of transformation of vegetable oils or animal fats with alcohol (ethanol, methanol, bioethanol, etc.), they were modified into the corresponding esters of fatty acids, which are commonly called diesel biofuels.

For the rapid flow of the above-mentioned process, various types of catalytic systems are used, the most common of which are potassium hydroxide (KOH) or sodium hydroxide (NaOH). Such catalysts destroyed the molecular bonds in triglycerides, which allowed them to react with alcohol, the product of this transformation was esters, which are a component of diesel biofuels. Various catalysts, acid catalysts, biocatalysts (enzymes), heterogeneous catalysts, and nanomaterial-based catalysts were used to perform the

transesterification reaction, each of these catalysts has its own advantages and disadvantages, and the choice depended on the type of raw material, reaction conditions, and final product requirements.

Diesel biofuels were obtained by performing an esterification or transesterification reaction. As a result of the transformation, fatty acid esters (FAE) and glycerol (crude glycerol) were formed. The reaction in this case occurred according to the scheme shown in Figure 1:

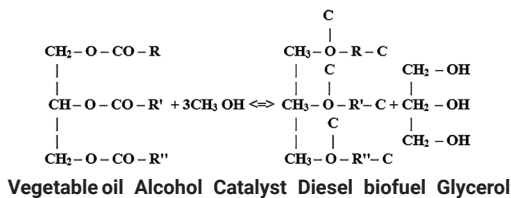


Figure 1. Scheme

of the transesterification reaction

Source: compiled by the author

The beginning of the re-esterification process was quite fast, but after 5-7 minutes the pace gradually decreased. The main amount of triglycerides was converted to diglycerides, producing FAEs (diesel biofuels), so this process was slower. Diglycerides were transformed into monoglycerides during the reaction, and those – into the corresponding esters, until the glycerol was completely precipitated. 1,520 minutes after the start, the reaction slowed down again, but did not stop completely. After 2 hours of the process at the appropriate temperature, which did not exceed 60°C, transesterification stopped, which was confirmed by stopping the phase separation.

The transesterification reaction was reversible and could proceed in two directions at different rates, which varied depending on a fixed value of the conversion rate b_n . To study changes in the reaction rate, a system of differential equations describing the process of waste oil synthesis was compiled:

$$d[\text{Tr}]/dt = b_1[\text{Tr}] + b_2[\text{Di}][\text{BE}], \quad (1)$$

$$d[\text{Di}]/dt = b_3[\text{Di}][\text{A}] + b_4[\text{Mo}][\text{BE}] + b_1[\text{Tr}][\text{A}] - b_2[\text{Di}][\text{BE}], \quad (2)$$

$$d[\text{Mo}]/dt = b_5[\text{Gl}][\text{BE}] + b_6[\text{Gl}][\text{BE}] + b_3[\text{Di}][\text{A}] - b_4[\text{Mo}][\text{BE}], \quad (3)$$

$$d[\text{Gl}]/dt = b_5[\text{Mo}][\text{A}] - b_6[\text{Gl}][\text{BE}], \quad (4)$$

$$d[\text{BE}]/dt = b_1[\text{Tr}][\text{A}] - b_2[\text{Di}][\text{BE}] + b_3[\text{Di}][\text{A}] - b_4[\text{Mo}][\text{BE}] + b_5[\text{Mo}][\text{A}] - b_6[\text{Gl}][\text{BE}], \quad (5)$$

$$d[\text{A}]/dt = -b_1[\text{Tr}][\text{A}] - b_2[\text{Di}][\text{BE}] + b_3[\text{Di}][\text{A}] - b_4[\text{Mo}][\text{BE}] + b_5[\text{Mo}][\text{A}] - b_6[\text{Gl}][\text{BE}], \quad (6)$$

$$d[\text{A}]/dt = d[\text{BE}]/dt, \quad (7)$$

where: [Tr] – triglycerides, [Di] – diglycerides, [Mo] – monoglycerides, [Gl] – glycerol, [A] – Alcohol, [BE] – bioethyl ether, $b_1, b_2, b_3, b_4, b_5, b_6$ – fixed values of the conversion process speed. To obtain a simplified solution of the system of equations, numerical methods using Microsoft Excel were used. Fixed values of the conversion process rate were obtained from the study by C.T. Pinheiro *et al.* (2021) and are presented in Table 1.

Table 1. Value of the transesterification reaction rate at 60°C for waste oils

Fixed values of the conversion process speed	b_1	b_2	b_3	b_4	b_5	b_6
Indicator, (Mol% min) ⁻¹	0.045	0.10	0.212	1.223	0.241	0.0065

Source: C.T. Pinheiro *et al.* (2021)

Under the appropriate temperature regime, the process of diesel biofuel formation occurred only if all components of the reacting mixture were energetically self-sufficient. According to

C.T. Pinheiro *et al.* (2021), such energy was defined as activation energy, and the molecules were activated independently. According to the equation, fixed values of the conversion process speed b

and activation energy E_a were associated with the corresponding dependencies:

$$b = A \cdot e^{-E_a/RT}, \quad (8)$$

where, E_a – activation energy value, A – frequency factor, R – universal gas constant (8.31 J/Mol·K), T – absolute temperature, K.

Therefore, under a fixed temperature regime, the conversion rate was determined by the activation energy level E_a . With an increase in E_a , the number of molecules that had sufficient energy levels for activation decreased, which, in turn, contributed to a decrease in the reaction rate, and vice versa. Accordingly, when E_a at zero, the reaction was instantaneous, since the molecules had

enough energy to quickly initiate the process. Indicator E_a characterised the specifics of the interaction of substances and was determined experimentally on the basis of dependence $b = f(T)$. By writing equation (8) in logarithmic form (9) and defining the constants at two temperatures (10), the value E_a was obtained:

$$\ln \frac{b_2}{b_1} = \frac{(T_2 - T_1)}{RT_2 \cdot T_1} E_a, \quad (9)$$

$$E_a = \frac{RT_1 T_2 \ln \left(\frac{b T_2}{b T_1} \right)}{T_2 - T_1}. \quad (10)$$

Table 2 shows the results of calculations of the activation energy for reactions, the constants of which are indicated in Table 1.

Table 2. Activation energy characteristics for potassium hydroxide (KOH)

Activation energy	E_1	E_2	E_3	E_4	E_5	E_6
Indicator, (Mol·K) ⁻¹	14,145	9,852	19,710	13,939	7,021	8,988

Source: C.T.Pinheiro *et al.* (2021)

The initial system of differential equations (1-7) can be represented as the following system of discrete equations:

$$(Tr^{P+1} - Tr^P)/\Delta t = b_1 Tr^P A^P + b_2 Di^P Bi^P, \quad (11)$$

$$(Di^{P+1} - Di^P)/\Delta t = b_1 Tr^P A^P - b_2 Di^P Bi^P - b_3 Di^P A^P + b_4 Mo^P Bi^P, \quad (12)$$

$$(Mo^{P+1} - Mo^P)/\Delta t = b_3 Di^P A^P - b_4 Mo^P BE^P - b_5 Mo^P A^P + b_6 Gl^P Bi^P, \quad (13)$$

$$(Gl^{P+1} - Gl^P)/\Delta t = b_5 Mo^P A^P + k_6 Gl^P Bi^P, \quad (14)$$

$$(Bi^{P+1} - Bi^P)/\Delta t = b_1 Tr^P A^P - b_2 Di^P Bi^P + b_3 Di^P A^P - b_4 Mo^P Bi^P + b_5 Mo^P A^P - b_6 Gl^P Bi^P, \quad (15)$$

$$(A^{P+1} - A^P)/\Delta t = -b_1 Tr^P A^P + b_2 Di^P Bi^P - b_3 Di^P A^P + b_4 Mo^P Bi^P - b_5 Mo^P A^P + b_6 Gl^P Bi^P, \quad (16)$$

where P – size-independent interval, Bi – bioethanol concentration, Mol, Δt – time step, h. The current time point t was calculated using the following equation:

$$t = p \cdot \Delta t. \quad (17)$$

Equations of the system (11-16) can be rewritten as:

$$Tr^{P+1} = (1 - b_1 \Delta t A^P) Tr^P + b_2 \Delta t Di^P Bi^P, \quad (18)$$

$$Di^{P+1} = (1 - b_2 \Delta t BE^P - b_3 \Delta t A^P) Di^P + b_1 \Delta t Tr^P A^P + b_4 \Delta t Mo^P BE^P, \quad (19)$$

$$Mo^{P+1} = (1 - b_4 \Delta t BE^P - b_5 \Delta t A^P) Mo^P + b_1 \Delta t Di^P A^P + b_6 \Delta t Gl^P BE^P, \quad (20)$$

$$Gl^{P+1} = (1 - b_6 \Delta t BE^P) Gl^P + b_5 \Delta t Mo^P A^P, \quad (21)$$

$$BE^{P+1} = (1 - b_2 \Delta t Di^P - b_4 \Delta t Mo^P - b_6 \Delta t Gl^P) BE^P + (b_1 \Delta t Tr^P + b_3 \Delta t Di^P + b_5 \Delta t Gl^P) A^P, \quad (22)$$

$$A^{P+1} = (1 - b_1 \Delta t Tr^P - b_3 \Delta t Di^P - b_5 \Delta t Gl^P) A^P + (b_2 \Delta t Di^P + b_4 \Delta t Mo^P + b_6 \Delta t Gl^P) BE^P, \quad (23)$$

The solution of this system of discrete equations is possible if the coefficients of the equations are not greater than one.

Results and Discussion

For calculations based on the results of experimental studies, the initial concentration of the reacting mixture was chosen in a molar ratio of 9:1. The calculation results obtained in Microsoft

Excel presented in Table 3 indicate that the reaction occurs with acceleration in the first 0.69 hours, after which the rate of diesel biofuel formation decreases.

Table 3. Time dynamics of the concentration of reaction components at a temperature of 65°C

Reaction time, h	Components of the reaction mixture				
	Tr	Di	Mo	Gl	BE
0	1	0	0	0	0
0.014	0.784	0.136	0.054	0.025	0.321
0.028	0.629	0.175	0.088	0.108	0.675
0.042	0.519	0.19	0.089	0.201	0.972
0.056	0.44	0.194	0.081	0.284	1.209
0.069	0.383	0.191	0.072	0.354	1.397
0.083	0.34	0.184	0.064	0.413	1.549
0.097	0.307	0.174	0.057	0.462	1.673
0.111	0.282	0.165	0.051	0.503	1.775
0.125	0.261	0.155	0.046	0.538	1.861
0.139	0.244	0.146	0.042	0.568	1.934
0.153	0.23	0.138	0.038	0.594	1.997
0.167	0.218	0.131	0.035	0.617	2.051
0.222	0.182	0.109	0.028	0.681	2.208
0.278	0.16	0.095	0.024	0.721	2.306
0.417	0.131	0.079	0.019	0.771	2.431
0.556	0.119	0.073	0.018	0.771	2.52
0.694	0.119	0.073	0.018	0.771	2.52
0.833	0.119	0.073	0.018	0.771	2.52
1.0	0.119	0.073	0.018	0.771	2.52

Note: Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ether

Source: developed by the author

The graphical dependencies shown in Figure 2 show the effect of temperature on the yield of bioethyl ether (diesel biofuel). Based on the results of modelling, it was found that an increase in temperature above 60°C does not cause a significant increase in the yield of biodiesel.

The results of experimental studies of the degree of conversion of waste oils to diesel biofuels in dynamics, compared with theoretical calculations of the mathematical model, showed that with a probability of 0.95, the obtained values lie within the confidence interval. Calculating the equations of the discrete system (18)-(23) proves the possibility of increasing the yield of

bioethyl ether from 86.7 to 87.4% and increasing the temperature of the transesterification process from 55°C to 60°C (Fig. 2a, 2b). An important technological indicator is the time to establish equilibrium during the reaction process (0.33-0.56 hours), which will be one of the main parameters that will determine the design characteristics of the reactor for the synthesis of diesel biofuels. It should be noted that the temperature increase to 70°C (Fig. 2b) reduces the ester yield to (85%). After determining the optimal process conditions, the most rational parameters are selected, which will serve as the basis for designing the appropriate equipment.

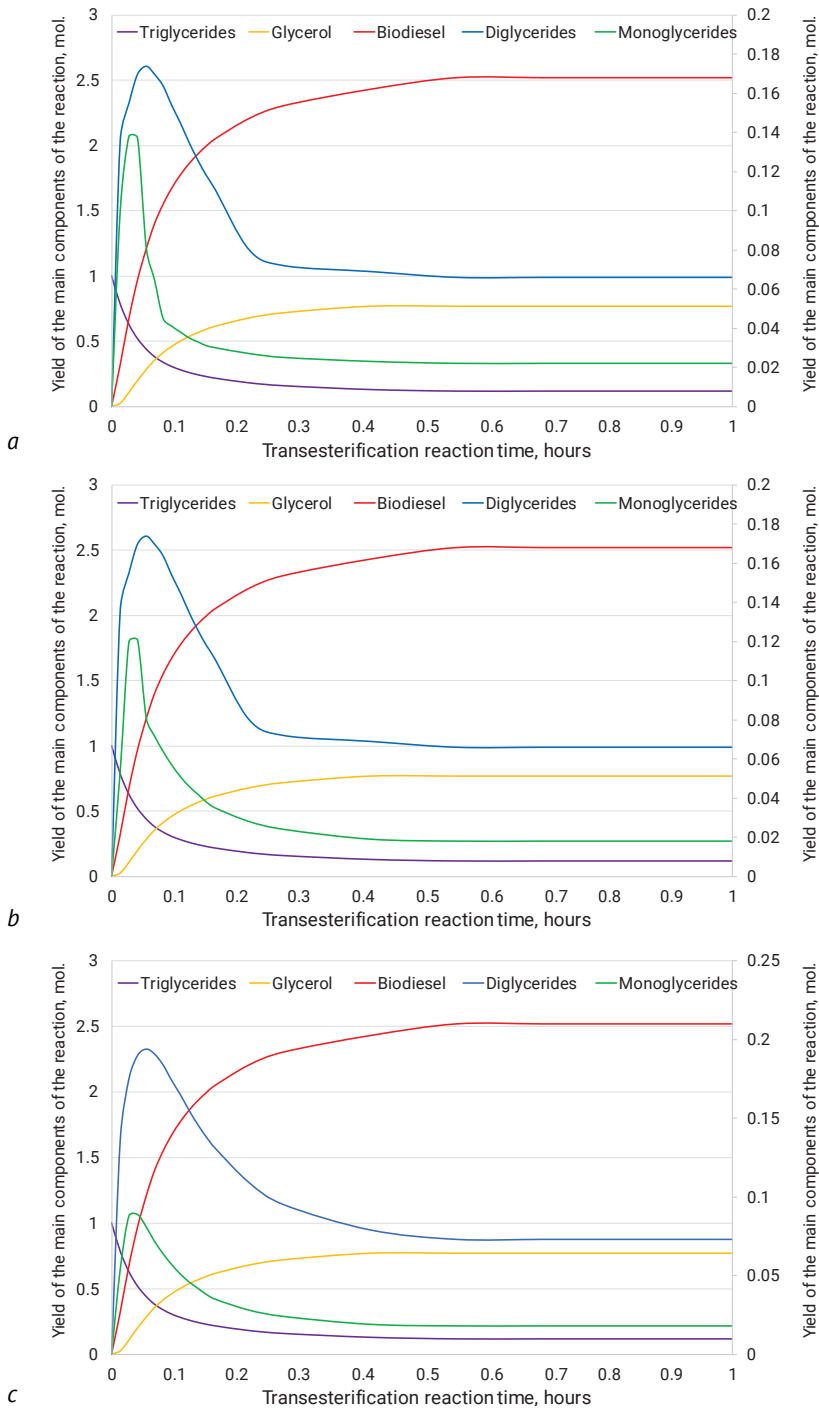


Figure 2. Influence of temperature on the productivity of the diesel biofuel production process using bioethanol

Note: a) reaction temperature – 55°C, b) reaction temperature – 60°C, c) reaction temperature – 65°C

Source: developed by the author

Molar balance equations are solved using the Matlab application package:

1. Change in Tr (triglyceride) concentration (Fig. 3, 4).

For the purpose of a more detailed study of changes in the concentration of Tr and BE (bioethyl ether), changes in the alcohol concentration were ignored, and the reaction time was limited to 2 hours:

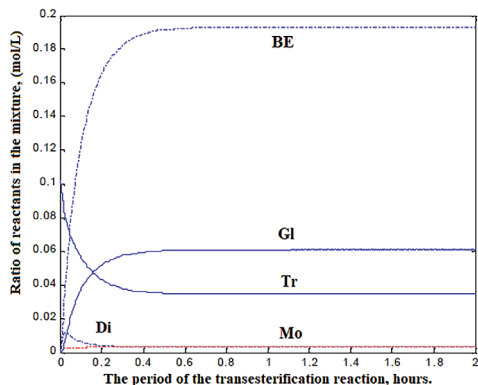


Figure 3. Effect of triglyceride concentration on the yield of reaction components: $V = 66.42\%$, $[Tr] = 0.034$, $[BE] = 0.1922$, $[Tr] \cdot 2 = 0.411$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

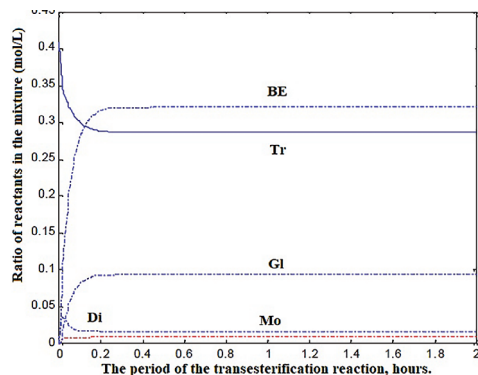


Figure 4. Effect of triglyceride concentration on the yield of reaction components:

$$V = 29.7\%, [Tr] = 0.278, [BE] = 0.298$$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

As can be seen from the graphs in Figures 3, 4, the conversion of triglycerides increases at low concentrations, and at higher ones.

2. Changes in bioethanol concentration, $[B]$: $[B]/2 = 1.3891$ (Fig. 5, 6).

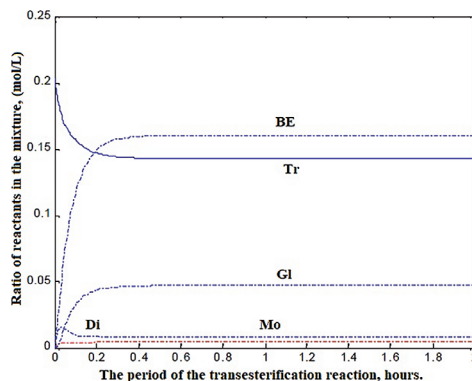


Figure 5. Effect of bioethanol concentration on the yield of reaction components: $V = 28.93\%$, $[Tr] = 0.1437$, $[BE] = 0.1606$, $[B] \cdot 2 = 5.662$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

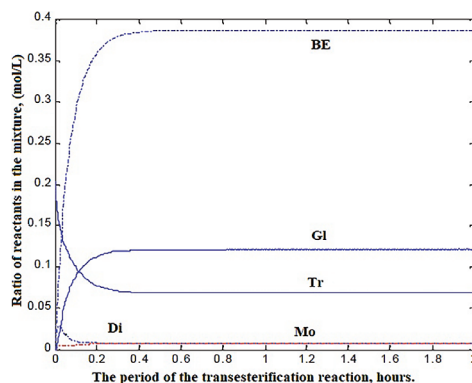


Figure 6. Effect of bioethanol concentration on the yield of reaction components: $V = 65.53\%$, $[Tr] = 0.06755$, $[BE] = 0.3862$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

After analysing the results of graphical dependencies (Fig. 5 and 6), it can be argued that the ester yield changes in proportion to the

bioethanol concentration, with an increase in the amount it increases, and with its decrease it decreases.

3. Effect of catalyst concentrations $[K]$. $[K]/2 = 4.025$ (Fig. 7, 8).

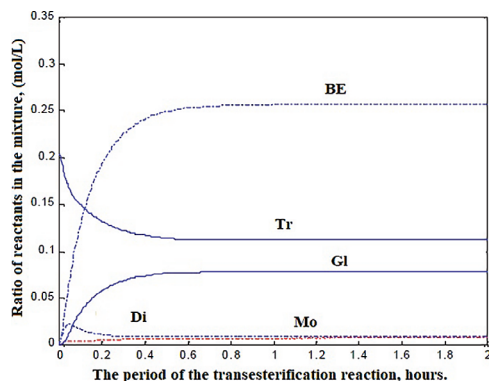


Figure 7. Effect of the catalyst concentration on the yield of reaction components: $V = 45.52\%$, $[Tr] = 0.1114$, $[BE] = 0.2562$, $[K] \cdot 2 = 15.9$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

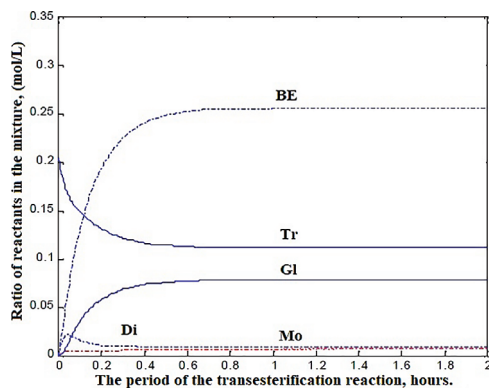


Figure 8. Effect of the catalyst concentration on the yield of reaction components: $V = 44.92\%$, $[Tr] = 0.111$, $[BE] = 0.256$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

The reaction rate remains unchanged when the catalyst concentration changes. Although it is possible to use a higher concentration in some

cases, it should be remembered that an excessive increase in it can negatively affect the yield of diesel biofuels. How the reaction course changes when the catalyst concentration decreases to 0.1% is shown in Figure 9 ($[K]/10 = 0.805$).

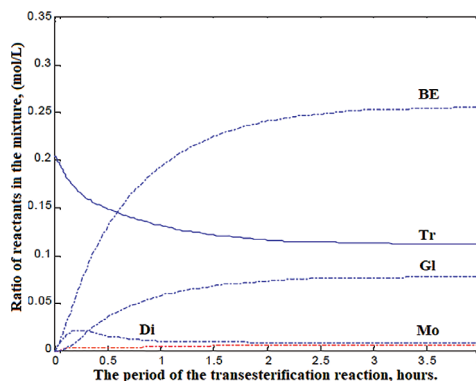


Figure 9. Effect of the catalyst concentration on the yield of reaction components: $V = 44.01\%$, $[Tr] = 0.112$, $[BE] = 0.2445$

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ester

Source: developed by the author

In order to improve the visualisation of changes in the concentrations of reaction components, Figure 10 does not show the concentration curves of bioethanol and catalyst.

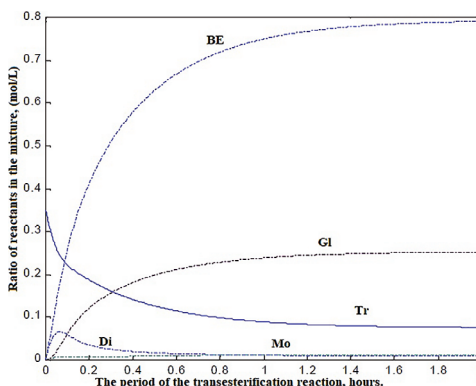


Figure 10. Final concentrations of reaction components after transesterification

Note: V – bioethyl ester yield, Tr – triglycerides, Di – diglycerides, Mo – monoglycerides, Gl – glycerol, BE – bioethyl ether

Source: developed by the author

Based on the results of computer modelling (Fig. 10), it was found that the rapid increase in the concentration of bioethyl ether is explained by its high conversion rate. However, triglycerides decompose more slowly than diglycerides, the conversion rate of which first increases and then decreases due to their subsequent conversion to monoglycerides and bioethyl ether. Reaching the equilibrium of the reaction is accompanied by an increase in the concentration of monoglycerides, the conversion rate of which is higher than that of diglycerides.

The results of the analysis of graphical dependencies indicate that a significant decrease in the level of reaction components leads to an increase in their residence time in the reactor. From the conducted studies, it follows that the reaction proceeds better at a reduced concentration of the catalyst and increased concentrations of triglycerides and methanol, but the concentration of the catalyst significantly affects the residence time of the mixture in the reactor. The conversion results are calculated:

$$V = (1 - 0.08/0.4) \cdot 100 = 79.2\%$$

The resulting value of converting oils to fuel is necessary for designing equipment with effective parameters. The results shown in Figure 2 show that an increase in temperature to 60°C contributes to an increase in the yield of methyl esters due to the acceleration of the transesterification reaction. However, a further increase in temperature above 60°C does not significantly improve the yield of biodiesel due to methanol evaporation and the possibility of adverse decomposition reactions. In particular, at 70°C, the product yield decreases slightly (up to 85%), which is consistent with the literature data (Cheliadyn *et al.*, 2020; Jayaraman *et al.*, 2022).

Based on the results of modelling, it was found that an increase in the ratio of alcohol to triglycerides from 3:1 to 6:1 provides an increase in ester yield by 8.5%. A further increase in this indicator to the level of 9:1 does not significantly increase the

yield, which confirms the need to rationalise alcohol consumption. The results obtained are consistent with studies by Z. Khan *et al.* (2021), which determined the economically feasible 6:1 ratio.

The results shown in Figures 7 and 8 show that the optimal concentration of the catalyst ensures an efficient reaction, while its excessive concentration can lead to the formation of undesirable byproducts, such as soap. Reducing the catalyst concentration to one-tenth of the optimal one significantly slows down the reaction, which requires an increase in the residence time of the mixture in the reactor. This was confirmed by O. Konur (2021), which emphasise the need to optimise the catalyst concentration, considering economic and technological aspects.

The results obtained are consistent with the conclusions of other researchers. For example, S. Ali *et al.* (2020) confirmed that at 60°C, the yield of biodiesel is maximum, and increasing the temperature to 70°C does not provide additional benefits. Similarly, the calculated activation energy values correspond to the range given by M. Athar & S. Zaidi (2020) and K.S. Eldiehy *et al.* (2022), which confirms the validity of the model.

Compared to research by P.B. Aurtherson *et al.* (2023), where alternative catalysts based on calcium and magnesium were used, the current model demonstrates higher efficiency when using classical alkaline catalysts at temperatures below 60°C. The main advantage of this study is the accuracy of predicting reaction kinetics and optimising parameters for industrial applications. The disadvantage is the need for additional purification of biodiesel from residual catalysts, which requires additional energy costs.

Compared to the approaches by Y. Devarajan *et al.* (2022), who used enzymatic catalysis, the current model has a significantly shorter reaction time and a higher yield of biofuels, but biocatalytic processes have environmental advantages due to the absence of residual chemical catalysts. This opens up prospects for further research on combined methods to improve the efficiency of biofuels. A.A. Babadi *et al.* (2022) pointed out the

need to improve the processes of purification of biodiesel from impurities. Compared to these results, the current study demonstrates a higher level of purity of the final product by optimising the catalyst neutralisation process. M. Mushtuk *et al.* (2022) proved that the use of acid catalysis has a number of technological disadvantages, among which is the mandatory neutralisation of the acid before transesterification, which leads to the development of precipitates in the form of salt, which complicate the further purification of the final product. With this in mind, active scientific research is aimed at developing heterogeneous catalysts that can be easily separated from the reaction medium after the process is completed. Despite the commercial availability of some of them, the effectiveness of such catalysts and their resistance to contamination at moderate temperatures and atmospheric pressure remain open questions.

The use of such secondary raw materials for the synthesis of diesel biofuels is a promising technology that will help to improve the environmental situation and reduce dependence on expensive petroleum products. Biodiesel made from recycled materials has a number of key advantages:

- the use of secondary raw materials in biofuel production helps to reduce greenhouse gas emissions due to lower CO₂ levels in diesel biofuels compared to conventional diesel fuel (Mushtuk *et al.*, 2024). This helps to reduce the negative impact on the climate and reduces the ecological footprint.

- recycling of secondary raw materials, reduces the cost of biofuel production (Mushtruk *et al.*, 2022). In addition, it reduces the cost of disposing of such waste and minimises its negative impact on the environment.

- waste oil synthesis technology on biodiesel ensures efficient use of resources and reduces the burden on natural resources (Zulqarnain *et al.*, 2021). This corresponds to the principles of a circular economy, where waste is converted into useful raw materials for new production cycles.

Mathematical modelling is a powerful tool for engineering analysis, which reduces the time of experimental research and reduces material costs. It minimises the need for large experimental installations by optimising process parameters through numerical analysis and theoretical forecasting. In particular, such models allow establishing patterns between the physical and chemical properties of transformation of secondary raw materials, which is an important stage in the development and improvement of energy-efficient technologies for the production of biodiesel from waste oils and industrial waste.

According to P.J. Ahranjani *et al.* (2024), one of the important technological factors that makes it impossible to use waste oils for a direct transesterification reaction is the high content of free fatty acids (FFA), usually exceeding 2 mg KOH/g. This makes it impossible to directly apply alkaline catalysis in the transesterification reaction, since the alkaline catalyst (NaOH, KOH) is used to neutralise FFA, which leads to the formation of soap residues and by-products. The formation of water during the reaction further complicates the purification of the resulting biodiesel, reducing its yield and quality. Y. Zhao *et al.* (2021) proved that one of the most common methods of overcoming this problem is esterification, which is quite widely used in industrial production. In addition, R. Kukana & O.P. Jakhar (2022) investigated alternative approaches, such as enzymatic catalysis and the use of supercritical synthesis of various types of alcohols, which can potentially improve the efficiency of the process.

Studying the possibility of using two-stage systems that simultaneously produce electrical and thermal energy is an important area for optimising waste oil processing processes. K. Ganesan *et al.* (2021) demonstrated the effectiveness of such systems based on bioreactors, where waste oils were used as a source of raw materials. As a result of their research, a mathematical model of a two-stage process was developed, which reduces energy consumption and carbon dioxide emissions, and increases the efficiency

of waste oil processing. Since biodiesel derived from waste oils can contain high levels of sulphur and oxygen-containing compounds, improving fuel purification processes is an important aspect. M.A. Hazrat *et al.* (2021) presented the latest method of elimination of sulphur and oxygen impurities of biodiesel using a combination of catalytic and physico-chemical processes, which can significantly reduce the level of sulphur and ensure compliance with international standards. The researchers created a mathematical model to describe the process, which allows optimising the cleaning parameters at all stages of production.

Considering the carbon balance in biodiesel production processes is crucial for assessing their sustainability. G.V. Subhash *et al.* (2022) developed a mathematical model that considers all stages of the biodiesel life cycle – from oil collection to fuel combustion in engines. The model includes not only CO₂ emissions, but also other pollutants, such as nitrogen and sulphur oxides, and allows comparing different technologies and raw materials for their environmental efficiency. The results showed that biodiesel made from waste oils has a significantly lower carbon footprint compared to conventional fuels.

Free fatty acids are a significant factor affecting the quality of biodiesel, as their high content can lead to the development of soap and reduce the yield of biofuels. R. Ganesan *et al.* (2021) studied the effect of the free fatty acid content in waste oils on the efficiency of transesterification and developed a mathematical model for their neutralisation before the esterification process. The researchers developed a strategy that includes multi-stage oil purification, which reduces the content of free fatty acids and increases the yield of biodiesel.

Development of rational technologies for improving the processing of waste oils N.H. Razak *et al.* (2021) considered bioengineered methods to improve the waste oil processing process, in particular, the use of genetically modified microorganisms to accelerate transesterification processes. Modelling of these

processes has shown that the use of catalytic systems based on modified bacteria can significantly reduce energy costs and reaction time.

Based on the results of the literature analysis, it was established that an important focus of research in the field of waste oil processing for diesel biofuels is the use of mathematical modelling to optimise technological processes. Modelling allows not only to more accurately predict the results of the reaction, but also to reduce energy costs, improve environmental indicators and economic efficiency of production.

Modelling in such areas as the use of catalysts, hydrogenation processes and biodiesel purification is particularly important. Models that consider carbon balance and environmental efficiency allow comparing different technologies and raw materials that contribute to the sustainable development of bioenergy. In addition, mathematical modelling is becoming an important tool for improving energy and economic efficiency, in particular, through the integration of cogeneration technologies, and when using bioengineered solutions.

A. Dahiya (2020) explored the possibility of integrating renewable energy sources into biodiesel production. In this study, such integration was not considered, but the proposed parameters allow minimising energy costs even in conventional production conditions. B. Chen *et al.* (2022) presented a model that considers the full carbon balance of biodiesel production. The current study focuses on the kinetic aspects of the process, but the results indicate a potential reduction in CO₂ emissions due to the efficient use of waste oils.

The study confirms the high level of efficiency of the developed mathematical model for transesterification of waste oils into biodiesel. Comparison of theoretical results obtained through numerical modelling with experimental data shows a strong correlation between forecasts and actual results. The key parameters that determine the efficiency of the process are the reaction temperature, the molar ratio of alcohol to triglycerides, and the concentration of the catalyst.

Conclusions

The mathematical model of the process of transesterification of used oils into biodiesel has demonstrated its effectiveness as a tool for optimising technological parameters. The use of Microsoft Excel and MathLab allowed predicting the dynamics of the process with high accuracy and adjusting the reaction conditions to increase the yield of the final product. Rational parameters of transesterification were established, which ensure the maximum yield of diesel biofuels (90%), a temperature of 60°C, an alcohol-to-triglyceride ratio of 6:1, and a catalyst concentration of 1.5%. This makes the process economically viable for industrial use. Based on the simulation results, it was found that the temperature regime is a key to the efficiency of the reaction. Raising the temperature to 65°C accelerates the conversion of triglycerides and increases the yield of biofuels. However, a further increase in temperature, especially above the boiling point of bioethanol (~65°C at atmospheric pressure), leads to alcohol loss, which reduces the efficiency of the reaction.

Graphical dependences of the yield of the main components of the reaction, including triglycerides, diglycerides, and methyl esters, allow visualising the effect of reagent and catalyst concentrations on the process. This contributes

to more accurate forecasting of the final characteristics of biofuels and improved process management. The results obtained can be used for further optimisation of industrial production of biodiesel, improvement of technological modes, and development of more efficient mathematical models for estimating the parameters of the obtained diesel biofuel.

Among the promising areas of further research are the integration of renewable energy sources into the production of biofuels, the creation of environmentally friendly catalysts, and the improvement of methods for cleaning the final product. It is also important to implement combined approaches to catalytic activation, including the use of bioengineering and nanotechnology solutions to improve the efficiency and environmental friendliness of production processes.

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Conflict of Interest

None.

References

- [1] Aghbashlo, M., Peng, W., Tabatabaei, M., Kalogirou, S.A., Soltanian, S., Hosseinzadeh-Bandbafha, H., & Lam, S.S. (2021). Machine learning technology in biodiesel research: A review. *Progress in Energy and Combustion Science*, 85, article number 100904. doi: [10.1016/j.pecs.2021.100904](https://doi.org/10.1016/j.pecs.2021.100904).
- [2] Ahranjani, P.J., Saei, S.F., El-Hiti, G.A., Yadav, K.K., Cho, J., & Rezaia, S. (2024). Magnetic carbon nanotubes doped cadmium oxide as heterogeneous catalyst for biodiesel from waste cooking oil. *Chemical Engineering Research and Design*, 201, 176-184. doi: [10.1016/j.cherd.2023.11.059](https://doi.org/10.1016/j.cherd.2023.11.059).
- [3] Ali, S., Shafique, O., Mahmood, S., Mahmood, T., Khan, B.A., & Ahmad, I. (2020). Biofuels production from weed biomass using nano catalyst technology. *Biomass and Bioenergy*, 139, article number 105595. doi: [10.1016/j.biombioe.2020.105595](https://doi.org/10.1016/j.biombioe.2020.105595).
- [4] Athar, M., & Zaidi, S. (2020). A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production. *Journal of Environmental Chemical Engineering*, 8(6), article number 104523. doi: [10.1016/j.jece.2020.104523](https://doi.org/10.1016/j.jece.2020.104523).
- [5] Aurtherson, P.B., Nalla, B.T., Srinivasan, K., Mehar, K., & Devarajan, Y. (2023). Biofuel production from novel Prunus domestica kernel oil: process optimization technique. *Biomass Conversion and Biorefinery*, 13(7), 6249-6255. doi: [10.1007/s13399-021-01551-5](https://doi.org/10.1007/s13399-021-01551-5).

- [6] Babadi, A.A., Rahmati, S., Fakhlaei, R., Barati, B., Wang, S., Doherty, W., & Ostrikov, K.K. (2022). Emerging technologies for biodiesel production: Processes, challenges, and opportunities. *Biomass and Bioenergy*, 163, article number 106521. doi: [10.1016/j.biombioe.2022.106521](https://doi.org/10.1016/j.biombioe.2022.106521).
- [7] Cheliadyn, L., Ribun, V., & Cheliadyn, V. (2020). Technological and environmental aspects of improving the biodiesel production from vegetable oils. *Ecological Safety and Balanced Use of Resources*, 11(2), 83-91. doi: [10.31471/2415-3184-2020-2\(22\)-83-91](https://doi.org/10.31471/2415-3184-2020-2(22)-83-91).
- [8] Chen B., Zheng, D., Xu, R., Leng, S., Han, L., Zhang, Q., Liu, N., Dai, C., Wu, B., Yu, G., & Cheng, J. (2022). Disposal methods for used passenger car tires: One of the fastest growing solid wastes in China. *Green Energy & Environment*, 7(6), 1298-1309. doi: [10.1016/j.gee.2021.02.003](https://doi.org/10.1016/j.gee.2021.02.003).
- [9] Dahiya, A. (2020). Cutting-edge biofuel conversion technologies to integrate into petroleum-based infrastructure and integrated biorefineries. In *Bioenergy* (pp. 649-670). London: Academic Press. doi: [10.1016/b978-0-12-815497-7.00031-2](https://doi.org/10.1016/b978-0-12-815497-7.00031-2).
- [10] Devarajan, Y., Munuswamy, D.B., Subbiah, G., Vellaiyan, S., Nagappan, B., Varuvel, E.G., & Thangaraja, J. (2022). Inedible oil feedstocks for biodiesel production: A review of production technologies and physicochemical properties. *Sustainable Chemistry and Pharmacy*, 30, article number 100840. doi: [10.1016/j.scp.2022.100840](https://doi.org/10.1016/j.scp.2022.100840).
- [11] Eldiehy, K.S., Daimary, N., Borah, D., Sarmah, D., Bora, U., Mandal, M., & Deka, D. (2022). Towards biodiesel sustainability: Waste sweet potato leaves as a green heterogeneous catalyst for biodiesel production using microalgal oil and waste cooking oil. *Industrial Crops and Products*, 187, article number 115467. doi: [10.1016/j.indcrop.2022.115467](https://doi.org/10.1016/j.indcrop.2022.115467).
- [12] Elgharbawy, A.S., Sadik, W., Sadek, O.M., & Kasaby, M.A. (2021). [A review on biodiesel feedstocks and production technologies](https://doi.org/10.1016/j.jchsc.2021.05.009). *Journal of the Chilean Chemical Society*, 66(1), 5098-5109.
- [13] Esmaeili, H. (2022). A critical review on the economic aspects and life cycle assessment of biodiesel production using heterogeneous nanocatalysts. *Fuel Processing Technology*, 230, article number 107224. doi: [10.1016/j.fuproc.2022.107224](https://doi.org/10.1016/j.fuproc.2022.107224).
- [14] Gad, M.S., Ağbulut, Ü., Afzal, A., Panchal, H., Jayaraj, S., Qasem, N.A., & El-Shafay, A.S. (2023). A comprehensive review on the usage of the nano-sized particles along with diesel/biofuel blends and their impacts on engine behaviors. *Fuel*, 339, article number 127364. doi: [10.1016/j.fuel.2022.127364](https://doi.org/10.1016/j.fuel.2022.127364).
- [15] Ganesan, R., Manigandan, S., Samuel, M.S., Shanmuganathan, R., Brindhadevi, K., Chi, N.T.L., & Pugazhendhi, A. (2020). A review on prospective production of biofuel from microalgae. *Biotechnology Reports*, 27, article number e00509. doi: [10.1016/j.btre.2020.e00509](https://doi.org/10.1016/j.btre.2020.e00509).
- [16] Hazrat, M.A., Rasul, M.G., Khan, M.M.K., Mofijur, M., Ahmed, S.F., Ong, H.C., & Show, P.L. (2021). Techniques to improve the stability of biodiesel: A review. *Environmental Chemistry Letters*, 19, 2209-2236. doi: [10.1007/s10311-020-01166-8](https://doi.org/10.1007/s10311-020-01166-8).
- [17] Hosseinzadeh-Bandbafha, H., Li, C., Chen, X., Peng, W., Aghbashlo, M., Lam, S.S., & Tabatabaei, M. (2022). Managing the hazardous waste cooking oil by conversion into bioenergy through the application of waste-derived green catalysts: A review. *Journal of Hazardous Materials*, 424, article number 127636. doi: [10.1016/j.jhazmat.2021.127636](https://doi.org/10.1016/j.jhazmat.2021.127636).
- [18] Jayaraman, J., Dawn, S.S., Appavu, P., Mariadhas, A., Joy, N., Alshgari, R.A., & Kumar, J.A. (2022). Production of biodiesel from waste cooking oil utilizing zinc oxide nanoparticles combined with tungsto phosphoric acid as a catalyst and its performance on a CI engine. *Fuel*, 329, article number 125411. doi: [10.1016/j.fuel.2022.125411](https://doi.org/10.1016/j.fuel.2022.125411).
- [19] Khan, Z., Javed, F., Shamair, Z., Hafeez, A., Fazal, T., Aslam, A., & Rehman, F. (2021). Current developments in esterification reaction: A review on process and parameters. *Journal of Industrial and Engineering Chemistry*, 103, 80-101. doi: [10.1016/j.jiec.2021.07.018](https://doi.org/10.1016/j.jiec.2021.07.018).

- [20] Konur, O. (2021). Biodiesel and petrodiesel fuels: Science, technology, health, and the environment. In *Biodiesel fuels* (pp. 3-36). Boca Raton: CRC Press. doi: [10.4324/9780367456238-2](https://doi.org/10.4324/9780367456238-2).
- [21] Kukana, R., & Jakhar, O. P. (2022). Performance, combustion and emission characteristics of a diesel engine using composite biodiesel from waste cooking oil – *Hibiscus Cannabinus* oil. *Journal of Cleaner Production*, 372, article number 133503. doi: [10.1016/j.jclepro.2022.133503](https://doi.org/10.1016/j.jclepro.2022.133503).
- [22] Maheshwari, P., Haider, M.B., Yusuf, M., Klemeš, J.J., Bokhari, A., Beg, M., & Jaiswal, A.K. (2022). A review on latest trends in cleaner biodiesel production: Role of feedstock, production methods, and catalysts. *Journal of Cleaner Production*, 355, article number 131588. doi: [10.1016/j.jclepro.2022.131588](https://doi.org/10.1016/j.jclepro.2022.131588).
- [23] Mathew, G.M., Raina, D., Narisetty, V., Kumar, V., Saran, S., Pugazhendi, A., & Binod, P. (2021). Recent advances in biodiesel production: Challenges and solutions. *Science of the Total Environment*, 794, article number 148751. doi: [10.1016/j.scitotenv.2021.148751](https://doi.org/10.1016/j.scitotenv.2021.148751).
- [24] Mushtruk, M., Bal-Prylypko, L., Slobodyanyuk, N., Boyko, Y., & Nikolaienko, M. (2022). Design of reactors with mechanical mixers in biodiesel production. In *Lecture notes in mechanical engineering* (pp. 197-207). Springer: Springer International Publishing. doi: [10.1007/978-3-031-06044-1_19](https://doi.org/10.1007/978-3-031-06044-1_19).
- [25] Mushtruk, M., Mushtruk, N., Slobodyanyuk, N., Vasylyv, V., & Zheplinska, M. (2024). Enhanced energy independence: Converting animal fat into biodiesel. *International Journal of Environmental Studies*, 81(1), 134-144. doi: [10.1080/00207233.2024.2314860](https://doi.org/10.1080/00207233.2024.2314860).
- [26] Pasha, M.K., Dai, L., Liu, D., Guo, M., & Du, W. (2021). An overview to process design, simulation and sustainability evaluation of biodiesel production. *Biotechnology for Biofuels*, 14, article number 129. doi: [10.1186/s13068-021-01977-z](https://doi.org/10.1186/s13068-021-01977-z).
- [27] Pinheiro, C.T., Quina, M.J., & Gando-Ferreira, L.M. (2021). Management of waste lubricant oil in Europe: A circular economy approach. *Critical Reviews in Environmental Science and Technology*, 51(18), 2015-2050. doi: [10.1080/10643389.2020.1771887](https://doi.org/10.1080/10643389.2020.1771887).
- [28] Razak, N.H., Hashim, H., Yunus, N.A., & Klemeš, J.J. (2021). Reducing diesel exhaust emissions by optimisation of alcohol oxygenates blend with diesel/biodiesel. *Journal of Cleaner Production*, 316, article number 128090. doi: [10.1016/j.jclepro.2021.128090](https://doi.org/10.1016/j.jclepro.2021.128090).
- [29] Subhash, G.V., Rajvanshi, M., Kumar, G.R.K., Sagaram, U.S., Prasad, V., Govindachary, S., & Dasgupta, S. (2022). Challenges in microalgal biofuel production: A perspective on techno economic feasibility under biorefinery stratagem. *Bioresource Technology*, 343, article number 126155. doi: [10.1016/j.biortech.2021.126155](https://doi.org/10.1016/j.biortech.2021.126155).
- [30] Suzihaque, M.U.H., Syazwina, N., Alwi, H., Ibrahim, U.K., Abdullah, S., & Haron, N. (2023). A sustainability study of the processing of kitchen waste as a potential source of biofuel: Biodiesel production from waste cooking oil (WCO). *Materials Today: Proceedings*, 63, S484-S489. doi: [10.1016/j.matpr.2022.04.526](https://doi.org/10.1016/j.matpr.2022.04.526).
- [31] Tucki, K., Orynych, O., Wasiak, A., Świć, A., Mruk, R., & Botwińska, K. (2020). Estimation of carbon dioxide emissions from a diesel engine powered by lignocellulose derived fuel for better management of fuel production. *Energies*, 13(3), article number 561. doi: [10.3390/en13030561](https://doi.org/10.3390/en13030561).
- [32] Vickram, S., Manikandan, S., Deena, S.R., Mundike, J., Subbaiya, R., Karmegam, N., & Awasthi, M.K. (2023). Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management – a critical review. *Bioresource Technology*, 387, article number 129660. doi: [10.1016/j.biortech.2023.129660](https://doi.org/10.1016/j.biortech.2023.129660).
- [33] Zhao, Y., Wang, C., Zhang, L., Chang, Y., & Hao, Y. (2021). Converting waste cooking oil to biodiesel in China: Environmental impacts and economic feasibility. *Renewable and Sustainable Energy Reviews*, 140, article number 110661. doi: [10.1016/j.rser.2020.110661](https://doi.org/10.1016/j.rser.2020.110661).

- [34] Zulqarnain, M.Y.M.H., Ayoub, M., Ramzan, N., Nazir, M.H., Zahid, I., Butt, T.A. (2021). Overview of feedstocks for sustainable biodiesel production and implementation of the biodiesel program in Pakistan. *ACS Omega*, 6(29), 19099-19114. doi: [10.1021/acsomega.1c02402](https://doi.org/10.1021/acsomega.1c02402).

Математична модель процесу перетворення відпрацьованих олій в дизельне біопаливо

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Анотація. Зростання попиту на відновлювані джерела енергії стимулює розвиток технологій виробництва біодизеля з відходів, однак високий вміст вільних жирних кислот у сировині ускладнює переестерифікацію, знижує вихід палива та підвищує потребу в очищенні. Метою дослідження була розробка та валідація математичної моделі процесу переестерифікації відпрацьованих олій у дизельне біопаливо для оптимізації технологічних параметрів. Раціоналізована модель детально описала закономірності трансформації тригліцеридів у присутності спирту та каталізатора. Вона дозволила відстежувати зміну концентрацій проміжних продуктів реакції, зокрема дигліцеридів, моногліцеридів, біодизеля та гліцерину, що є критично важливим для прогнозування ефективності процесу. Сталі значення швидкості процесу переестерифікації вказані через рівняння Арреніуса, що дозволили оцінити вплив температури та співвідношення реагентів на загальну кінетику реакції. У рамках дослідження проведено чисельне моделювання та кореляцію моделі шляхом систематизації результатів з даними, які були отримані під час проведення досліджень та отриманих за результатами аналізу літературних джерел. Було проаналізовано каталітичні та некаталітичні варіанти процесу, що дозволило визначити найефективніші умови проведення реакції. Результати моделювання підтвердили, що збільшення температурних показників до 60°C призводить до збільшення виходу дизельного біопалива, тому надмірне нагрівання понад температуру кипіння метанолу спричиняє його випаровування, що призводить до зниження ефективності процесу та втрати сировини. Визначено оптимальні технологічні параметри, які забезпечують максимальний вихід біодизеля при мінімальних матеріальних та енергетичних витратах. Запропонована математична модель може бути використана в промислових умовах для оптимізації процесу виробництва біопалива, сприяючи підвищенню ефективності переробки вторинної сировини

Ключові слова: кінетична модель; вільні жирні кислоти; оптимізація параметрів; температурний режим; вихід біопалива; енергетична ефективність



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Automated OptiMix-360 system for continuous dough mixing: Technical solutions and efficiency

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Abstract. Enhancing the efficiency and stability of industrial dough production is achievable through the implementation of innovative technologies that optimise quality and reduce costs. The objective of this study was to evaluate the efficiency of the OptiMix-360 system for industrial dough production by integrating technologies such as gravimetric dosing, premixers, and dough mixers and to determine its impact on improving productivity and final product quality. The research methodology was based on an experimental approach that assessed the efficiency of the OptiMix-360 system compared to traditional methods by measuring product quality parameters and process performance under different operating conditions. The study analysed the effectiveness of the GraviFlow Master, TORNADO-2, and ProMix D-Helix equipment based on performance indicators, energy consumption, dosing accuracy, and final product quality when these technologies were integrated into the production process. The implementation of the OptiMix-360 system resulted in a significant productivity increase to 1500 kg/h, a 30% reduction in energy consumption, and consistent dough batch quality. The gravimetric dosing system ensured an accuracy of <0.1%, enhancing composition stability, while the TORNADO-2 premixer improved flour hydration and gluten formation, positively affecting the texture and strength of the final product. The production process was stabilised, and product quality fluctuations were minimised due to automation and adaptive settings. The obtained results confirmed the effectiveness of the OptiMix-360 system in industrial practice. This technology not only improved dough quality but also reduced energy consumption costs and increased productivity. The application of the OptiMix-360 system in the food industry holds high potential for improving production efficiency, reducing energy costs, and ensuring consistent product quality.

Keywords: food industry; rheology; fibrin; gluten; bakery industry**Suggested Citation:**

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Introduction

The development of the food industry, especially the bakery industry, largely depends on the introduction of innovative technologies, since the market places high demands on the quality, stability, and variety of products. In this context, there is a need to optimise technological processes, in particular in the production of dough, which is the main component of bakery products. The growing scale of production and the requirements for its efficiency increase the relevance of integrating automated mixing systems.

Conventional methods of periodic kneading of dough used in many enterprises have a number of disadvantages. The main ones are the heterogeneity of the final texture, high energy intensity, and a significant influence of the human factor on production processes. These problems were analysed by O.I. Petrova & N.P. Shevchuk (2020), who pointed out the importance of implementing automated solutions to improve the quality of dough and reduce losses. M. Sanitska (2023) noted the need to adapt the mixing systems used to the requirements of medium and large enterprises to improve production efficiency. However, many issues remain unresolved, in particular, the integration of continuous kneading processes and their automation.

Automation of technological processes in the bakery industry was considered as an important area of industry development. A.A. Solianyuk (2021) studied in detail the impact of automated lines on the production of sponge products, emphasising their ability to increase productivity and reduce energy consumption. However, the main focus of his research was on confectionery products, while kneading dough for bakery products requires a specific approach, considering the variety of recipes and processing parameters.

M. Obadi *et al.* (2022) also focused on improving kneading technologies, especially in the production of noodles. Studies have shown that the integration of new technologies, such as the use of premixes and automated dough mixers, significantly improves the quality of the final product.

However, questions about the economic feasibility of implementing such systems for bakery products remain poorly understood. Similar accents were indicated in the study by A. Singh (2021), where the researcher reviewed the evolution of technology in the bakery industry. The author noted the importance of switching to automated continuous processes, but most of the analysis concerned general aspects of automation, without a detailed analysis of the specifics of kneading dough.

Research in the field of dough kneading indicates the need to improve technologies. In particular, G. Campbell & P. Martin (2020) emphasised the importance of aeration of the dough during kneading, as it directly affects the rheological properties and the level of rise of the dough during baking. The researchers also focused on the critical role of the interaction of ingredients and technological parameters in the aeration and dough structure.

Y.-L. Yang *et al.* (2021) conducted a study that focused on the effect of vacuum degree, mixing rate, and water quantity on moisture distribution and rheological properties of wheat flour dough. The results provided new opportunities for optimising technological parameters in the processing of flour dough. As noted by A. Cappelli *et al.* (2020), kneading is one of the key stages of bakery production, affecting not only the structure of the dough, but also the final organoleptic properties of bread. The researchers systematised approaches to improving the rheology of the dough by adjusting the intensity of mechanical impact, and integrating new ingredients that improve the structural characteristics of the dough. However, their research focused mainly on laboratory conditions and did little to highlight the adaptation of these methods for large-scale industrial production.

S. Tietze *et al.* (2019) made a significant contribution to understanding the effect of mechanical shear on the development of the gluten mesh. They focused on the relationship between the intensity of kneading and the quality of dough,

especially in the production of wheat bread. However, their research pointed to the problems of overheating of the dough and uneven influence of mechanical energy when using conventional kneading systems. These aspects highlight the need to improve existing technologies to minimise the shortcomings of traditional approaches. R. Jerome *et al.* (2019) in their review paper examined the role of analytical control technologies in the bakery industry, noting their importance for optimising technological processes. The researchers noted that the introduction of process-analytical technologies can increase the level of production automation, reduce the influence of the human factor, and ensure the stability of product quality.

However, the specific analysis of continuous mixing systems remains poorly covered in their research, which has created gaps in understanding the benefits of such systems for industrial scale.

The purpose of this study was to create and analyse the effectiveness of the OptiMix-360 automated continuous dough kneading system, capable of working with various types of flour.

Materials and Methods

The study was conducted using the integrated technological system OptiMix-360, specially adapted for the production conditions of food industry enterprises. The technological scheme of the equipment is shown in Figure 1.

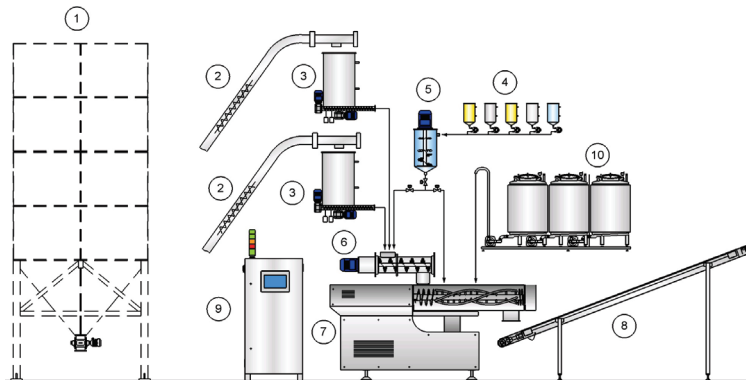


Figure 1. Machine and hardware diagram of the OptiMix-360 system

Note: 1 – flour storage silo (Golfetto Sangati, Italy); 2 – flexible screw feeder for flour transportation (Flexicon, USA); 3 – gravimetric dosing system GraviFlow Master (Chronos Richardson, Great Britain); 4 – microdosing unit for liquid components (Dosatron D30WL2, France); 5 – turbomixer for pre-solution (Ika Ultra-Turrax, Germany); 6 – premixer TORNADO-2 (Tetra Pak, Sweden); 7 – continuous dough mixer Promix D-Helix (WP Kemper, Germany); 8 – conveyor for dough maturation (Intralox, USA); 9 – control unit with programmable logic controller (Siemens S7 – 1500, Germany); 10 – CIP system for automatic washing (Alfa Laval, Sweden)

Source: compiled by the author

At the first stage of the study, precise micro-dosing of liquid components was performed using a specialised Dosatron D30WL2 unit (France). The components were pre-weighed on a high-precision laboratory scale Mettler Toledo (Switzerland). The dosage error did not exceed 0.1% of the total weight of the components. The unit provided automated injection of liquids in appropriate proportions, which helped to avoid the influence of the human factor and ensured the stability of the

process. Mixing of liquid components with water was carried out in a turbomixer (Ika Ultra-Turrax, Germany) for the solution, which ensured uniform distribution of the liquid and the formation of a homogeneous liquid phase for subsequent introduction into dry ingredients. The resulting liquid ingredients were mixed with water until a homogeneous liquid phase was formed. At this stage, a turbomixer (Ika Ultra-Turrax, Germany) was used, which ensured complete homogenisation of the

mixture before its subsequent integration with dry components.

The GraviFlow Master System (UK) provided continuous gravimetric dosing of three types of flour, depending on the requirements of the recipe. Using load cells, the accuracy of flour weight measurements was $\pm 0.05\%$, which guaranteed the stability of the resulting dough. The liquid phase was gradually added to the dry components in the TORNADO-2 premixer (Sweden), which provided the initial combination of ingredients. A special feature of this stage was the active development of a gluten mesh, which is necessary for the correct structure of the dough.

At the main kneading stage, the ProMix D-Helix dough mixer (Germany) was used, which provided a soft but energy-efficient introduction of mechanical energy into the dough. The process took place in two stages: one stream of the liquid phase was fed to the premixer, the other – directly to the dough mixer. The system worked with maintaining a stable temperature of 28–30°C using a double jacket, which provided optimal conditions for the development of the dough structure.

Automation of the OptiMix-360 system was carried out using a programmable logic controller Siemens S7-1500 (Germany), which performed monitoring and adaptive control functions at all stages of the technological process. Built-in sensors tracked key parameters such as humidity, temperature, ingredient proportions, and component flow rate. Data from the sensors was processed in real time, which allowed automatically adjusting the equipment settings. The Human-Machine Interface (HMI) provided intuitive process control for the operator, visualising key parameters and system status. The remote monitoring function based on the Internet of Things technology helped to perform diagnostics and quickly respond to any deviations, reducing equipment downtime.

The effectiveness of the study was evaluated by indicators of stability of the consistency of the finished dough (40–45% moisture, depending on the recipe); process productivity (1,200 kg/h) and

minimisation of material losses (dosage deviation $< 0.1\%$). All measurements were carried out under laboratory and semi-industrial conditions, which allowed adapting the results for practical application.

The study also evaluated the conventional system of periodic kneading of dough Diosna W240A (Germany), which involves the use of large bins or bowls. This system is characterised by a number of disadvantages: limited flexibility, since each batch of dough requires individual settings; heterogeneity of quality due to uneven mixing; high energy intensity caused by significant mechanical losses; and labour intensity of maintenance. In contrast, the OptiMix-360 provides a continuous, energy-efficient and fully automated process, reducing the impact of the human factor and improving quality and productivity.

During the implementation study of the OptiMix-360 technology system, a number of ISO standards were observed that ensure high quality, safety, and efficiency of processes. In particular, the ISO 9001:2015 (2015) standard was used for quality management systems, which ensures compliance with all requirements at every stage of the production process. It also considered the requirements of ISO 22000:2018 (2018) for the food safety management systems, which is important for the production of food components, and ISO 45001:2018 (2018) for occupational safety, which reduces risks to personnel, especially when working with high-tech systems. These standards have become the basis for ensuring the stability and safety of the studied processes in industrial conditions.

Results

Characteristics of the main technological components of the OptiMix-360 system. The GraviFlow Master gravimetric dosing system is an innovation in the field of bulk material dosing and belongs to the category of continuous weighing systems (Fig. 2). It provides a precise and stable flow of components, which is critical for industrial processes such as dough kneading. The

main principle of operation of the system is to continuously measure the weight of material in the hopper using load cells that transmit data to the controller. The controller analyses this data and automatically adjusts the feed rate, ensuring the stability of the material flow in accordance with the specified parameters. The hopper used for storing bulk materials is designed to ensure their smooth and uniform flow. High-precision load cells constantly measure the weight of the material in the hopper, which is the basis for the operation of the system. A screw conveyor or vibrating feeder is often used as a feeding device, which provides a controlled flow of materials. The controller integrates all sensor data, analyses it in real time, and adjusts the feed rate if deviations are detected to ensure that the actual material flow matches the desired one.



Figure 2. GraviFlow Master gravimetric dosing system

Note: the system consists of the following key elements: a hopper for storing bulk materials (provides storage of the metered component, optimising its feed); load cells (located on the hopper, they continuously measure the weight of the material in real time); a controller (processes data from load cells and, depending on the information received, adjusts the feed rate of the material); a feed device (screw conveyor or vibrating feeder), which provides a controlled flow of material based on the received signals from the controller

Source: compiled by the author

The system control loop is based on the feedback principle. When the desired feed rate is set, the system continuously compares it with the

actual speed obtained from the load cell readings. The controller processes this data, and if it detects discrepancies, it instantly corrects the operation of the feed devices. This ensures that a stable material feed rate is maintained even under variable production conditions.

GraviFlow Master has a number of important advantages. The accuracy of the system allows minimising dosing errors to less than 0.1%, which is critical for the stability of the dough characteristics. Consistency and uniformity of dosage ensure uniformity of the composition and quality of the product. The effectiveness of this technology is also manifested in saving materials and reducing the amount of waste, which increases the economic feasibility of its use. The flexibility of GraviFlow Master allows adapting it to work with different types of materials and requirements of production processes. When implementing continuous weighing system, certain difficulties may arise, in particular, inhomogeneities in the flow of materials due to vibrations or pressure fluctuations, which can affect the accuracy of measurements. To solve such problems, methods of vibration isolation, advanced control of motors of feed devices and compensation of pressure fluctuations are used. GraviFlow Master has proven its efficiency and adaptability in dynamic industrial environments. Its integration into production lines such as the OptiMix-360 system has ensured accurate dosing, process stability, and improved the quality of the finished dough.

Another important step in the production of dough is pre-mixing, as it significantly affects the characteristics and quality of the final product. This process begins with a combination of ingredients such as flour and water, which leads to the formation of gluten – the structure that ensures the strength and elasticity of the dough (Sattarov *et al.*, 2024). It is pre-mixing that creates the necessary conditions for the activation of flour proteins, gliadin and glutenin, and an even distribution of moisture.

The TORNADO-2 premixer has demonstrated significant advantages in this process due to its

innovative design. The device provides a fast and efficient combination of ingredients with minimal loss of mechanical energy, which avoids the development of lumps and preserves the integrity of the dough structure. Chemical and physical interactions in the dough that occur during pre-mixing play an important role in its structure and texture. The process of protein hydration is the first step: proteins absorb water and interact with each other, forming a three-dimensional gluten structure. Gliadin is responsible for the stretchability of the dough, and gluten gives it strength. In addition, starch hydration contributes to the creation of a homogeneous mass, acting as a filler and connector between proteins. The mechanical energy transferred during the mixing process helps to stretch and align protein molecules, strengthening the structure of gluten. However, excessive exposure to mechanical energy can disrupt the structure of the dough, so precise control of the process is an important factor. Temperature plays an equally important role: optimal protein hydration conditions are provided in the range of 26-36°C.

TORNADO-2 allows optimising all aspects of pre-mixing. It is designed to maintain a stable temperature regime, and the use of advanced mechanical elements minimises possible disadvantages, such as overheating or structural damage. The result is a high-quality dough with an even distribution of moisture, a stable texture and a strong gluten mesh. Pre-mixing in TORNADO-2 provided an efficient start to the dough forming process, creating optimal conditions for subsequent stages such as kneading and maturation. This device has proven its effectiveness in improving the consistency of dough, which is the key to high quality bakery and pasta products. Due to the introduction of this technology, it was possible to achieve stable quality of the final product and reduce the number of defects in the production process. The ProMix D-Helix dough mixer is a solution in continuous dough kneading technology that offers numerous advantages over conventional periodic kneading methods. Its design ensures high efficiency, compactness and

reliability, making this machine an ideal choice for industrial production (Fig. 3).



Figure 3. ProMix D-Helix dough mixer

Source: compiled by the author

One of the main advantages of ProMix D-Helix is the use of an innovative bowl with a circulation cooling system, which allows precisely controlling the temperature regime throughout the entire process. This is necessary to maintain the optimal texture of the dough and prevent it from overheating. A special feature of the dough mixer is the unique kneading organs made in a combination of two shapes (Fig. 4). One part is shaped like an auger, which allows for directional movement of the dough, while the second, similar to the “DNA molecule”, promotes delicate mixing without excessive shear or cutting, which can negatively affect the quality of the dough structure.



Figure 4. Kneading part of the ProMix D-Helix dough mixer

Source: compiled by the author

ProMix D-Helix uses the principle of careful use of mechanical energy. The energy distribution during kneading aligns and stretches gluten molecules, contributing to the development of a stable and elastic gluten mesh. This process ensures the correct development of the dough structure, making it elastic and able to maintain its shape during baking. It is important to note that controlling the kneading intensity avoids excessive mechanical impact, which can disrupt the gluten mesh, turning the dough into an excessively elastic and dense mass.

Special attention is paid to the effect of friction during kneading, since the release of heat can increase the temperature of the dough. ProMix D-Helix, due to its cooling system, provides a stable temperature, which prevents protein denaturation and weakening of the gluten mesh. The result of this control is high quality dough with a strong texture and optimal properties for further production. The flexibility of the ProMix D-Helix design allows adapting the kneading organs for different types of dough, such as lingering cookies or rye bread. The versatility of this technology makes it easy to replace components for working with various formulations, which is an additional advantage for large-scale industrial processes. Thus, the use of ProMix D-Helix significantly improves all key indicators of dough kneading, including its texture, stability and adaptability to various production conditions.

The results of the implementation of the OptiMix-360 system for continuous kneading of dough in industrial conditions demonstrate significant advantages over conventional methods of periodic kneading. The study provides key metrics obtained during system testing, including dough quality, energy saving, production capacity, production flexibility, and ease of operation and maintenance.

Dough quality. The OptiMix-360 system provides excellent consistency stability for each batch of dough due to precise compliance with technological parameters and uniform processing conditions. Thanks to the integration of

advanced gravimetric dosing systems and automatic mixing control, the gluten mesh was formed evenly, which guaranteed high elasticity of the dough. The mechanical action of the ProMix D-Helix system, combined with controlled hydration, helped to avoid structural breaks, which is often observed in conventional systems. The stable consistency reduced baking variations, which is an important factor for large-scale production. This allowed increasing the predictability and quality of the finished product, minimising production waste due to defects in the structure or consistency of the dough.

Due to the precise observance of temperature and humidity parameters throughout the entire process, the OptiMix-360 system has created a dough with a perfect texture. Smoothness and uniformity of the surface were achieved by step-by-step introduction of liquid components through the TORNADO-2 premixer and efficient mixing in ProMix D-Helix. It is important to note that the structure of the dough eliminated the problem of tearing off the top of the bread, which was characteristic when using conventional kneading methods.

This characteristic significantly improved the final quality of baked goods, preserving their shape and texture properties. Combined with the ability to work with different types of flour (rye, wheat, mixed recipes), OptiMix-360 demonstrates advantages in the production of a wide range of bread.

Compared to conventional batch kneading systems such as Diosna W240A or Kemper SP150, the OptiMix-360 system provides significantly better dough texture uniformity due to its continuous processing process. The absence of the need for unloading and re-dosing reduced the risk of local changes in the mixing of components, which positively affected the overall quality. Due to this, the final baked goods were characterised by stable dimensions, smooth surface, and more pronounced organoleptic properties. The high quality of the dough texture also contributed to better moisture retention in baked goods, increasing their freshness period.

During the testing process, it was found that the dough processed by the OptiMix-360 system has optimal strength and tensile ability, which are key indicators of high-quality bakery products. The elasticity of the dough helped to significantly reduce breaks when forming products and cutting ready-made bread.

Productivity and energy efficiency of the process.

The OptiMix-360 system demonstrated high productivity, reaching a production capacity of up to 1,500 kg/h, which exceeds the originally planned figure of 1,200 kg/h. This result is made possible by integrating a continuous flow of technological processes, which eliminates the need to stop between mixing stages. This significantly reduces the time spent on preparatory operations. The key is full automation, which reduces the risk of human exposure. Programmable logic controllers, together with sensors that monitor all the main parameters (humidity, temperature, component feed rate), helped to maintain ideal conditions for the process, which guarantees the stability and uniformity of each batch of dough. Thus, production operated continuously, which significantly increases the volume of products without loss of quality.

The OptiMix-360 system reduces power consumption by 30% compared to conventional periodic mixing systems. This savings were achieved by reducing the mechanical load on the dough due to the uniform distribution of energy during mixing. Additionally, automated process control ensures precise temperature control using a double jacket, which eliminates overheating of the dough and irrational energy consumption. A key role in achieving energy efficiency was played by sensors that provided constant monitoring of process parameters and timely adjustment of equipment operation. The integration of such components helped to optimise energy consumption at all stages of kneading.

Flexibility, adaptability and ease of use. The OptiMix-360 system has demonstrated the ability to work effectively with a variety of dough recipes,

including rye, wheat, and rye-wheat. This flexibility allowed adapting the production process to various technological requirements that arose due to changes in the characteristics of raw materials or consumer requests. The system provided the ability to quickly adjust parameters in real time due to the integration of sensors and control algorithms. Making changes to the formulation did not affect the quality of the final product due to precise control over all parameters – from temperature to the proportions of components. Adaptability ensured the stability of the process and helped to avoid losses of raw materials even in conditions of variable dough composition.

The OptiMix-360 made it easy to operate with an intuitive HMI that allowed operators to access visualised system status data. The controllers monitored key parameters, and any deviations from the set indicators were immediately displayed on the operators' screens. This made it easier to make decisions and faster to respond to potential problems. The remote monitoring function based on the Internet of Things helped to quickly diagnose and fix problems, minimising equipment downtime. The simplicity of the system's design also played an important role: the components were positioned in such a way as to provide easy access for maintenance and cleaning. This reduced the time and effort required to prepare the equipment for further operation, which further increased overall efficiency.

Thus, the implementation of the OptiMix-360 system allowed achieving stable dough quality, increasing production efficiency, and reducing operating costs (Table 1). The results obtained indicate its suitability for large-scale implementation in industrial bakery enterprises.

The results obtained during the study of the OptiMix-360 system indicate significant advantages of this technology in the industrial production of dough. All key aspects – from dough consistency to energy efficiency – showed a significant improvement over conventional batch kneading methods. Due to precise control at every stage, starting with microdosing of components

and ending with final kneading, it was possible to achieve a stable consistency and uniformity of gluten mesh formation. This result directly

affected the improvement of the dough texture, which became the basis for the production of high-quality baked goods.

Table 1. OptiMix-360 system performance compared to the conventional method

Indicator (%)	Conventional method	OptiMix-360 system
Quality	70	95
Energy saving	50	80
Production capacity	100	125
Production flexibility	65	85
Easier operation and maintenance	55	75

Source: compiled by the author

The energy efficiency of the system is another significant achievement. The recorded reduction in energy consumption by 30% compared to conventional systems was made possible by the use of upgraded process control mechanisms and minimising the mechanical load on the dough. This not only reduced operating costs, but also helped to optimise production processes, making the system more environmentally friendly. The OptiMix-360's performance, which has reached 1,500 kg/h, is proof of its technical improvement. The ability to maintain high productivity without compromising product quality has significantly increased production volumes, which is especially important for large industrial enterprises.

Advantages and limitations of the system. The introduction of the OptiMix-360 system in production has led to several strategic advantages. In particular, due to the continuity of the mixing process and full automation, it was possible to eliminate downtime characteristic of periodic systems and achieve a reduction in overall energy, repair, and maintenance costs. In addition, the uniformity and stability of the dough parameters were ensured by final products with improved texture, structure, and taste qualities. This not only meets consumer expectations, but also meets high market standards.

In addition, the system allowed adapting to different types of flour, recipes, and quickly changing production parameters without stopping the

technological process. This has expanded the product range, allowing products to be produced for various consumer segments, including organic and speciality products. Intuitive HMI, process automation, and easy maintenance reduced the need for a large number of maintenance personnel and reduced downtime.

Along with the advantages, the study also revealed certain limitations of the OptiMix-360 system. The first and most significant is the high cost of implementation. The initial cost of purchasing and installing the system can be significant for small and medium-sized enterprises, which can become a barrier to its mass implementation. In addition, high automation requires a qualified approach. To maximise the use of the system's capabilities, training of operators and technical personnel is required. An important aspect of successful operation is the dependence on the accuracy of settings, since for optimal operation it is necessary to configure the system for specific production conditions, and errors at this stage can lead to a decrease in productivity or product quality. The influence of external factors, such as vibrations or pressure fluctuations in the production environment, can affect the accuracy of dosing or settings, which requires additional stabilisation solutions. The results of the implementation of the OptiMix-360 system show that it is a promising tool for optimising production processes, in particular in the bakery industry. Consideration of limitations and potential risks will avoid

difficulties and ensure its maximum effectiveness in the long term.

All stages of production met the requirements of ISO 9001:2015 (2015) for quality management systems, which ensured compliance with all critical requirements. The ISO 22000:2018 (2018) standard for the food safety management systems confirmed proper risk management in food production, and ISO 45001:2018 (2018) contributed to minimising production risks and improving occupational safety, especially in the use of technologies with high requirements for accuracy and efficiency, such as the OptiMix 360 system. Due to compliance with these standards, the stability and safety of technological processes at all stages is achieved.

Discussion

The results of the study confirm that the integration of the OptiMix-360 system has significantly improved the quality of dough, increased the efficiency of production processes, and reduced energy costs. In particular, the study confirmed a significant impact of process structure and control on dough quality, which is consistent with the results published by A. Ktenioudaki *et al.* (2010). The researchers investigated the effect of various kneading processes on the rheological characteristics of the dough, finding that the uniformity of mechanical energy supply and effective hydration are crucial for obtaining a uniform texture. The OptiMix-360 system, due to the TORNADO-2 pre-mixer and the ProMix D-Helix dough mixer, ensured proper hydration and energy distribution, which helped to achieve a high-quality gluten mesh. One of the key areas of modern development of production systems is the introduction of artificial intelligence and automated control algorithms, which was confirmed by E. Carpanzano & D. Knüttel (2022). Their findings show that the use of intelligent systems in production processes can significantly improve stability and productivity. The OptiMix-360 system implements similar approaches – automated process control is carried out using programmable logic controllers

(Siemens S7-1500), which allows quickly adapting the process parameters.

The study by V. Piddubnyi *et al.* (2024) showed that proper design of kneading processes helps to improve the quality of the final product and reduce energy consumption. Optimisation of the kneading process through automatic gravimetric dosing and pre-mixing, which is used in OptiMix-360, confirmed these results, in particular, in reducing energy consumption by 30%. S. Dhal *et al.* (2023) analysed the effect of mixing time on the properties of whole-grain flour cookie dough. It was found that the optimal mixing time helps to achieve the necessary uniformity and texture of the dough, which also confirms the importance of mixing control in this study. The study used innovative approaches, in particular, gravimetric dosing and adaptive mixers, which automate and more precisely regulate the mixing process for stable dough quality.

Z. Muchová & B. Žitný (2010) emphasised the importance of improving approaches to dough mixing, considering various external factors, such as vibrations. The OptiMix-360 system takes these aspects into account, as it has design solutions to minimise the impact of vibrations on dosing accuracy and process stability. C. Rosell & C. Collar (2009) focused on the effect of temperature and consistency on dough performance. In particular, they investigated how different temperature conditions affect the formation of gluten mesh and the strength of the dough. The ProMix D-Helix circulation cooling system prevents the dough from overheating during kneading, which ensures proper structure development. This is consistent with the authors' conclusions, which emphasise the need for strict control of temperature conditions to achieve stability of dough quality. The use of a circulating cooling system in ProMix D-Helix reduced the risk of overheating of the dough, which is consistent with the recommendations of F. Aghili (2021) on mechanical load management in production processes. The OptiMix-360 system uses adaptive algorithms for adjusting electric drives, which helped not only

to minimise overheating of the dough but also to improve its texture.

K. Kansou *et al.* (2013) studied changes in the porosity and stability of dough depending on kneading conditions. Optimal mixing parameters have been found to be key to preventing excessive dough density or loss of stability during the ageing process. In the study of the OptiMix-360 system, porosity stability was achieved due to the uniform distribution of mechanical energy and hydration, which confirms the authors' conclusions about the need to provide such conditions for improving the quality of production.

Research by A. Wooding *et al.* (1999) revealed the dependence of dough strength on mixing intensity. The results obtained in this study also showed that precise control of the kneading intensity in the OptiMix-360 system helps to maintain the flexibility of the gluten mesh, which positively affected its ability to withstand mechanical processing during the moulding of products. In addition, the use of an expert system to monitor key parameters, as described in K. Kansou *et al.* (2014), similar to the approaches used, allows for precise process control and maintenance of dough stability under variable production conditions. The study by A. Van der Mijnsbrugge *et al.* (2016) focused on the distribution of the gluten phase as a function of mixing parameters. In turn, OptiMix-360, due to the use of appropriate equipment, ensured a uniform distribution of gluten, which is confirmed by the stability of the dough structure at all stages of the process. In addition, the implemented automation made it possible to minimise the impact of the human factor.

Innovations in mixing weak dough are presented in the study by A. Parenti *et al.* (2013), which investigated mixing control for weak wheat dough using sourdough. OptiMix-360 demonstrated a similar approach, providing precise control of rheological properties even in complex formulations. This proves that the introduction of automation in the system allows maintaining the consistency of the dough regardless of the type of flour and recipe. S. Peighambardoust *et al.* (2006)

emphasised the role of the initial mixing phase in the formation of the dough structure. The use of TORNADO-2 premixer in the implemented technology created optimal conditions for the initial combination of ingredients and the development of gluten mesh, which ensured a high-quality initial stage of kneading. An equally significant role is played by the introduction of sensor technologies in food production. The study by R. Morales *et al.* (2022) confirms that the integration of sensor systems for monitoring parameters such as humidity, temperature, and ingredient flow rate contributes to process stability. Similar principles are implemented in OptiMix-360, which made it possible to ensure high dosing accuracy (<0.1%) and control of process parameters in real time.

Automated control of technological processes, based on modern regulatory algorithms, is one of the key approaches to improving product quality. Research by P.K. Juneja *et al.* (2021) proved the effectiveness of such methods, which is fully consistent with the practice used in OptiMix-360. The use of adaptive control algorithms ensured high dosage accuracy and stability of key technological parameters, reducing the influence of the human factor and increasing the repeatability of product characteristics. J. Lee *et al.* (2023) confirmed that the use of data processing algorithms in the food industry significantly improves control over production processes. In the case of OptiMix-360, the use of automatic analysis of process parameters and algorithmic control of the dough composition contributes to the achievement of high production stability and quality of the final product, which corresponds to general trends in the field of smart production. In addition, research by N.J. Watson *et al.* (2021) highlighted the need to combine sensor control with algorithmic control to ensure process stability. The implementation of these principles in OptiMix-360 allowed achieving uniform kneading and high dosing accuracy, which meets modern requirements for food production automation.

Ultimately, research by H.J. Kaur *et al.* (2024) confirmed the effectiveness of automated

solutions in ensuring product quality stability and optimising production costs. OptiMix-360 implements similar principles, namely gravimetric dosing, automated control of the kneading process, and adaptive parameter control, which significantly reduces material losses and ensures controlled dough quality. The use of the GraviFlow Master system ensured dosing accuracy with a deviation of less than 0.1%, which contributed to the stability of the dough composition. TORNADO-2 premixer optimised the process of moistening flour and forming a gluten mesh, which improved the texture and strength of the final product. The ProMix D-Helix continuous dough mixer helped to evenly distribute mechanical energy and avoid overheating of the dough, which ensured the uniformity of its structure. In addition, automated control based on the Siemens S7-1500 programmable logic controller allowed real-time monitoring of humidity, temperature and proportions of ingredients, which helped to minimise changes in the quality of the final product.

Thus, the results obtained showed that the OptiMix-360 system not only meets the current requirements of the bakery industry, but also demonstrates significant potential for improving kneading processes. Comparison with other studies has highlighted the importance of integrating automated solutions such as stable temperature maintenance, precise hydration, and uniform distribution of mechanical energy. Thus, the results of the study confirmed the feasibility of using OptiMix-360 for industrial production, offering new approaches to solving rheological and technological problems.

Conclusions

The results of the study confirmed the efficiency and innovation of implementing the OptiMix-360 system in industrial dough production. The combination of high-tech equipment such as GraviFlow Master, TORNADO-2, and ProMix D-Helix allowed significantly improving the quality of dough and optimising production processes. Compared to conventional methods, the continuous nature of

the process, automation and adaptability of system settings ensured an increase in productivity up to 1,500 kg/h, a reduction in energy consumption by 30%, and a stable quality of each batch of dough. This helped to minimise losses due to deviations in consistency and ensure a uniform structure, which is especially important for large-scale industrial production.

The use of the GraviFlow Master gravimetric dosing system helped to increase the dosing accuracy to <0.1%, which ensured the stability of the dough composition. The TORNADO-2 premixer allowed optimising the hydration of flour, and the active formation of gluten mesh, which is critical for the texture and strength of the final product. Due to its design features, the ProMix D-Helix dough mixer maintained a stable temperature and uniform distribution of mechanical energy, which prevented overheating of the dough and disruption of its structure.

The main advantages of the system are high energy efficiency, easy operation, and reduced dependence on the human factor through the integration of automated solutions, including HMI and remote monitoring. Stable process parameters provided by an automated control system contributed to high productivity and quality. However, the system has certain limitations, which include the high cost of implementation, the need for specialised training of personnel, dependence on the accuracy of settings and sensitivity to external factors such as vibrations and pressure fluctuations. The results obtained showed the potential of the OptiMix-360 system for wide implementation in the food industry, in particular, in the bakery industry. Its use has significantly increased production efficiency, improved the quality of finished products and reduced costs, which makes it an important element of the technological process.

A limitation of this study was the use of only one type of technology, which may limit the possibility of comparison with other existing methods in other areas of the food industry. The study also did not address the long-term economic effects of

introducing new technologies in different market economies. The results also open up prospects for further research. One of the areas is a detailed analysis of the impact of the system on various types of raw materials, in particular, whole grain or gluten-free flour. It is also worth investigating how the introduction of such systems can affect the taste characteristics of products and their nutritional value. In addition, integrating the system with platforms based on the Internet of Things or

artificial intelligence can improve the data analysis process and automate adjustments. Developing more affordable system options for small businesses is also an interesting area.

None.

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Conflict of Interest

References

- [1] Aghili, F. (2021). *Energy efficient control of electric motors*. Retrieved from <https://arxiv.org/pdf/2109.11113>
- [2] Campbell, G.M., & Martin, P.J. (2020). Bread aeration and dough rheology: An introduction. In S.P. Cauvain (Ed.), *Breadmaking* (3rd ed.) (pp. 325-371). London: Woodhead Publishing. doi: 10.1016/B978-0-08-102519-2.00011-6.
- [3] Cappelli, A., Bettaccini, L., & Cini, E. (2020). The kneading process: A systematic review of the effects on dough rheology and resulting bread characteristics, including improvement strategies. *Trends in Food Science & Technology*, 104, 91-101. doi: 10.1016/j.tifs.2020.08.008.
- [4] Carpanzano, E., & Knüttel, D. (2022). Advances in artificial intelligence methods applications in industrial control systems: Towards cognitive self-optimizing manufacturing systems. *Applied Sciences*, 12(21), 10962. doi: 10.3390/app122110962.
- [5] Dhal, S., Anis, A., Shaikh, H.M., Alhamidi, A., & Pal, K. (2023). Effect of mixing time on properties of whole wheat flour-based cookie doughs and cookies. *Foods*, 12(5), article number 941. doi: 10.3390/foods12050941.
- [6] ISO 22000:2018. (2018). *Food safety management systems – requirements for any organization in the food chain*. Retrieved from <https://www.iso.org/ru/standard/65464.html>.
- [7] ISO 45001:2018. (2018). *Occupational health and safety management systems – requirements with guidance for use*. Retrieved from <https://www.iso.org/ru/standard/63787.html>.
- [8] ISO 9001:2015. (2015). *Quality management systems – requirements*. Retrieved from <https://www.iso.org/ru/standard/62085.html>.
- [9] Jerome, R.E., Singh, S.K., & Dwivedi, M. (2019). Process analytical technology for bakery industry: A review. *Journal of Food Process Engineering*, 42(5), article number e13143. doi: 10.1111/jfpe.13143.
- [10] Juneja, P.K., Sunori, S.K., Sharma, A., Sharma, A., Pathak, H., Joshi, V., & Bhasin, P. (2021). A review on control system applications in industrial processes. *IOP Conference Series: Materials Science and Engineering*, 1022, article number 012010. doi: 10.1088/1757-899X/1022/1/012010.
- [11] Kansou, K., Chiron, H., Della Valle, G., Ndiaye, A., & Roussel, P. (2014). Predicting the quality of wheat flour dough at mixing using an expert system. *Food Research International*, 64, 772-782. doi: 10.1016/j.foodres.2014.08.007.
- [12] Kansou, K., Chiron, H., Valle, G.D., Ndiaye, A., Roussel, P., & Shehzad, A. (2013). Modelling wheat flour dough proofing behaviour: Effects of mixing conditions on porosity and stability. *Food and Bioprocess Technology*, 6, 2150-2164. doi: 10.1007/s11947-012-0854-1.

- [13] Kaur, H.J., Shiv, T., Chopra, R., Dutta, R., Kaur, D.P., Malhotra, P. (2024). Smart bakery: Technology and automation. In A. Verma, P. Verma, K.K. Pattanaik, S.K. Dhurandher & I. Woungang (Eds.), *Advanced network technologies and intelligent computing* (pp. 225-239). Cham: Springer. doi: [10.1007/978-3-031-64076-6_15](https://doi.org/10.1007/978-3-031-64076-6_15).
- [14] Ktenioudaki, A., Butler, F., & Gallagher, E. (2010). The effect of different mixing processes on dough extensional rheology and baked attributes. *Journal of the Science of Food and Agriculture*, 90(12), 2098-2104. doi: [10.1002/jsfa.4057](https://doi.org/10.1002/jsfa.4057).
- [15] Lee, J., Kim, Y., & Kim, S. (2023). The study of an adaptive bread maker using machine learning. *Foods*, 12(22), article number 4160. doi: [10.3390/foods12224160](https://doi.org/10.3390/foods12224160).
- [16] Morales, R., Fernández-Caballero, A., Somolinos, J.A., & Sira-Ramírez, H. (2022). Integration of sensors in control and automation systems 2020. *Journal of Sensors*, 2022, article number 9765679. doi: [10.1155/2022/9765679](https://doi.org/10.1155/2022/9765679).
- [17] Muchová, Z., & Žitný, B. (2010). [New approach to the study of dough mixing processes](#). *Czech Journal of Food Sciences*, 28(2), 94-107.
- [18] Obadi, M., Zhang, J., He, Z., Zhu, S., Wu, Q., Qi, Y., & Xu, B. (2022). A review of recent advances and techniques in the noodle mixing process. *LWT*, 154, article number 112680. doi: [10.1016/j.lwt.2021.112680](https://doi.org/10.1016/j.lwt.2021.112680).
- [19] Parenti, A., Guerrini, L., Granchi, L., Venturi, M., Benedettelli, S., & Nistri, F. (2013). Control of mixing step in the bread production with weak wheat flour and sourdough. *Journal of Agricultural Engineering*, 44(2), 327-330. doi: [10.4081/jae.2013.307](https://doi.org/10.4081/jae.2013.307).
- [20] Peighambardoust, S.H., Van der Goot, A.J., Boom, R.M., & Hamer, R.J. (2006). Mixing behaviour of a zero-developed dough compared to a flour-water mixture. *Journal of Cereal Science*, 44(1), 12-20. doi: [10.1016/j.jcs.2005.12.011](https://doi.org/10.1016/j.jcs.2005.12.011).
- [21] Petrova, O.I., & Shevchuk, N.P. (2020). [Technology of bread, pasta, confectionery and food concentrates](#). Mykolaiv: Mykolaiv National Agrarian University.
- [22] Piddubnyi, V., Sabadosh, A., Mushtruk, M., Chahaida, A., Fedorov, V., Kravcheniuk, K., Krasnozhon, S., & Radchenko, I. (2024). Innovative thermodynamic modeling for enhanced yeast dough mixing: Energy perspectives and applications. *Potravinarstvo Slovak Journal of Food Sciences*, 18, 251-267. doi: [10.5219/1951](https://doi.org/10.5219/1951).
- [23] Rosell, C.M., & Collar, C. (2009). Effect of temperature and consistency on wheat dough performance. *International Journal of Food Science & Technology*, 44(3), 493-502. doi: [10.1111/j.1365-2621.2008.01758.x](https://doi.org/10.1111/j.1365-2621.2008.01758.x).
- [24] Sanitska, M. (2023). [Technology of production of flour confectionery products in the conditions of LLC "Ternovsky Bread Factory" city Mykolaiv](#). Mykolaiv: Mykolaiv National Agrarian University.
- [25] Sattarov, K., Jankurazov, A., & Khazratkulov, J. (2024). Use of food additives in bakery products. *Scientific Horizons*, 27(11), 118-128. doi: [10.48077/scihor11.2024.118](https://doi.org/10.48077/scihor11.2024.118).
- [26] Singh, A. (2021). Evolution of bakery and confectionary technology. In G.K. Sharma, A. Dutt Semwal & D.K. Yadav (Eds.), *Advances in cereals processing technologies* (pp. 25-48). London: CRC Press. doi: [10.1201/9781003261124](https://doi.org/10.1201/9781003261124).
- [27] Solianyuk, A.A. (2021). [Automation of biscuit production with a capacity of 500 units/hour](#). Sumy: Sumy State University.
- [28] Tietze, S., Jekle, M., & Becker, T. (2019). Advances in the development of wheat dough and bread by means of shearing. *Journal of Food Engineering*, 247, 136-143. doi: [10.1016/j.foodeng.2018.12.001](https://doi.org/10.1016/j.foodeng.2018.12.001).

- [29] Van der Mijnsbrugge, A., Auger, F., Frederix, S., & Morel, M.H. (2016). Image analysis of dough development: Impact of mixing parameters and wheat cultivar on the gluten phase distribution. *Journal of Food Engineering*, 171, 102-110. doi: [10.1016/j.jfoodeng.2015.10.006](https://doi.org/10.1016/j.jfoodeng.2015.10.006).
- [30] Watson, N.J., Bowler, A.L., Rady, A., Fisher, O.J., Simeone, A., Escrig, J., Woolley, E., & Adedeji, A.A. (2021). Intelligent sensors for sustainable food and drink manufacturing. *Front. Sustain. Frontiers in Sustainable Food Systems*, 5, article number 642786. doi: [10.3389/fsufs.2021.642786](https://doi.org/10.3389/fsufs.2021.642786).
- [31] Wooding, A.R., Kavale, S., MacRitchie, F., & Stoddard, F.L. (1999). Link between mixing requirements and dough strength. *Cereal Chemistry*, 76(5), 800-806. doi: [10.1094/CCHEM.1999.76.5.800](https://doi.org/10.1094/CCHEM.1999.76.5.800).
- [32] Yang, Y.-L., Guan, E.-Q., Zhang, L.-L., Pang, J.-Y., Li, M.-M., & Bian, K. (2021). Effects of vacuum degree, mixing speed, and water amount on the moisture distribution and rheological properties of wheat flour dough. *Journal of Food Science*, 86(6), 2421-2433. doi: [10.1111/1750-3841.15752](https://doi.org/10.1111/1750-3841.15752).

Автоматизована система OptiMix-360 для безперервного замішування тіста: технічні рішення та ефективність

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Анотація. Підвищення ефективності та стабільності промислового виробництва тіста можливе завдяки впровадженню інноваційних технологій, які оптимізують якість і знижують витрати. Метою цього дослідження було оцінити ефективність системи OptiMix-360 для промислового виробництва тіста через інтеграцію таких технологій, як гравіметричне дозування, преміксери та тістоміси, визначити її вплив на покращення продуктивності та якості кінцевого продукту. Методологія дослідження базувалася на експериментальному підході, який передбачав оцінку ефективності системи OptiMix-360 у порівнянні з традиційними методами шляхом вимірювання параметрів якості продукції та продуктивності процесів за різних умов експлуатації. Здійснено аналіз ефективності обладнання GraviFlow Master, TORNADO-2 та ProMix D-Helix на основі показників продуктивності, енергоспоживання, точності дозування, якості кінцевого продукту при впровадженні цих технологій у виробничий процес. Впровадження системи OptiMix-360 дозволило досягти суттєвого підвищення продуктивності до 1500 кг/год, зменшення енергоспоживання на 30 %, а також стабільної якості кожної партії тіста. Гравіметрична система дозування забезпечила точність <0,1 %, що поліпшило стабільність складу, тоді як преміксер TORNADO-2 покращив процес зволоження борошна і утворення клейковини, що позитивно позначилося на текстурі та міцності готового продукту. Процес виробництва був стабілізований, вдалося мінімізувати коливання в якості продукції завдяки автоматизації та адаптивним налаштуванням. Отримані результати підтвердили ефективність впровадження системи OptiMix-360 у виробничу практику. Технологія забезпечила не тільки покращення якості тіста, але й зменшення витрат на енергоспоживання та підвищення продуктивності. Використання системи OptiMix-360 у харчовій промисловості, має високий потенціал для покращення ефективності виробництва, зменшення витрат на енергію та забезпечення стабільної якості продукції

Ключові слова: харчова промисловість; реологія; клейковина; глютен; хлібопекарська галузь



Influence of electromagnetic radiation on the growth and productivity of agricultural crops in the agro-industrial complex

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Abstract. The purpose of this study was to determine the characteristics of the effect of different levels of electromagnetic radiation on biometric indicators and yields of major agricultural crops, such as wheat, corn, and soybeans. The study was conducted on samples of wheat, corn, and soybeans grown

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in agroclimatic conditions of the Kharkiv region. The cultures were exposed to radiation in the range from 50 to 200 Hz using special equipment. The main measurements included analysis of biometric characteristics: plant height, leaf count, root system mass, morbidity index, and overall yield. The results showed that low levels of electromagnetic radiation stimulated wheat growth, increasing yields by 12-15%, and also increasing the number of leaves by 10-12%. For corn, the effect of radiation was positive, in particular, there was an increase in the mass of the root system by 18% and a decrease in the morbidity index by 15%. Soybeans showed the greatest response to radiation, with an increase in growth by 19.23%, root system mass by 25%, and a decrease in the incidence index by 15-20%. The results of the study indicate the potential for using controlled electromagnetic radiation to increase the productivity of individual crops, especially soybeans in difficult agroclimatic conditions. The data obtained can be useful for the development of new technologies in the field of agriculture aimed at increasing yields, contributing to the achievement of Sustainable Development Goals, and providing a more environmentally friendly approach to increasing crop yields and sustainability

Keywords: biometric indicators; yield; agrotechnical factors; plant productivity

Introduction

In the modern agro-industrial complex, the issue of increasing crop productivity is becoming increasingly relevant due to global climate change, population growth, and the need to ensure food security. One of the new technological strategies that attracts attention is the use of electromagnetic radiation to stimulate plant growth. The problems associated with optimising growing conditions are more urgent than ever since the efficiency of agricultural production directly depends on many agronomic and environmental factors. Despite the research that has already been conducted in this area, there are still many unexplored aspects of the impact of electromagnetic radiation on agricultural crops. The results of work conducted by various authors indicate that the influence of the electromagnetic field can vary depending on the type of crop, the level of irradiation, and the specific features of agroclimatic conditions.

Scientific research in the field of light radiation exposure to plants is important for understanding the biophysical processes occurring in the plant body. The main areas under study in this sphere are represented by the papers of individual foreign researchers. The examination of this phenomenon is especially important for countries with agroclimatic conditions similar to

Ukraine, as it can help to find new approaches to integrating modern technologies into traditional agriculture. The crops considered, such as wheat, corn, and soybeans, show different sensitivity to changes in the electromagnetic field, which requires more in-depth study. They are the main agricultural products that ensure food security, promote economic development, and form the country's export potential.

R. Dennis *et al.* (2021) investigated the effect of pulsing electromagnetic fields (PEMF) on seed germination. The study showed that certain levels of electromagnetic exposure can stimulate germination, while excessive exposure can have a negative effect. This highlights the importance of optimising impact parameters to achieve maximum results in agricultural production. The results of the study open up new prospects for the use of PEMF in agronomy, showing how electromagnetic fields can be an effective tool for improving seed germination processes.

Similarly, L. Popescu & A.S. Safta (2021) in their study analysed the possible effects of electromagnetic waves emitted from various sources on agricultural production. The authors emphasised the growing interest in assessing the impact of these waves on plant growth and yield,

especially in the context of technological development in the agricultural sector. They considered both the positive and negative effects of exposure to electromagnetic waves, noting that some frequencies can promote growth, while others can disrupt biological processes.

H.G.J. Snell *et al.* (2021) investigated the use of electromagnetic fields in precision agricultural practice using the example of corn to determine the dry matter content. The results showed the possibility of improving the accuracy and speed of measurements, which, in turn, can help agronomists better plan fertiliser application and field management.

S. Ayesha *et al.* (2023) similarly considered the mechanisms of influence of electromagnetic fields on sustainable plant production and food security. The study presented results that confirm that electromagnetic fields can promote the development of the root system, increase resistance to stressful conditions, and improve the overall condition of plants.

It is also important to consider the contribution of Ukrainian scientists to the study and examination of the influence of electromagnetic radiation on agricultural crops, which adapt methods and results to the specific conditions of Ukraine's agricultural climate.

O. Pankova *et al.* (2021) examined in detail the effects of electromagnetic radiation on plants, focusing on the physiological responses of plants to electromagnetic fields. The monograph has become a source for further work in this area, providing experimental data that support the possibility of using electromagnetic fields to improve agronomic practices.

L. Haidai (2019) considered the specific features of the formation of productivity and functioning of the legume-rhizobial symbiosis of common beans in the conditions of the Right-Bank Forest-Steppe of Ukraine. The study focused on the importance of rhizobial bacteria for improving the nitrogen nutrition of plants, which, in turn, has a positive effect on their productivity. The author examined the influence of various

factors, such as soil conditions and climatic features, on the development of symbiosis, emphasising the role of such relationships in increasing the yield of legumes.

Evidently, the amount of research in this area is quite substantial, which indicates the relevance of the topic. Problems related to the impact of light conditions on plant growth and productivity are becoming important due to the need to improve the efficiency of the agricultural sector, which is especially important for agricultural countries such as Ukraine. The aim of this study was to determine the optimal parameters of electromagnetic exposure for improving biometric indicators of plants, such as height, number of leaves, root system mass, and overall yield, as well as to assess the potential benefits of using electromagnetic radiation in the modern agro-industrial complex.

Materials and Methods

The study was conducted during one growing season, which is optimal for monitoring the growth and productivity of agricultural crops. The experiment began with the spring sowing campaign of 2024, which took place in April and lasted until the harvest in the fall, in September-October. The total duration of the study was 5-6 months, which allowed fully assessing the effect of electromagnetic radiation on the growth and development of the studied crops. Seeds of agricultural crops were exposed to electromagnetic radiation. Irradiation was conducted before sowing, which allowed creating a stimulating effect on the initial phases of plant development. After the irradiation procedure, the seeds were planted in prepared areas in the field.

The list of agricultural crops that were used in the experiment included wheat (*triticum aestivum*), corn (*zea mays*), and soy (*glycine max*). Wheat and corn are the main crops for the agro-industrial complex of the Kharkiv region, as they are of great importance for ensuring food security and forming the country's export potential. Soy, in turn, as of 2024, is not a widespread crop in the agro-industrial complex of the region

but its cultivation is promising. Therefore, in particular, for soybeans, the goal was to examine the effects of electromagnetic radiation to improve its productivity and promote the expansion of this crop in the region. For the experiment, the Kharkiv region was chosen, where the climatic conditions differ from the southern regions of Ukraine, in particular, with a lower level of sunlight. This helps investigate the effect of electromagnetic radiation in conditions close to typical for the northern agricultural zones of the country. Kharkiv region is characterised by a temperate continental climate with sufficient precipitation and cooler summers, which avoids overheating of plants and creates more favourable conditions for analysing the effects of electromagnetic radiation on their development. This choice of location is also justified by the fact that the results of the study will be relevant for other agricultural regions of Ukraine with similar climatic and agronomic characteristics, which will contribute to the integration of electromagnetic stimulation technologies throughout the country. In the study, various methods of measuring plant biometrics were used to assess the effect of electromagnetic radiation on crop growth and productivity, in particular, plant height, leaf count, root system mass, and total yield.

Plant height measurement was performed using an ultrasonic plant height meter (model: LIDAR plant Height Meter, manufacturer: Yantai Maohai Intelligent Technology Co., Ltd., China, 2020). The device allows accurately determining the height of plants in the field due to laser technology, which ensures high accuracy and speed of measurement. The number of leaves was established manually, by counting it and determining the arithmetic mean of this value. The results were compared with data obtained using an optical photometer for sheet surface analysis (model: Leaf Area Meter, manufacturer: CID Bio-Science, USA, 2019). This device accurately measures the area of the leaf surface, which is important for assessing the photosynthetic activity of plants. The mass of the root system was calculated using

analogue weighing platforms (model: Wittmann AG, manufacturer: Wittmann, Germany, 2021). After removing the root system from the soil, it was cleaned and measured to determine the mass of the roots, which is an important biometric indicator. Yield assessment was conducted using an electronic crop analyser (model: Harvestmaster GrainGage, manufacturer: Crop Test, USA, 2020). This device quickly and accurately measures the mass and volume of the crop, allowing for a complete picture of crop productivity.

The study on electromagnetic radiation was conducted under controlled conditions of a field experiment, which allowed bringing the conditions of exposure to the electromagnetic field as close as possible to real field conditions where crops are grown. However, the irradiation process itself was conducted in a specially equipped enclosed space on the basis of the agronomic station of the Kharkiv National University, where all the necessary conditions were created to control the radiation parameters. Electromagnetic radiation was provided by an alternating current generator (model: Elma EMF 2020, manufacturer: Elma GmbH, Germany, 2019). The generator provided regulated radiation in a given frequency and power range. Experimental settings allowed varying the frequency and intensity of radiation within a certain range, examining the effect of various parameters of the electromagnetic field on plant growth.

Plants were irradiated at different stages of vegetation to assess the effect of the electromagnetic field on various aspects of growth and development. Irradiation was conducted in several variants:

1. Periodic exposure. Irradiation was conducted several times a week during certain periods of crop development (for example, at the stage of germination, during flowering and at the stage of fruit formation).

2. Constant exposure. Irradiation was conducted without interruptions throughout the growing season to determine the cumulative effect of exposure to an electromagnetic field.

The electromagnetic field on plants was affected by two main types of installations. Inductive coils located around the plants were used to provide a direct effect on plants, creating an alternating electromagnetic field. The plants were installed inside the coils, where they were irradiated according to the principle of alternating field induction. Additionally, the technique of creating an electric field by applying a potential between two electrodes was used, which provided contact with the root system of plants. This method is designed to examine the effect of electrical properties on biological processes, in particular, to stimulate the growth of the root system and accelerate water supply.

Monitoring of the parameters of electromagnetic radiation was conducted in the laboratory using special sensors for measuring voltage, current, and electromagnetic field, which allowed maintaining the stability and accuracy of the experiment. The experiment used an alternating current generator to ensure the accuracy and stability of electromagnetic radiation which helped to control the frequency and intensity of radiation. The generator allowed setting frequencies in the range of 50-200 Hz, which is critical for assessing the influence of various electromagnetic fields on plant growth and productivity.

The voltage applied to the generator electrodes could vary according to the requirements of the experiment, which provided the required electric field intensity. During the experiment, radiation parameters were regularly monitored to avoid fluctuations in frequency and intensity values that could affect the results. Before starting the experiment, the equipment was calibrated to ensure the accuracy of the measurements and the correspondence between the set values and the actual radiation parameters. Before starting calibration, all elements of the system, including the generator, electrodes, and measuring instruments, were checked to ensure that there was no mechanical damage and that the connection was correct. The generator was tuned to the initial frequency (50 Hz) and the voltage that was planned for the

experiment. This provided a starting point for further calibration. Adjusting the generator settings may include changing the voltage or frequency to achieve the required electric field level. All measurement results were recorded in the calibration protocol. In particular, the initial settings of the generator, the obtained values of the electric field and the adjustments made were indicated.

Calibration was repeated on a regular basis to ensure the stability and accuracy of the experiment, especially before each serious stage of the experiment. The selected radiation parameters-frequencies of 50, 100, 150, and 200 Hz – are based on studies conducted to assess the effect of electromagnetic fields on plant biological processes (Petrovskiy & Volkov, 2011; Christie *et al.*, 2012). Previous studies have shown that variable fields in this range can stimulate plant growth, activating photosynthetic processes and improving metabolism.

Thus, the parameters of the frequency and intensity of electromagnetic radiation were selected based on previous studies confirming their potential to stimulate the growth and productivity of agricultural crops. Several basic analysis approaches are usually used to assess the effect of electromagnetic radiation on crop growth and productivity (Chalker-Scott, 1999; Sviren *et al.*, 2016). Biometric indicators (plant height, number of leaves, root system mass, total yield, etc.) are measured, and then, these values are compared in the control and experimental groups. Basic parameters for assessing the impact of electromagnetic radiation:

1. Plant height (H) – measured in centimetres from the soil surface to the top of the plant.
2. Number of leaves (N) – the total number of leaves on each plant is counted.
3. Root system Mass (M_r) – determined by removing the root system after harvesting the plant and weighing it.
4. Yield (Y) – defined as the total amount of yield per unit area (tonnes/ha).

The growth index (GI) was calculated using the Formula (1):

$$GI = \frac{H_1}{H_0} \cdot 100\%, \quad (1)$$

where H_0 – the average plant height in the control group; H_1 – the average plant height in the experimental group.

This allows comparing the average plant growth in the experimental group with the control plants and evaluating the effectiveness of radiation exposure. The following Formula (2) was used to calculate the root system development index:

$$IRK = \frac{M_1}{M_0} \cdot 100\%, \quad (2)$$

where M_0 – the average root mass in the control group; M_1 – the average root mass in the experimental group.

This formula estimates how much the mass of the root system has changed as a result of exposure to electromagnetic radiation. Plant disease is also one of the most critical factors that negatively affect their yield and product quality. Pathogens can substantially reduce plant growth and development by disrupting photosynthesis, transpiration, and nutrient absorption. In the current experiment, resistance to diseases such as pyrenophorosis (on wheat), multicoloured mould (on soy), and corn rot (Pinchuk *et al.*, 2018).

The Bobby scale was used to assess the degree of damage, which allows quantifying the spread of the disease on a five-point scale. This technique provides convenience in the field and allows quickly assessing the degree of damage at different stages of plant development. Measurements were performed on plants of the control and experimental groups, followed by data analysis to calculate the overall plant resistance to diseases. The Bobby scale includes the following categories:

- 1 point – healthy plants, no visible symptoms of the lesion;
- 2 points – weak lesion covering approximately 10% of the plant area;
- 3 points – moderate damage covering approximately 25% of the area;
- 4 points – substantial lesion that affects 50% of the plant;

- 5 points – severe lesion covering more than 75% of the plant.

The defeat index was calculated using the following Formula (3):

$$I = \frac{\sum(a \cdot b)}{N \cdot K} \cdot 100\%, \quad (3)$$

where I – the lesion index as a percentage; a – the number of plants with a certain degree of damage; b – the lesion score according to the scale; N – the total number of plants examined; K – the maximum possible lesion score (in this case, 5).

This index allows quantifying the level of disease damage and using these data for further agrotechnical decisions to increase plant resistance and reduce crop losses. For each crop (wheat, corn, soy), the results can be summarised separately. Changes in biometric characteristics after treatment are evaluated for each plant. These results are then compared to determine the greatest impact on a particular culture. In the course of conducting this study, all ethical standards specified in legislative acts were observed (Convention “On Biological Diversity”, 1992; Law of Ukraine No. 1264-XII, 2024). All research practices related to the collection of vegetation data were conducted in accordance with the Principles of Sustainable Use of Natural Resources and Protection of Biodiversity.

Results

A study conducted during one growing season in the Kharkiv region showed a substantial effect of electromagnetic radiation on the growth and development of agricultural crops, in particular, wheat, corn, and soybeans. According to the results of the experiment, it was determined that radiation has a positive effect on all the studied crops but the most impressive changes were observed in soybeans which allows considering the use of electromagnetic radiation as the most relevant for this crop.

The temperature regime was one of the critical parameters that was monitored throughout the experiment. During the growing season, the air temperature ranged from 18 to 25°C, which is

optimal for most crops, including wheat and corn (Zymarioieva, 2019). However, for soybeans, which are more sensitive to temperature fluctuations, these indicators may have been less favourable, which is especially important to consider when interpreting the results of exposure to electromagnetic radiation.

Air humidity also varied throughout the experiment, in particular, during the period of plant irradiation, it was in the range of 60 to 80%. This provided stable conditions for plant development and minimised the impact of arid conditions on the results of the experiment. According to scientific guidelines, humidity control is an important

factor in maintaining proper plant development when exposed to external factors such as electromagnetic radiation (Pankova et al., 2021).

After the irradiation was completed, the seeds were planted on experimental plots in compliance with agrotechnical standards, including the standard sowing scheme for each crop. It is important to emphasise that the irradiated seeds grew under conditions similar to the control samples, allowing the comparison of the results without additional changes in external conditions. The data in Table 1 show how the height of the plants participating in the experiment changed during 6 weeks of exposure.

Table 1. Changes in plant height under the influence of electromagnetic radiation during the growing season

Crop	Growing season	Control group (cm)	Experimental group (cm)
Wheat	2 weeks	25	30
	4 weeks	45	52
	6 weeks	60	68
Corn	2 weeks	40	45
	4 weeks	90	100
	6 weeks	140	150
Soybeans	2 weeks	20	26
	4 weeks	35	42
	6 weeks	52	62

Source: compiled by the authors

The data show changes in plant height under the influence of electromagnetic radiation during the growing season. The results obtained allowed calculating such an important indicator as GI. The results for each of the crops were considered separately to analyse the growth index at 6 weeks. GI for wheat was calculated based on the average plant height in the control (60 cm) and experimental groups (68 cm):

$$\text{GI wheat} = \frac{68}{60} \cdot 100\% \approx 113.33\%.$$

This indicator indicates moderate stimulation of wheat growth in conditions of electromagnetic radiation. For corn, the average plant height in the control group was 140 cm, and in the experimental group – 150 cm:

$$\text{GI corn} = \frac{150}{140} \cdot 100\% \approx 107.14\%.$$

This result indicates some improvement in corn growth, although the effect was less pronounced compared to other crops. The average height of soybean plants in the control group was 52 cm, and in the experimental group – 62 cm:

$$\text{GI soybean} = \frac{62}{52} \cdot 100\% \approx 119.23\%.$$

High GI in soybeans indicates substantial growth stimulation under the influence of electromagnetic radiation. Thus, the results of the Growth Index obtained at week 6 of the experiment demonstrate a positive effect of electromagnetic radiation on plant development. Wheat showed a GI of 113.33%, indicating moderate

stimulus. Corn, with an index of 107.14%, showed some improvement, although less pronounced. The highest index of 119.23% was recorded in soybeans, which indicates a substantial stimulation of its growth.

Table 2 shows data on the mass of the root system in grams for control and experimental

groups at different stages of vegetation (after 2, 4, and 6 weeks). These indicators allow assessing the effect of electromagnetic radiation on the development of the root system of each crop and determining the potential to increase their stability and productivity under experimental conditions.

Table 2. Dynamics of changes in the mass of the root system under the influence of electromagnetic radiation

Crop	Vegetation period	Control group (g)	Experimental group (g)
Wheat	2 weeks	5	6
	4 weeks	10	12
	6 weeks	15	18
Corn	2 weeks	7	8
	4 weeks	18	20
	6 weeks	25	28
Soybeans	2 weeks	3	4
	4 weeks	6	8
	6 weeks	8	10

Source: compiled by the authors

The root system mass index (RSMI) was calculated to analyse the effect of electromagnetic radiation on root system development throughout the experiment. Next, the above index was calculated for the sixth week of vegetation, which was the most substantial since it helped to assess future trends. For wheat:

1. Average root weight in the control group (M_0): 15 g.
2. Average root weight in the experimental group (M_1): 18 g:

$$\text{RSMI wheat} = \frac{18}{15} \cdot 100\% \approx 120\%.$$

This result indicates that the mass of the wheat root system in the experimental group is 20% higher than in the control group, which indicates a positive effect of electromagnetic radiation. For corn:

1. Average root weight in the control group: 25 g.
2. Average root weight in the experimental group: 28 g:

$$\text{RSMI corn} = \frac{28}{25} \cdot 100\% \approx 112\%.$$

Consequently, the mass index of the corn root system in the experimental group is 12% higher compared to the control variant. This is a positive result. For soybeans:

1. Average root weight in the control group: 8 g.
2. Average root weight in the experimental group: 10 g:

$$\text{RSMI soybean} = \frac{10}{8} \cdot 100\% \approx 125\%.$$

This indicator indicates that the mass of the soybean root system in the experimental group exceeds the control by 25%, which confirms the effectiveness of exposure to electromagnetic radiation. Consequently, the results obtained indicate an overall increase in the mass of the root system of all three crops in the experimental groups. Wheat, corn, and soybeans show a marked improvement in root system development under the influence of radiation of

varying degrees. The increase in root system mass observed in the experimental groups indicates an increased ability of plants to absorb water and nutrients from the soil. This is a vital

factor for plant growth. The generalised results of biometric indicators of plants under the influence of electromagnetic radiation are presented in Table 3.

Table 3. Specific effect of electromagnetic radiation on biometric indicators (in %)

Crop	Indicator	Control group	Experimental group
Wheat	Plant height	78	90
	Root system mass	15	18
Corn	Plant height	170	185
	Root system mass	25	28
Soybeans	Plant height	52	62
	Root system mass	8	10

Source: compiled by the authors

The results of the experiment showed that in the control group of wheat, the average height of plants was 78 cm, while in the group that was exposed to electromagnetic radiation, plants grew to 90 cm. This indicates a 15.38% increase in plant height under the influence of radiation. Similarly, an increase in the mass of the root system was observed: in the control group it was 15 g, and in the experimental group – 18 g, which confirms an improvement in the root structure and overall viability of plants (an increase of 20%).

For corn, a positive effect of electromagnetic radiation was also observed. In the control group, the average plant height was 170 cm, while in the experimental group, it was 185 cm, which shows a growth of 8.82%. This may indicate the stimulation of plant growth under the influence of radiation, which is an important factor for optimising the use of land resources and increasing yields.

As for the mass of the root system, it increased from 25 g in the control group to 28 g in the experimental group, which corresponds to an increase of 12%. The change in yield for corn was 8.33%, which also confirms the positive effect of electromagnetic radiation on the overall condition of plants and their productivity. Although the changes are not as impressive in comparison with other crops, for corn this may be an indicator of a possible increase in the efficiency of cultivation in

the agroclimatic conditions of the Kharkiv region.

The greatest interest was aroused by the effect of electromagnetic radiation on soybeans. Soy is a relatively less common crop in the agro-industrial complex of the Kharkiv region, which is due to a number of agroclimatic factors, in particular, the limited thermal resource and insufficient amount of solar radiation necessary for its full growth and development. In the control group, the average plant height was only 52 cm, which is quite low for this crop. However, in the group that was exposed to electromagnetic radiation, the height of the plants increased to 62 cm, which is 19.23% more.

The mass of the root system also showed substantial changes: in the control group it was 8 g and in the experimental group – 10 g, which indicates a 25% increase. This result is especially important for soybeans, as root mass is a key indicator of plant development, which determines its resistance to stress and the efficiency of absorbing nutrients from the soil.

One of the important aspects of the study is the assessment of plant resistance to infections, fungal and bacterial diseases after exposure. Radiation exposure can alter the activity levels of antioxidant systems, which in turn help reduce exposure to diseases. In addition, it can affect the increased immune response of plants due

to changes in their metabolism (Balan & Aheieva, 2018). Based on the results, it was established that in the experimental groups (with medium and strong levels of radiation exposure), a substantial decrease in the level of plant damage was observed compared to the control groups.

During each stage of exposure, the level of disease damage was reduced compared to the control groups. The greatest effect was observed in groups with medium and strong irradiation, which indicates the ability of electromagnetic radiation to strengthen the mechanisms of plant protection against diseases.

The calculation of the lesion index for three cultures was based on data on the degree of lesion in the control and experimental groups. For wheat (pyrenophorosis):

1. Control Group: A1 – 20, average lesion score b1 – 4 (substantial lesion).

2. Experimental group (medium exposure level): A2 – 20, average lesion score b2-2 (weak lesion).

3. Total number of plants N – 50:

$$I \text{ control} = \frac{20 \cdot 4}{50 \cdot 5} \cdot 100\% = 32\%,$$

$$I \text{ experiment} = \frac{20 \cdot 2}{50 \cdot 5} \cdot 100\% = 16\%.$$

For soybeans (multi-coloured mould):

1. Control group: A1 – 15, average lesion score b1 – 5 (severe lesion).

2. Experimental group (strong exposure level): A2 – 15, average lesion score b2 – 3 (moderate lesion).

3. Total number of plants N – 40:

$$I \text{ control} = \frac{15 \cdot 5}{40 \cdot 5} \cdot 100\% = 37.5\%,$$

$$I \text{ experiment} = \frac{15 \cdot 3}{40 \cdot 5} \cdot 100\% = 22.5\%.$$

For corn (corn rot):

1. Control group: A1 – 25, average lesion score b1 – 3 (moderate lesion).

2. Experimental group (average exposure level): A2 – 25, average lesion score b2 – 1 (weak lesion).

3. Total number of plants N – 50:

$$I \text{ control} = \frac{25 \cdot 3}{50 \cdot 5} \cdot 100\% = 30\%,$$

$$I \text{ experiment} = \frac{25 \cdot 1}{50 \cdot 5} \cdot 100\% = 10\%.$$

Thus, for all three crops, a substantial decrease in the lesion index was observed in the experimental groups compared to the control groups, which indicates a positive effect of electromagnetic radiation on plant resistance to diseases. These results correspond to the average radiation level (81-120 Hz) for the three types of crops. Generalised data on the effect of radiation exposure on the number of healthy plants can be seen in Figure 1.

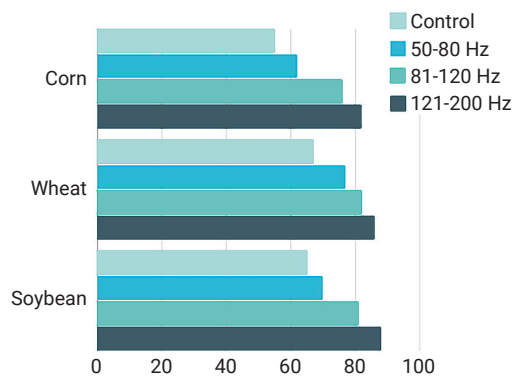


Figure 1. Number of healthy plants (%) at different levels of pre-exposure to seeds

Source: compiled by the authors

These results are important because they demonstrate substantial potential for using electromagnetic radiation to stimulate soybean growth and increase soybean yields in regions with limited growing conditions. In particular, changes in the development of the root system, plant height, and yield show that irradiation can contribute to improving the overall condition of soybeans and increasing their productivity, which is of great importance for expanding the production of this crop in Ukraine.

The difference in the reactions between wheat, corn, and soy to electromagnetic radiation in the experiment may be due to several factors

that are both biological and agrotechnical in nature. For a better understanding, it is worth considering the genetic characteristics of each crop, the biological processes occurring in their cells under the influence of electromagnetic radiation, as well as the agrotechnical aspects of growing each crop in specific conditions of the Kharkiv region.

Wheat and corn have a more developed root system and mechanisms for adapting to stresses such as changes in environmental conditions. Wheat, as an annual grain crop, is adapted to a wide range of temperatures and lighting, which allows it to respond to electromagnetic radiation with minimal negative consequences at medium intensity. Accordingly, the average radiation level (150 Hz) contributed to an improvement in metabolic processes, such as photosynthesis, and provided optimal conditions for plant growth.

Corn, as a crop with a greater ability to actively absorb water and nutrients through the root system, also showed positive results under medium exposure. The strength of this plant species lies in its ability to quickly adapt to different climatic conditions, which allows it to use electromagnetic waves more efficiently to stimulate growth at a lower dose of radiation. However, at high radiation intensity (200 Hz), corn began to show negative effects, which may be the result of disruption of the normal functioning of the cell membrane caused by excessive radiation energy. This may be due to increased levels of oxidative stress and impaired plant metabolism (Kovalenko *et al.*, 2020).

Soy, unlike wheat and corn, showed the greatest changes in results due to its growth characteristics and biological sensitivity. Soybeans are more sensitive to environmental changes such as light levels and temperature, making them more vulnerable to environmental stresses, including electromagnetic radiation. The greatest stimulating effect was observed at a medium level of exposure, which was likely optimal for this culture. However, at high exposure intensity, soybeans showed slow growth, which may result from disruption of the normal development of the root system and a decrease in the ability to fix

nitrogen in the soil, which is critical for soybean growth (Haidai, 2019; Osokina *et al.*, 2024).

Wheat and corn have a higher tolerance to electromagnetic radiation due to their adaptive mechanisms, such as more active regulation of water balance and greater ability to photosynthesise even under changing conditions. This allows them to use electromagnetic energy more efficiently to stimulate growth in the early stages of development. Thereby, soy, as a legume crop, has other biological needs, such as optimal root system growth for nitrogen fixation. High levels of radiation exposure can disrupt these processes, reducing the ability to develop and grow normally, as well as integrate nutrients.

Soy may also be more sensitive to energy changes at the cellular level due to its ability to symbiosis with nitrogen-fixing bacteria, which are critical for its normal development. High radiation intensity can disrupt normal biochemical reactions in plants, which can affect the effectiveness of nitrogen fixation and overall plant growth.

In addition to biological and genetic reasons, the agrotechnical conditions in which the experiment was conducted are important. For each crop, different growing conditions, such as soil temperature, humidity, and lighting, may have affected the effectiveness of exposure (Shaked *et al.*, 2001; Semenov *et al.*, 2017). In the case of corn and wheat, which are less sensitive to such changes, the results were less dependent on environmental conditions, compared to soybeans, which, due to their developmental characteristics, may be more vulnerable to changes in parameters such as light intensity and temperature.

Therefore, the difference in crop responses may be related to their genetic characteristics, physiological processes, and agrotechnical conditions. Wheat and corn showed improved growth and development at medium exposure levels due to their adaptation to changing environmental conditions and biological resistance to stress. Soy, on the other hand, showed better results at moderate levels of exposure, but at high intensity, there were substantial negative effects

due to disruption of key biochemical processes. These data allow evaluating not only the effect of radiation on plant growth but also its ability to increase the stress resistance of plants, which is an important aspect for increasing yield and resistance to adverse conditions.

Discussion

The results confirmed that electromagnetic radiation has a positive effect on the growth and development of wheat, corn and, most importantly for the context of discussion, soybeans. Research shows that exposure to soybean seeds contributes to increased biomass and yield in conditions that are usually less favourable for this crop. During the study, it was established that wheat and corn also respond to radiation but their response was less substantial compared to soy. This may be due to the fact that these crops are already adapted to the conditions of the region, and electromagnetic stimulation does not play a crucial role in their productivity.

A similar effect of electromagnetic radiation on plant growth has been considered in other studies. For example, a study by L. Chervinsky & O. Romanenko (2016) analysed the spectral requirements for artificial irradiation for growing plants in closed-ground structures. Despite the similarity in the analysis of the effects of different radiation parameters, the current study has important differences. It covers the effect of electromagnetic radiation not only on certain growth parameters in artificial conditions but also in open field conditions of the Kharkiv region. This allows considering the importance of climatic factors and assessing the resistance of plants to natural stress factors.

A study by M. Marenych & S. Yurchenko (2017) was devoted to the examination of the effect of pre-sowing seed treatment with biologically active substances on the growth and development of winter wheat plants in the early stages. The similarity with the experiment lies in the general idea of influencing the initial stages of plant growth through seed treatment, which

in the context of this study was conducted using electromagnetic radiation. However, the current study is more versatile, as it includes not only the impact on growth but also on other biometric indicators (for example, root system development and stress resistance, expanded by examining the reactions of different crops (wheat, corn, soybeans) and the impact on their productivity in real-world field conditions.

A paper of A. Semenov *et al.* (2017) is closely related to this study, as it focuses on the role of ultraviolet radiation in the development and productivity of various crops. Their study demonstrates how specific radiation ranges can substantially affect physiological processes in plants, in particular, metabolism, stress resistance, and increased yields. This publication is particularly important for understanding how the electromagnetic radiation used in the experiment can affect plant growth and development, which is also important for agricultural research.

H. Balan & O. Aheieva (2018) focused on the importance of predicting the development of diseases in agricultural production. They consider the impact of various adverse environmental factors on plants and their resistance to diseases, which is an important aspect of effective crop management and plant protection. The current study, in particular, examines exposure to electromagnetic radiation, which is an important additional variable in the context of stressors that can affect plant health. Although there are differences in approaches (electromagnetic radiation versus traditional agronomic factors) between the two reviews, both studies contribute to a deeper understanding of plant interactions with adverse environmental conditions and adaptation mechanisms. The current study may complement the recommendations of H. Balan & O. Aheieva (2018), in particular, in terms of how various stressors affect the development of diseases and the general condition of plants.

It is important to pay attention to international experience, which demonstrates substantial results in improving the sustainability and

productivity of agricultural crops under the influence of various factors. S. Premaiatha *et al.* (2006) focus on the analysis of necrosis genes and assess wheat rust resistance, which is an important aspect of plant stress resistance. The current experiment also allows analysing the resistance of crops to various stressful conditions, such as diseases and adverse climatic factors. The general focus is on finding ways to increase the resilience of crops to external threats. However, the current study places more emphasis on technological aspects, in particular, on the use of the latest radiation methods to stimulate plant growth and development, which is a distinctive feature.

A study by J.M. Christie *et al.* (2012) focused on the role of the UVR8 photodetector in plants, which is activated by UV-B radiation due to the destruction of salt bridges between dimers caused by tryptophan. Researchers have investigated the molecular mechanisms by which plants are able to sense UV-B light and adapt their physiology to this factor. Similar to their study, the current paper also examines the effects of external physical factors but focuses on electromagnetic radiation and its ability to alter physiological processes such as growth, metabolic changes, and plant resistance in the field. The new study is unique in that it is aimed at exploring the agricultural impact in specific climatic conditions, which allows evaluating the results in an applied context for agricultural productivity and optimisation of growing conditions.

M. Wada *et al.* (2005) considered the mechanisms of plant photosensitivity, the interaction of plants with various types of light signals, such as phytochromes, cryptochromes, and other photoreceptors. They provided information on photomorphogenesis, including the effect of different light spectra on plant development, which is of great importance for understanding plant adaptation to changing environmental conditions. In the context of a new study that examines the effects of electromagnetic radiation, the concept of plant light sensitivity can serve as an important basis for comparison. Although this paper focuses

on electromagnetic waves, the principles of plant adaptation to light stimuli may seem similar, highlighting the importance of external physical factors for plant growth and development.

Thus, the current study supports the hypothesis of a positive effect of electromagnetic radiation on crop productivity, especially in conditions that are unfavourable for soybean cultivation. This opens up new opportunities for further improvement of agricultural technologies and promotion of sustainable development of the agro-industrial complex in Ukraine and abroad.

Conclusions

The conducted study showed that electromagnetic radiation in the range of 50-200 Hz has a positive effect on the growth and productivity of agricultural crops, in particular, wheat, corn, and soybeans, in the agroclimatic conditions of the Kharkiv region. An increase in biometric indicators, such as plant height and root system mass, was noted. Especially substantial changes were recorded in soybeans, which usually show lower growth and development indicators in the Kharkiv region. Under the influence of electromagnetic radiation, there was an increase in soybean growth by 19.23%, root system mass – by 25% and a decrease in the crop morbidity index by 15-20%. This confirms the effectiveness of using electromagnetic radiation to increase plant resistance to diseases and improve their overall condition, which is promising for increasing productivity in the agricultural sector. The results obtained allow recommending the introduction of electromagnetic irradiation technologies within the specified range to improve crop productivity in regions with similar agroclimatic conditions. The greatest effect is observed when growing soybeans which traditionally have a low yield in the Kharkiv region. The use of this technology can also be useful in regions with insufficient natural light or unfavourable conditions for growing crops. It is advisable to analyse the optimal modes of electromagnetic exposure to further improve the results, in

particular, the frequency and duration of exposure for each culture. It is also necessary to assess the impact on other crops and assess the long-term consequences for the agroecosystem, including the impact on soil microorganisms and soil fertility. One of the limitations of the study was its implementation in the same region (Kharkiv region), which may affect the universality of the results obtained. In addition, the limited duration of the experiment did not allow for assessing the long-term effect of electromagnetic radiation on soil yield and condition. In addition to optimising radiation modes, the effect of electromagnetic fields on the quality of final products should also be considered, in particular, on the protein and

nutrient content in wheat, corn, and soy grains. This will help to understand whether electromagnetic radiation can improve not only quantitative but also qualitative indicators of the crop. It is also important to investigate the economic efficiency of implementing this technology in large agricultural enterprises, which will allow farmers to better assess the feasibility of using it in commercial agriculture.

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Conflict of Interest

None.

References

- [1] Ayesha, S., *et al.* (2023). Enhancing sustainable plant production and food security: Understanding the mechanisms and impacts of electromagnetic fields. *Plant Stress*, 9, article number 100198. [doi: 10.1016/j.stress.2023.100198](https://doi.org/10.1016/j.stress.2023.100198).
- [2] Balan, H., & Aheieva, O. (2018). *Forecasting the development of crop diseases*. Odesa: Odesa State Agrarian University.
- [3] Chalker-Scott, L. (1999). Environmental significance of anthocyanins in plant stress responses. *Photochemistry and Photobiology*, 70(1), 1-9. [doi: 10.1111/j.1751-1097.1999.tb01944.x](https://doi.org/10.1111/j.1751-1097.1999.tb01944.x).
- [4] Chervinsky, L., & Romanenko, O. (2016). [Requirements for artificial spectral composition of optical radiation source for growing plants in greenhouses plants](https://doi.org/10.1016/j.energy.2016.08.088). *Energy and Automation*, 3, 88-95.
- [5] Christie, J.M., *et al.* (2012). Plant UVR8 photoreceptor senses UV-B by tryptophan-mediated disruption of cross-dimer salt bridges. *Science*, 335(6075), 1492-1496. [doi: 10.1126/science.1218091](https://doi.org/10.1126/science.1218091).
- [6] Convention "On Biological Diversity". (1992, June). Retrieved from <https://surl.li/nxovzj>.
- [7] Dennis, R., Tommerdahl, A., & Dennis, A. (2021). Inductively coupled electrical stimulation – part 4: Effect of PEMF on seed germination; evidence of triphasic inverse hormesis. *The Journal of Science and Medicine*, 3(1). [doi: 10.37714/josam.v2i4.58](https://doi.org/10.37714/josam.v2i4.58).
- [8] Haidai, L. (2019). *Features of productivity formation and functioning of legume-rhizobial symbiosis of common bean in the conditions of the Right-Bank Forest-Steppe of Ukraine*. (Doctoral dissertation, Higher Educational Institution "Podillia State University", Kamianets-Podilskyi, Ukraine).
- [9] Kovalenko, O., Gamayunova, V., & Drobitko, O. (2020). *Stress and plant adaptation*. Mykolaiv: Mykolaiv National Agrarian University.
- [10] Law of Ukraine No. 1264-XII "On Environmental Protection". (2024, November). Retrieved from <https://zakon.rada.gov.ua/laws/show/1264-12#Text>.
- [11] Marenych, M., & Yurchenko, S. (2017). Influencing of pre-sowing seed treatment with the biologically active substances on growth and development of plants of wheat winter on the initial stages. *Scientific Progress & Innovations*, 1-2, 38-42. [doi: 10.31210/visnyk2017.1-2.08](https://doi.org/10.31210/visnyk2017.1-2.08).
- [12] Osokina, N., Kostetska, K., Herasymchuk, O., Podopriatov, H., & Piddubnyi, V. (2024). Effect of an ultra-high frequency electromagnetic field on the physical properties of spelt grain. *Scientific Horizons*, 27(3), 64-72. [doi: 10.48077/scihor3.2024.64](https://doi.org/10.48077/scihor3.2024.64).

- [13] Pankova, O., Puzik, V., & Lysychenko, M. (2021). [The effect of electromagnetic radiation on plants](#). Kharkiv: Planeta-Print LLC.
- [14] Petrovskiy, O., & Volkov, S. (2011). [Determination of the most suitable range of electromagnetic radiation for pre-sowing seed treatment](#). *Bulletin of Poltava State Agrarian Academy*, 1, 163-165.
- [15] Pinchuk, N., Vergeles, P., Kovalenko, T., & Okrushko, S. (2018). [General phytopathology](#). Vinnytsia: Vinnytsia National Agrarian University.
- [16] Popescu, L., & Safta, A.S. (2021). Analyses regarding possible effects of electromagnetic waves emitted on agricultural productions. *Environmental Sciences Proceedings*, 8(1), article number 43. [doi: 10.3390/ecas2021-10701](#).
- [17] Premaitha, S., Reddy, V.R.K., Thamayanthi, K., & Kannan, R. (2006). [Distribution of necrosis genes and evaluation of resistance to rusts in some bread wheats](#). *Annual Wheat Newsletter*, 52, 38-42.
- [18] Semenov, A., Sakhno, T., & Kozhushko, H. (2017). [Analysis of the role of UV radiation on development and productivity of various crops](#). *Lighting and Power Engineering*, 49(2), 3-16.
- [19] Shaked, H., Kashkush, K., Ozkan, H., Feldman, M., & Levy, A.A. (2001). Sequence elimination and cytosine methylation are rapid and reproducible responses of the genome to wide hybridisation and allopolyploidy in wheat. *The Plant Cell*, 13(8), 1749-1759. [doi: 10.1105/tpc.010083](#).
- [20] Snell, H.G.J., Oberndorfer, C., Lücke, W., & Van den Weghe, H.F. (2021). Precision agriculture: Use of electromagnetic fields for the determination of the dry matter content of chopped maize. *Biosystems Engineering*, 82(3), 269-277. [doi: 10.1006/bioe.2002.0074](#).
- [21] Sviren, M., Shmat, S., Ivanko, I., & Amosov, V. (2016). [Utilisation of the Earth's electromagnetic field energy to increase crop yields](#). *Technique and Technologies of the Agro-Industrial Complex*, 86(11), 26-28.
- [22] Wada, M., Shimazaki, K., & Iino, M. (2005). [Light sensing in plants](#). Tokyo: Springer.
- [23] Zymarioieva, A. (2019). Assessment of the climate changes impact on the productivity of maize within the Polissya and Forest Steppe ecoregions within Ukraine. *Scientific Horizons*, 22(11), 113-120. [doi: 10.33249/2663-2144-2019-84-11-113-120](#).

Вплив електромагнітного опромінення на ріст та продуктивність сільськогосподарських культур в агропромисловому комплексі

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Анотація. Метою цього дослідження було визначити особливості впливу різних рівнів електромагнітного випромінювання на біометричні показники та врожайність основних сільськогосподарських культур, таких як пшениця, кукурудза та соя. Дослідження було проведено на зразках пшениці, кукурудзи та сої, вирощених у агрокліматичних умовах Харківської області. Культури піддавалися впливу випромінювання в діапазоні від 50 до 200 Гц з використанням спеціального обладнання. Основні вимірювання включали аналіз біометричних характеристик: висоту рослин, кількість листя, масу кореневої системи, індекс захворюваності та загальну врожайність. Результати показали, що низькі рівні електромагнітного опромінення стимулювали ріст пшениці, підвищуючи врожайність на 12-15 %, а також збільшили кількість листя на 10-12 %. Для кукурудзи ефект опромінення виявився позитивним, зокрема спостерігалось збільшення маси кореневої системи на 18 % і зменшення індексу захворюваності на 15 %. Соя показала найбільший відгук на опромінення, з підвищенням росту на 19,23 %, маси кореневої системи на 25 % та зменшенням індексу захворюваності на 15-20 %. Висновки дослідження свідчать про потенційну можливість використання контрольованого електромагнітного випромінювання для підвищення продуктивності окремих сільськогосподарських культур, особливо сої у складних

агрокліматичних умовах. Отримані дані можуть бути корисними для розробки нових технологій у сфері агропромислового комплексу, спрямованих на підвищення врожайності, сприяють досягненню цілей сталого розвитку, забезпечуючи більш екологічний підхід до підвищення врожайності та стійкості сільськогосподарських культур

Ключові слова: біометричні показники; врожайність; агротехнічні фактори; рослинна продуктивність



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The impact of climate change on the sanitary condition of pine forests in Polissia

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Abstract. The study was aimed at identifying the key factors that affect the sanitary condition of pine forests in Polissia under climate change, as well as developing recommendations for their adaptation to new environmental challenges. For the analysis, 30 trial plots of 0.1 hectare each were laid out, where pine stands of different age classes were studied. The work recorded key climate trends: the average annual temperature increased by 1.2°C over the period 1968-2024, precipitation decreased by 25 millimetres, and the hydrothermal moisture coefficient decreased from 1.3 to 0.9, indicating drought. In regions with a moisture deficit, the proportion of dry-topped trees increased from 8% to 20%, and root sponge damage from 5% to 12%. Decreased soil moisture levels disrupted transpiration, limited photosynthesis and reduced wood growth by 18% compared to healthy trees. It was found that the number of pine sawfly and bark beetles increased by 67% and 150%, respectively, in dry conditions. The analysis showed that mechanical damage caused by strong winds creates conditions for the active spread of pests and diseases. The results obtained indicate that climate change has caused degradation of forest stands due to increased physiological stress of trees. To adapt, the authors propose the selection of resistant pine varieties, the introduction of irrigation systems, monitoring of forest conditions using geographic information technologies, and an increase in the area of forestry in favourable areas. These measures will help preserve forest ecosystems in the region in the face of climate change

Keywords: drought; hydrothermal coefficient; dryland; environmental factors; root sponge

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Introduction

Climate change is one of the most pressing challenges of the modern world, affecting ecosystems on a global scale. Forests, in particular pine forests in Polissia, are under significant anthropogenic and climatic pressure, which manifests itself in the form of rising temperatures, decreasing precipitation, frequent extreme weather events and moisture deficit. These factors disrupt the sanitary condition of forests, causing trees to dry out and spread pests and diseases. Polissia's forests play an important ecological role, including maintaining biodiversity, regulating water regimes, and providing valuable resources such as timber. However, increasing physiological stress due to environmental degradation threatens their sustainability. Scientific approaches to assessing the impacts of climate change on forest ecosystems are critical to developing adaptation measures that can sustain these ecosystems in the long term.

The decrease in soil moisture is one of the most important factors that disrupts the water balance of trees and their physiological activity. V. Turko & V. Moroz (2023) noted that insufficient soil moisture leads to reduced transpiration of pine trees, which in turn affects photosynthetic activity and metabolic processes in wood. Their results also show that insufficient transpiration significantly affects the ability of trees to maintain water balance in dry conditions, but the study did not consider the long-term effects of these changes in the context of the Polissia climate.

Pests, such as pine beetle and bark beetles, are another significant factor contributing to the degradation of forest stands in drought conditions. V. Moroz & Y. Nykytiuk (2021) noted that under conditions of moisture deficit, the number of pine beetles can double, and the activity of bark beetles can increase by more than 150%. Their study showed that weakened trees become an easy target for these pests, which accelerates the drying out of trees. The authors also noted that the pests develop resistance to standard control measures under high temperatures, but their findings did not take into account the specific

interaction between the pests and the mechanical damage to trees often caused by storms.

Mechanical damage caused by strong winds is an important additional factor in the degradation of forest stands. S.K. Ghosh *et al.* (2022) investigated the impact of storms on the structural integrity of pine trees and found that damaged trees become more vulnerable to bark beetles and root diseases such as sponge. According to them, strong winds contribute to the spread of pathogens through mechanical cracks in tree trunks. At the same time, the authors' study did not include a comprehensive analysis of the synergy between mechanical damage and drought, which is relevant for Polissia.

Root sponge is one of the most common diseases of pine trees, which significantly affects their viability. A. Buras *et al.* (2023) studied the impact of the disease on the physiological state of stands and found that affected trees reduce wood growth by 15-20%. In addition, they found that root sponge infection increases under conditions of prolonged periods of moisture deficit. However, their study focused mainly on the conditions in Central Europe, leaving aside the specific climate conditions of Polissya.

The physiological stress caused by water deficit is exacerbated by climatic factors such as rising temperatures. H. Dang *et al.* (2021) showed that with decreased soil moisture, transpiration decreases by 30%, which is accompanied by impaired photosynthesis and reduced biomass production. Their study confirmed the critical importance of water regime for maintaining the stability of forest stands, but did not take into account the long-term impact of climate change on the dynamics of these processes.

Among the physiological consequences of climate change, an increase in the level of oxidative stress is of particular importance. E.X. Ellis *et al.* (2024) proved that under conditions of chronic drought, oxidative stress becomes the main cause of tree cell damage. They found a 25-30% decrease in antioxidant protective activity,

which makes trees more vulnerable to external stressors. However, their study did not consider the specifics of the impact of oxidative stress on pine forests in Polissia.

Geographic information systems (GIS) and other modern monitoring technologies are important tools for analysing changes in the sanitary condition of forests. M. Hartmann *et al.* (2023), A.K. Bose *et al.* (2022) emphasised the effectiveness of GIS in the early diagnosis of degradation processes, in particular tree drying. They also pointed out that these technologies allow for real-time assessment of pest risks, but their study was limited to lowland forests, making it difficult to adapt the results to the worse environmental conditions of Polissia.

The study aimed to assess key climate trends and their impact on the health status of pine forests in Polissia, as well as to develop practical measures to ensure the adaptation of these ecosystems to climate change.

The study identified the following objectives: to study the impact of climate change, such as increased temperature, decreased precipitation and reduced hydrothermal coefficient, on the health of pine forests; to analyse the dynamics of pests and tree diseases in arid conditions; to study physiological changes in trees, including transpiration activity, photosynthesis, and wood growth; and to develop practical recommendations for adapting Polissia forests to climate change.

Materials and Methods

The study was conducted in 2020-2024 in the Polissia region of Ukraine, in particular in the Zhytomyr and Kyiv regions. The objects of the study were pine forests (*Pinus sylvestris* L.) belonging to different age classes and growing in natural conditions of fresh subsoil. It was established 30 trial plots (15 plots in each oblast) of 0.1 ha each, covering areas with different levels of climate change impact, including altitude, soil types and microclimatic features. The geographical coordinates of the test plots were determined using a Garmin GPSMAP 64st (USA) and are located

within 50°15'53"N 28°40'36"E (Zhytomyr region) and 50°27'00"N 30°31'00"E (Kyiv region).

To assess the sanitary condition of the stand, it was used the methodology of categorising trees by sanitary characteristics in accordance with Forest Stewardship Council (FSC) standards. The assessment was carried out by recording such signs as dryness, pest or disease damage, mechanical damage and other pathologies. A Nikon Forestry Pro II laser height meter (Japan) was used to determine the height of the trees, and the diameter at breast height was measured with a Haglöf Mantax Precision diameter tape (Sweden).

Climatic parameters, including mean annual air temperature, precipitation, and hydrothermal coefficient of humidification (HCH), were obtained from the Ukrainian Hydrometeorological Centre for the period 1968-2024. Temperature was measured in degrees Celsius (°C), and precipitation in millimetres (mm). The HCH was calculated using the Selyaninov formula (1), which takes into account the ratio of precipitation to the sum of active temperatures above 10°C during the growing season:

$$HCH = \frac{\sum P}{0,1 \times \sum t_{act > 10}}, \quad (1)$$

where: $\sum P$ – total precipitation per month, in mm; $\sum t$ – the sum of the average daily temperature above 10°C. The dynamics of pests was studied using pheromone traps Csalomon (Hungary), which were placed in the test plots at a height of 1.5-2 m from the ground. The traps were collected every two weeks during the growing season. The detected pests were identified by morphological features using an Olympus SZ61 binocular microscope (Japan). For the study of phytodiseases, molecular diagnostics was carried out by polymerase chain reaction (PCR). DNA was extracted from the tissues of root sponge (*Heterobasidion annosum*) using a Qiagen DNeasy Plant Mini Kit (Germany), and amplification was performed on an Applied Biosystems 2720 thermocycler (USA). The data obtained were analysed using the CLC Genomics Workbench software.

Correlation analysis was performed to analyse the relationship between climate change and the sanitary condition of forest stands. The number of damaged trees affected by pests or diseases was compared with the average annual temperature, precipitation and HCH. Statistical calculations were performed using SPSS Statistics software (version 27, IBM, USA). Correlation analysis to assess the strength and direction of the relationship between variables included the method of determining the Pearson correlation coefficient (r). The significance of the correlation was tested at the level of $p < 0.05$.

To assess the impact of solar activity, it was used data on the Wolf number obtained from the international solar activity centre Solar Influences Data Centre (SIDC). These data were compared with the number of major pests by year. Histological studies of tree tissues were performed using a Leica RM2125 RTS microtome

(Germany). Samples were fixed in 10% neutral formalin, dehydrated, embedded in paraffin and sections were made 5-7 μm thick. Haematoxylin and eosin staining allowed assessing pathological changes in the tissues.

Results

An analysis of the Polissia region's climate data for the period 1968-2024 shows significant changes in key climate indicators that are of great importance to the ecosystem, including the state of pine forests, which are the main forest-forming species in the region (Table 1). Over these 56 years, air temperature increased by an average of 1.2°C, reaching 8.6°C in 2018-2024. The largest changes were recorded in the summer, when temperatures not only exceeded long-term averages but also reached extreme values more often, which creates increased stress on forest ecosystems.

Table 1. Climate indicators of the Polissia region (average values for decades)

Indicator	1968-1977	1978-1987	1988-1997	1998-2007	2008-2017	2018-2024
Average annual temperature, °C	7.4	7.6	7.8	8.1	8.5	8.6
Average annual precipitation, mm	620	615	610	605	600	595
HCH	1.3	1.2	1.1	1.0	0.9	0.9

Source: processed by the author

The rise in temperature was accompanied by an uneven distribution of precipitation, which was another key change in climate conditions. Total annual precipitation decreased by only 25 mm, but this figure does not reflect a significant change in its seasonal distribution. The growing season, which is critical for the growth and development of trees, was characterised by a significant moisture deficit due to long periods without rain. This led to a decrease in soil moisture levels, which became particularly noticeable during periods of active pine growth. In winter, rising temperatures resulted in more frequent thaw episodes, which were accompanied by the formation of an ice crust that impedes normal gas exchange in the soil and can cause damage to root systems. In the spring, earlier snowmelt

combined with a lack of uniform precipitation led to a deterioration in conditions for the initial phase of forest growth.

The HCH, which is a complex indicator that considers the relationship between precipitation and temperature, has shown a significant deterioration in recent decades. In the period 1968-1977, the average value of the HCH was 1.3, which characterises the conditions of excessive moisture favourable for the growth and development of pine forests. However, by 2018-2024, this figure dropped to 0.9, indicating that the region is transitioning to moderate drought conditions. This is an important signal of the deterioration of the hydrothermal balance in the Polissia region.

The decline in the HCH has serious environmental consequences, as moisture levels play

a key role in the formation and maintenance of natural ecosystems. A decrease in moisture levels leads to a deficit of soil moisture, which negatively affects physiological processes in trees, including photosynthesis, transpiration, and biomass accumulation. In pine forests, this is manifested through reduced wood growth rates, decreased crown density, and increased vulnerability to stressors such as pests, diseases, and droughts.

The decline in HCH is a crucial factor affecting the stability of pine stands, especially in natural fresh-successional conditions. Under moisture deficit, there is a decrease in wood growth, which is confirmed by long-term field studies. In particular, the deterioration of the sanitary condition of forest stands in Zhytomyr region coincided with periods of abnormally high temperatures in 2010-2020. An additional negative factor that significantly affects the sanitary condition of pine forests is the increasing frequency of extreme weather events. Strong winds cause mechanical damage to trees, including dryness, branch breakage, and even partial uprooting of weakened trees. Such damage significantly reduces the trees' resistance to pests and pathogens. For example, mechanically damaged trees become a favourable environment for the spread of the root sponge (*Heterobasidion annosum*), which can infect neighbouring trees through the root system, creating foci of infection in forest stands.

This phenomenon is particularly noticeable in regions with low HCH, where climatic conditions make it difficult to regenerate damaged trees. In such areas, the share of trees with mechanical damage increased from 15% in 1980 to 35% in 2020 (Moroz & Nykytiuk, 2021). Reduced moisture availability, rising temperatures, and fre-

quent weather anomalies create additional stress for trees, which reduces their defence potential, including their ability to secrete resin, which is a natural barrier to pests.

Affected areas of the forest become centres of active reproduction of the pine sawfly (*Neodiprion sertifer*) and other pests. The increase in the number of these insects in damaged forest stands reached 50-70% compared to healthy areas. A similar situation is observed with bark beetles, whose populations increase significantly in drought conditions and after mechanical damage. This leads to a chain reaction: mechanical damage increases the vulnerability of trees to pests, and the spread of pests contributes to further deterioration of the sanitary condition of forests. Such climate change has a significant impact on the forest ecosystems of Polissia, in particular on the ability of pine trees to adapt to new conditions. For example, prolonged periods of drought affect the depth of penetration of root systems, which reduces their ability to receive moisture and nutrients. At the same time, changes in the temperature regime led to a reduction in the period of active photosynthesis, which negatively affects the overall condition of the stand.

The sanitary condition of pine forests in Polissia clearly depends on climatic conditions, especially the level of moisture, which is determined by the HCH. In regions with sufficient moisture, where the HCH exceeds 1.0, the stands demonstrate a stable ecological condition with minimal signs of pathology. Such areas are characterised by a low incidence of dry tops and diseases such as root sponge (*Heterobasidion annosum*), indicating optimal conditions for tree growth and regeneration (Table 2).

Table 2. Categorisation of the sanitary condition of pine trees depending on the HCH

Indicator	HCH > 1.0	HCH = 1.0	HCH < 1.0
Share of dry-topped trees, %	8.0	14.5	20.0
Root sponge infestation, %	5.0	8.0	12.0
Total level of damage, %	13.0	22.5	32.0

Source: processed by the author

However, in arid zones, where the HCH drops below 1.0, there is a sharp deterioration in the sanitary condition of the stands. Reducing the level of available moisture creates conditions for physiological stress in trees, reducing their ability to withstand pathogens and pests. Out of 30 test plots, it was observed that the proportion of dry-top trees increases from 8% in regions with sufficient moisture to 20% in areas with moisture deficit. In addition, the prevalence of root sponge is increasing in arid areas: while it affects 5% of trees in humid conditions, this figure reaches 12% in arid areas.

These changes are largely due to a decrease in soil and atmospheric moisture, which disrupts the water balance of trees. The lack of moisture limits transpiration, weakens plant immunity and promotes the development of pathogens that actively use the weakened state of trees to reproduce. In particular, the root sponge becomes more aggressive in conditions of reduced soil moisture, which further complicates the situation.

The increase in the frequency of dry tree canopy in arid regions is a consequence of reduced moisture availability, which negatively affects the vital activity of trees, in particular photosynthesis. Moisture deficit causes a disturbance in the water balance, which causes needles to lose turgor and gradually die, leading to a decrease in the photosynthetic surface of the tree, which is critical for maintaining its physiological processes. Trees with significant damage to the upper tiers of the

crowns, where photosynthetic activity is most intense, lose up to 18% of their growth compared to healthy trees. The reduction in growth is directly related to the restriction of the production of organic substances necessary for growth and tissue regeneration. This also reduces the ability of trees to adapt, as energy resources are spent on compensating for damage rather than strengthening the structure. In addition, damage to the upper tiers of crowns increases the impact of environmental stresses such as drought, as it reduces the ability of trees to transpire, which is important for maintaining temperature balance and protecting against overheating. Affected trees become more vulnerable to pathogens, which further reduces their viability and threatens the sustainability of the entire forest.

In addition, in regions with a moisture deficit, there is an increase in the number of trees affected by pests (Table 3). In particular, populations of pests such as the pine sawfly (*Diprion pini*) have been found to increase rapidly in dry years when air humidity drops to critical levels, in particular below 30%. This phenomenon is explained by the weakening of trees under the influence of stress caused by a lack of moisture. Trees experiencing a moisture deficit reduce the production of protective resinous substances, which makes them more vulnerable to pests. This dynamic is an additional factor that threatens the stability of forest ecosystems in arid regions.

Table 3. The number of main pests and the frequency of disease attacks in pine forests

Indicator	HCH > 1.0	HCH = 1.0	HCH < 1.0
Pine sawfly, individuals/100 trees	45	60	75
Bark beetles, individuals/100 trees	20	35	50
Root sponge damage, %	5	8	12
General level of damage, %	10	18	28

Source: processed by the author

The incidence of root sponge disease (*Heterobasidion annosum*) is also increasing significantly in regions with low HCH. This disease not only weakens the physiological state of trees, but also significantly reduces their mechanical

stability, increasing the risk of falling during strong wind loads or storms. Affected trees demonstrate weakened connections between the tissues of the root system, which negatively affects their ability to withstand external influences.

An analysis of histological sections of wood showed that trees affected by root sponge have up to 30% more necrotic changes in the structure of the root system compared to healthy trees. This includes degeneration of the vascular system, reduced water and nutrient conductivity, and loss of structural integrity of the wood. These changes significantly limit the trees' ability to regenerate and contribute to their further degradation.

Physiological changes in pine stands caused by moisture deficit include a significant decrease in chlorophyll content in needles, which reaches 12% compared to trees with sufficient moisture. A decrease in chlorophyll content indicates a weakening of photosynthetic activity, as this pigment is responsible for absorbing light and generating energy for tree growth. In addition, moisture deficit leads to metabolic disorders, including the transport of nutrients and water in the vascular system of wood.

Weakening of photosynthetic activity is a key factor that causes a decrease in wood growth, stunted growth of young shoots and loss of trees' ability to adapt to external stressors. Studies also show that weakened trees are more likely to be targeted by pests such as bark beetles and pathogens, such as fungi of the genus *Heterobasidion*. This is due to a decrease in the production of protective resinous substances that normally inhibit the growth of pathogens and repel pests.

Pest and disease damage to pine forests is an important factor that significantly affects their sanitary condition, especially in the context of climate change. Increasing average annual temperatures and decreasing precipitation create ideal conditions for an increase in the number of pests such as pine sawfly (*Neodiprion sertifer*), bark beetles and other insects that can actively damage trees weakened by environmental stressors. The weakening of trees is caused by a lack of moisture, which significantly reduces their natural defences, including the ability to secrete resin, which is a barrier to pests.

Field studies confirm a significant dependence of pest activity on HCH. In regions with a

HCH of less than 1.0, which are characterised by dry conditions, the number of pine beetle infestations reached 75 individuals per 100 trees. This is 67% more than in regions with a HCH of more than 1.0, where the number of pests was only 45. This trend can be explained not only by the weakness of trees due to lack of moisture, but also by the fact that dry conditions are favourable for pest reproduction, as they reduce the effectiveness of natural predators and entomophages that control pest populations. Bark beetles also show a clear correlation with soil and air moisture levels. In areas with low HCH, their numbers reached 50 individuals per 100 trees, which was 2.5 times higher than in regions with sufficient moisture, where the number of bark beetles was only 20. Such a significant increase in bark beetle populations in arid conditions indicates their ability to quickly adapt to climate change and attack trees whose defence mechanisms are significantly weakened.

The study of the impact of climate change and solar activity on pine forests confirmed the significant role of environmental factors in shaping their sanitary condition. A long-term increase in the average annual air temperature, accompanied by a decrease in precipitation, creates favourable conditions for the spread of pests and diseases. In particular, rising temperatures promote the development of pathogens such as the root sponge (*Heterobasidion annosum*), which is particularly active in trees in conditions of low soil moisture.

In addition to climate change, solar activity, as measured by the Wolfe number, has a significant impact on the spread of pests. The data show that an increase in the intensity of solar activity correlates with an increase in the number of pine sawfly (*Neodiprion sertifer*). In the years with the highest solar activity (2019-2021), the number of this pest increased by 15%. This phenomenon can be explained by the cumulative impact of solar radiation on environmental conditions, in particular on the microclimate in forests, which favours the development of pests.

Climate change has significantly affected the structure and condition of pine forests. In arid regions, there has been a marked decrease in tree density, which is associated with an increase in mortality due to moisture deficit. In areas with high intensity of solar activity, stem damage caused by increased stress from ultraviolet radiation was recorded more often. These changes indicate that traditional approaches to forest management may not be sufficient to maintain ecological balance in the face of

new climate challenges (Levchenko & Gumenuk, 2024). Adaptation of forest ecosystems requires the implementation of integrated forest management systems (Table 4). This includes the selection of resistant pine varieties that can better tolerate higher temperatures, moisture deficits and intense solar radiation. The use of biological methods of pest control, such as the introduction of entomophages, can significantly reduce the negative impact of pests on forest stands.

Table 4. Recommendations for adapting pine forests to climate change

Climatic conditions	Recommendations	Expected effect
Arid regions (HCH < 1.0)	Introduction of drip irrigation	Reducing stress from moisture deficit
Areas with high solar activity	Use of biological products against pests	Reducing the number of harmful insects
Regions with frequent diseases	Selection of varieties resistant to fungal diseases	Improved resistance to pathogens
Areas with variable precipitation	Mulching the soil to preserve moisture	Increased tree vitality

Source: developed by the author

Remote sensing and regular monitoring of forest conditions will allow for a prompt response to changes in the sanitary condition of plantations. The introduction of geographic information systems and the use of satellite data will help to identify damage at an early stage, which will prevent the spread of pests and diseases. It is also advisable to update the regulatory framework for forest management to take into account climate change, which will allow for more effective conservation of pine forests as a valuable natural resource.

In addition, it is recommended to increase the area under forestry in regions with medium humidity, such as the central part of Polissia. These areas are optimal for growing new forest stands due to favourable hydrothermal conditions that ensure stable tree growth. Expansion of forest areas in these regions will help compensate for the losses caused by degradation of plantations in arid zones and contribute to the preservation of ecosystem functions of forests.

These measures should be implemented in close cooperation with local communities, whose involvement will ensure better adaptation to the socio-economic conditions of the region. Educational campaigns aimed at raising environmental awareness and citizen participation in the planning and maintenance of new plantations will lay the groundwork for the long-term sustainability of these measures. It is also important to integrate these initiatives into local development programmes, which will optimise the use of resources and gain additional support at the national level.

Discussion

An analysis of climate change in the Polissia region over the past 56 years has shown a significant increase in the average annual air temperature by 1.2 °C, accompanied by significant changes in the seasonal distribution of precipitation. This research has confirmed that such changes affect the region's ecosystems, especially the state of pine forests. J. Li *et al.* (2023) noted

that an increase in temperature in summer creates conditions for increased tree stress, which is consistent with the results obtained. According to L. Matallana-Ramirez *et al.* (2021), the impact of heat stress is exacerbated by long periods without rain. This is confirmed by the above analysis of changes in the hydrothermal coefficient.

Calculations of the hydrothermal coefficient showed a decrease from 1.3 to 0.9, indicating a transition to moderate drought conditions. This is a determining factor in the deterioration of the sanitary condition of pine stands. B. Sensuła & S. Wilczyński (2022) emphasised the critical role of soil moisture in maintaining tree viability, which correlates with the results of field studies. A. Acarer (2024) also confirmed that moisture deficit reduces transpiration and biomass accumulation, which is consistent with observations in areas with a low hydrothermal coefficient.

Extreme weather events, such as strong winds and droughts, have a significant impact on pine forests, contributing to mechanical damage to trees. The proportion of trees with mechanical damage has increased to 35% in arid regions. K. Mechergui *et al.* (2021) pointed to an increase in the vulnerability of damaged trees to pests and diseases, which is consistent with the results above, which showed an increase in the number of pine beetle in such conditions. Á. Enríquez-de-Salamanca (2024) emphasised the importance of sanitary measures to limit the spread of pests, which confirms the need for an integrated approach to forest management.

Climate change has also led to an increase in the number of bark beetles and the spread of root sponges, which significantly weaken trees. It was found that in arid regions, the proportion of trees affected by root sponge reached 12%, which correlates with the research of X. Ouyang *et al.* (2022), which indicate an increase in the aggressiveness of pathogens under conditions of moisture deficit. M. Mikalajūnas *et al.* (2021) also noted that root diseases increase the risk of tree fall during storms, which correlates with the observation in the Polissia region.

Physiological changes caused by climatic factors clearly demonstrate a significant impact on the state of pine forests in the Polissia region. This research has confirmed that a decrease in the chlorophyll content of needles is accompanied by impaired transpiration, which makes it difficult to maintain the water balance of trees. The decrease in photosynthetic activity has led to a reduction in wood growth to critical levels. The analysis of wood sections revealed up to 30% of necrotic changes in the structures of the root system, which reflects the accumulation of physiological stress in trees. These results coincide with the studies of N. Markos *et al.* (2023), which also indicated the impact of moisture deficit on root tissue damage. T. Dimitrijević *et al.* (2023) emphasised that in arid regions, reduced wood growth is a common consequence of climate change, which is consistent with the reductions in photosynthetic activity and reduced adaptive capacity of trees that it was found in current research.

Increasing pest populations, such as pine beetle and bark beetle, pose a serious threat to the sustainability of pine forests in the region. This current research has confirmed that the reduced production of protective resinous substances, which is typical for trees in drought conditions, greatly facilitates the spread of pests. This correlates with the findings of V. Loewe-Muñoz *et al.* (2024), who pointed out the crucial role of these substances in counteracting the invasion of insect pests. Additionally, the observations of the current study show that in regions with low SOC, natural predators that usually control pest populations lose their effectiveness due to moisture deficits. This is confirmed by the research of R.M. Navarro-Cerrillo *et al.* (2022), who focused on the impact of drought conditions on the ecological balance in forest ecosystems. Thus, it was found that the combination of weakening of the natural resistance of trees and a decrease in the activity of natural predators contributes to an uncontrolled increase in the number of pests, which negatively affects the sanitary condition of pine forests.

The sanitary condition of pine forests deteriorates significantly under the influence of extreme temperatures and reduced precipitation. The results of the study showed that in arid zones, the proportion of dry-topped trees increased to 20%. J. Stolz *et al.* (2021) highlighted that such changes reduce the photosynthetic activity and adaptive potential of trees, which correlates with the above data. J. Brichta *et al.* (2024) also pointed out the critical role of water balance in maintaining the sustainability of forest stands, which is confirmed by the results of the above studies.

The impact of solar activity on the sanitary condition of pine forests was significant and requires more detailed study. It was found that the number of pine sawfly increased by 15% during increased solar activity, which correlates with microclimate changes that promote the development of pests. These results confirm the findings of K. Bowman & X. Chen (2022), who emphasised the correlation between solar radiation intensity and the spread of insect pests. D. Karnosky *et al.* (2003) added that an increase in ultraviolet radiation affects the formation of a drier microclimate in forest stands, creating conditions for the activation of pests. The findings are consistent with the identified trends showing how changes in solar activity affect the biological balance of pine ecosystems.

Recommendations for adaptation of pine forests to climate change include the introduction of drip irrigation, the use of biological products for pest control and the selection of resistant pine varieties. R.S. Pacaldo *et al.* (2024) noted the effectiveness of biological control of pests, which is supported by research proposals for the integration of these methods into forest management systems. D. Nadal-Sala *et al.* (2017) also pointed out the importance of remote sensing for monitoring forest health, which is consistent with recommendations on the use of geographic information systems.

Involvement of local communities in forest management is a key factor for the conservation of Polissia ecosystems. The participation of local residents in forest restoration activities not

only increases the effectiveness of such initiatives, but also increases the level of community responsibility for the state of forests. The study showed that communities that are actively involved in environmental programmes are reducing uncontrolled deforestation and improving the quality of restoration work. A.L. Giambelluca *et al.* (2024) emphasised the importance of integrating educational campaigns that teach local residents effective reforestation methods, which is consistent with the above recommendations for the development of environmental education. According to a study by X. Tang *et al.* (2021), community involvement in local development programmes increases the resilience of forests to climate change, creating conditions for the long-term conservation of forest resources. The results of the current study also highlight that cooperation with communities will ensure better consideration of local environmental conditions and facilitate forest adaptation to climate challenges, which is in line with the findings of other authors.

An integrated approach to forest management, including the introduction of modern monitoring methods, selection of resistant varieties and community engagement, is essential for the adaptation of forest ecosystems to climate challenges. M. Tsaktsira *et al.* (2023) emphasised the importance of updating the regulatory framework for forest management, which coincides with the recommendations of the study of the sanitary condition of pine forests in Polissia. D. Nadal-Sala *et al.* (2021) also highlighted the need to expand the area of afforestation in favourable regions, which is consistent with the findings on optimising forest management in the face of climate change.

Overall, the conducted research highlights the complex and multidimensional impact of climate change, moisture deficit, and solar activity on the sanitary condition and stability of pine forests in the Polissia region. The observed deterioration in hydrothermal balance, increased frequency of extreme weather events, and rising pest and disease pressures significantly reduce the resilience of pine ecosystems. Long-term

changes in key climatic indicators, coupled with physiological stress in trees, have led to a decline in growth rates, crown density, and adaptive capacity, especially in arid zones.

Conclusions

The study of climate change in the Polissia region over the period 1968-2024 revealed a significant increase in the average annual temperature (+1.2°C) and a decrease in the HCH level from 1.3 to 0.9, indicating a deterioration in moisture conditions. Changing climatic conditions have had a negative impact on pine forests, causing moisture deficits, frequent droughts and extreme weather events that increase stress on trees. Soil moisture deficit and frequent winter thaws have contributed to the deterioration of forest health, including an increased risk of root sponge disease (*Heterobasidion annosum*) and an increase in pest populations such as pine sawfly and bark beetle. In regions with a HCH below 1.0, the number of pests increased to 75 individuals per 100 trees, which is twice as high as in areas with sufficient moisture.

The analysis of pine physiological processes showed a decrease in photosynthetic activity and chlorophyll accumulation in the needles, which reduced wood growth and the adaptive potential of trees. Changes in the temperature regime affected the duration of active pine growth, and mechanical damage to trees due to strong winds increased vulnerability to pathogens and pests. Field data confirmed that the proportion of dry-top trees in arid regions with a HCH<1.0 reached 20%, and the level of root sponge damage increased to 12%.

For the adaptation of pine forests, it is recommended to introduce drip irrigation, select resistant tree varieties, mulch the soil and use biological products against pests. Regular monitoring using geographic information systems and the involvement of local communities in forest management will help preserve forests in the new climate conditions. Prospects for further research include modelling adaptation strategies and studying the long-term impact of climate change on forest ecosystems.

The study has certain limitations, including insufficient detail on local environmental conditions and the impact of anthropogenic factors, such as logging and pollution, which can exacerbate the negative effects of climate change. In addition, the analysis was based on long-term averages, which may not consider short-term fluctuations in climate parameters and their impact on pine forests. Prospects for further research include expanding the number of test plots, integrating remote sensing to monitor forest conditions, and modelling possible scenarios for forest ecosystems to adapt to climate change. It is also important to study the genetic characteristics of pine trees' resistance to drought, diseases, and pests to develop breeding programmes aimed at creating sustainable forest plantations.

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Conflict of Interest

None.

References

- [1] Acarer, A. (2024). Response of black pine (*Pinus nigra*) in southwestern Anatolia to climate change. *BioResources*, 19(4), 8594-8607. doi: [10.15376/biores.19.4.8594-8607](https://doi.org/10.15376/biores.19.4.8594-8607).
- [2] Bose, A.K., et al. (2022). Lessons learned from a long-term irrigation experiment in a dry Scots pine forest: Impacts on traits and functioning. *Ecological Monographs*, 92(2), article number e1507. doi: [10.1002/ecm.1507](https://doi.org/10.1002/ecm.1507).
- [3] Bowman, K., & Chen, X. (2022). Current standing of longleaf pine trees under climate change. *Journal of Botanical Research*, 4(1), 28-39. doi: [10.30564/jbr.v4i1.4350](https://doi.org/10.30564/jbr.v4i1.4350).
- [4] Brichta, J., et al. (2024). Effects of climate change on scots pine (*Pinus sylvestris* L.) growth across Europe: Decrease of tree-ring fluctuation and amplification of climate stress. *Forests*, 15(1), article number 91. doi: [10.3390/f15010091](https://doi.org/10.3390/f15010091).

- [5] Buras, A., Rehschuh, R., Fonti, M., Lange, J., Fonti, P., Menzel, A., Gessler, A., Rigling, A., Treydte, K., & von Arx, G. (2023). Quantitative wood anatomy and stable carbon isotopes indicate pronounced drought exposure of Scots pine when growing at the forest edge. *Frontiers in Forests and Global Change*, 6, article number 1233052. doi: [10.3389/ffgc.2023.1233052](https://doi.org/10.3389/ffgc.2023.1233052).
- [6] Dang, H., Han, H., Chen, S., & Li, M. (2021). A fragile soil moisture environment exacerbates the climate change-related impacts on the water use by Mongolian Scots pine (*Pinus sylvestris* var. *mongolica*) in northern China: Long-term observations. *Agricultural Water Management*, 251, article number 106857. doi: [10.1016/j.agwat.2021.106857](https://doi.org/10.1016/j.agwat.2021.106857).
- [7] Dimitrijević, T., Ratknic, M., & Hadrović, S. (2023). Climate characteristics and diameter increment of Eastern white pine: Potential use in afforestation in the Belgrade area (Republic of Serbia). *Sustainable Forestry: Collection*, 87-88, 99-113. doi: [10.5937/sustfor2388099d](https://doi.org/10.5937/sustfor2388099d).
- [8] Ellis, E.X., Guy, R.D., & Wei, X.A. (2024). Seasonal shifts in depth-to-water uptake by young thinned and overstocked lodgepole pine (*Pinus contorta*) forests under drought conditions in the Okanagan Valley, British Columbia, Canada. *Hydrology and Earth System Sciences*, 28, 4667-4684. doi: [10.5194/hess-28-4667-2024](https://doi.org/10.5194/hess-28-4667-2024).
- [9] Enríquez-de-Salamanca, Á. (2024). Influence of climate change on carbon sequestration in pine forests of central Spain. *Atmosphere*, 15(10), article number 1178. doi: [10.3390/atmos15101178](https://doi.org/10.3390/atmos15101178).
- [10] Ghosh, S.K., Slot, J.C., Visser, E.A., Naidoo, S., Sovic, M.G., Conrad, A.O., Kyre, B., Vijayakumar, V., & Bonello, P. (2022). Mechanisms of pine disease susceptibility under experimental climate change. *Frontiers in Forests and Global Change*, 5, article number 872584. doi: [10.3389/ffgc.2022.872584](https://doi.org/10.3389/ffgc.2022.872584).
- [11] Giambelluca, A.L., Hermosilla, T., Álvarez-Mozos, J., & González-Audícana, M. (2024). Identifying forest harvesting practices: Clear-cutting and thinning in diverse tree species using dense Landsat time series. *Forest Ecology and Management*, 578, article number 122442. doi: [10.1016/j.foreco.2024.122442](https://doi.org/10.1016/j.foreco.2024.122442).
- [12] Hartmann, M., Herzog, C., Brunner, I., Stierli, B., Meyer, F., Buchmann, N., & Frey, B. (2023). Long-term mitigation of drought changes the functional potential and life-strategies of the forest soil microbiome involved in organic matter decomposition. *Frontiers in Microbiology*, 14, article number 1267270. doi: [10.3389/fmicb.2023.1267270](https://doi.org/10.3389/fmicb.2023.1267270).
- [13] Karnosky, D., Percy, K., Chappelka, A., & Krupa, S. (2003). Air pollution and global change impacts on forest ecosystems: Monitoring and research needs. In D.F. Karnosky, K.E. Percy, A.H. Chappelka, C. Simpson & J. Pikkarainen (Eds.), *Air pollution, global change and forests in the new millennium* (pp. 447-459). Oxford: Elsevier. doi: [10.1016/s1474-8177\(03\)03025-0](https://doi.org/10.1016/s1474-8177(03)03025-0).
- [14] Levchenko, V., & Gumenuk, V. (2024). Regarding the issue of growing Scots Pine forests in Polissya. *Ukrainian Journal of Forest and Wood Science*, 15(4), 25-39. doi: [10.31548/forest/4.2024.25](https://doi.org/10.31548/forest/4.2024.25).
- [15] Li, J., Xie, Y., Wulan, T., Liu, H., Wang, X., Zheng, Y., Qi, Q., Gao, Z., Gao, S., & Shen, Z. (2023). Drought resilience of Mongolian Scotch pine (*Pinus sylvestris* var. *mongolica*) at the southernmost edge of its natural distribution: A comparison of natural forests and plantations. *Forest Ecology and Management*, 542, article number 121104. doi: [10.1016/j.foreco.2023.121104](https://doi.org/10.1016/j.foreco.2023.121104).
- [16] Loewe-Muñoz, V., Cachinero-Vivar, A.M., Camarero, J.J., del Río, R., Delard, C., & Navarro-Cerrillo, R.M. (2024). Dendrochronological analysis of *Pinus Pinea* in Central Chile and South Spain for sustainable forest management. *Biology*, 13(8), article number 628. doi: [10.3390/biology13080628](https://doi.org/10.3390/biology13080628).
- [17] Markos, N., Preisler, Y., Radoglou, K., Rotenberg, E., & Yakir, D. (2023). Physiological and phenological adjustments in water and carbon fluxes of Aleppo pine forests under contrasting climates in the Eastern Mediterranean. *Tree Physiology*, 44(1), article number tpad125. doi: [10.1093/treephys/tpad125](https://doi.org/10.1093/treephys/tpad125).

- [18] Matallana-Ramirez, L., Whetten, R., Sanchez, G., & Payn, K. (2021). Breeding for climate change resilience: A case study of loblolly Pine (*Pinus taeda* L.) in North America. *Frontiers in Plant Science*, 12, article number 606908. doi: [10.3389/fpls.2021.606908](https://doi.org/10.3389/fpls.2021.606908).
- [19] Mechergui, K., Altamimi, A., Jaouadi, W., & Naghmouchi, S. (2021). Climate change impacts on spatial distribution, tree-ring growth, and water use of stone pine (*Pinus pinea* L.) forests in the Mediterranean region and silvicultural practices to limit those impacts. *Iforest – Biogeosciences and Forestry*, 14(2), 104-112. doi: [10.3832/IFOR3385-013](https://doi.org/10.3832/IFOR3385-013).
- [20] Mikalajūnas, M., Pretzsch, H., Mozgeris, G., Linkevičius, E., Augustaitienė, I., & Augustaitis, A. (2021). Scots pine's capacity to adapt to climate change in hemi-boreal forests in relation to dominating tree increment and site condition. *Iforest – Biogeosciences and Forestry*, 14(5), 473-482. doi: [10.3832/IFOR3703-014](https://doi.org/10.3832/IFOR3703-014).
- [21] Moroz, V., & Nykytiuk, Y. (2021). Current state of pineries in Zhytomyr Polissia under the influence of environmental factors. *Scientific Horizons*, 24(8), 37-46. doi: [10.48077/scihor.24\(8\).2021.37-46](https://doi.org/10.48077/scihor.24(8).2021.37-46).
- [22] Nadal-Sala, D., Grote, R., Birami, B., Lintunen, A., Mammarella, I., Preisler, Y., Rotenberg, E., Salmon, Y., Tatarinov, F., Yakir, D., & Ruehr, N.K. (2021). Assessing model performance via the most limiting environmental driver in two differently stressed pine stands. *Ecological applications: A Publication of the Ecological Society of America*, 31(4), article number e2312. doi: [10.1002/eap.2312](https://doi.org/10.1002/eap.2312).
- [23] Nadal-Sala, D., Keenan, T.F., Sabaté, S., & Gracia, C. (2017). Forest eco-physiological models: Water use and carbon sequestration. In F. Bravo, V. LeMay & R. Jandl (Eds.), *Managing forest ecosystems: The challenge of climate change* (pp. 81-102). Cham: Springer. doi: [10.1007/978-3-319-28250-3_5](https://doi.org/10.1007/978-3-319-28250-3_5).
- [24] Navarro-Cerrillo, R.M., Ruiz-Gómez, F.J., Camarero, J.J., Castillo, V., Barberá, G.G., Palacios-Rodríguez, G., Navarro, F.B., Blanco, J.A., Imbert, J.B., Cachinero-Vivar, A.M., Molina, A.J., & del Campo, A.D. (2022). Long-term carbon sequestration in pine forests under different silvicultural and climatic regimes in Spain. *Forests*, 13(3), article number 450. doi: [10.3390/f13030450](https://doi.org/10.3390/f13030450).
- [25] Ouyang, X., Chen, A., Li, Y., Han, X., & Lin, H. (2022). Predicting the potential distribution of pine wilt disease in China under climate change. *Insects*, 13(12), article number 1147. doi: [10.3390/insects13121147](https://doi.org/10.3390/insects13121147).
- [26] Pacaldo, R.S., Aydin, M., & Amarille, R.K. (2024). Soil respiration and controls in warmer winter: A snow manipulation study in postfire and undisturbed black pine forests. *Ecology and Evolution*, 14(3), article number e11075. doi: [10.1002/ece3.11075](https://doi.org/10.1002/ece3.11075).
- [27] Sensuła, B., & Wilczyński, S. (2022). Dynamics changes in basal area increment, carbon isotopes composition and water use efficiency in Pine as response to water and heat stress in Silesia, Poland. *Plants*, 11(24), article number 3569. doi: [10.3390/plants11243569](https://doi.org/10.3390/plants11243569).
- [28] Stolz, J., van der Maaten, E., Kalanke, H., Martin, J., Wilmking, M., & van der Maaten-Theunissen, M. (2021). Increasing climate sensitivity of beech and pine is not mediated by adaptation and soil characteristics along a precipitation gradient in northeastern Germany. *Dendrochronologia*, 67, article number 125834. doi: [10.1016/j.dendro.2021.125834](https://doi.org/10.1016/j.dendro.2021.125834).
- [29] Tang, X., Yuan, Y., Li, X., & Zhang, J. (2021). Maximum entropy modeling to predict the impact of climate change on pine wilt disease in China. *Frontiers in Plant Science*, 12, article number 652500. doi: [10.3389/fpls.2021.652500](https://doi.org/10.3389/fpls.2021.652500).
- [30] Tsaktsira, M., Tsoulpha, P., Economou, A., & Scaltsoyiannes, A. (2023). Mitigation of global climate change through genetic improvement of resin production from resinous pines: The case of *Pinus halepensis* in Greece. *Sustainability*, 15(10), article number 8052. doi: [10.3390/su15108052](https://doi.org/10.3390/su15108052).
- [31] Turko, V., & Moroz, V. (2023). [The impact of weather conditions on natural regeneration of *Pinus sylvestris* in the central Polissya region](https://doi.org/10.3390/ijms14050005). *German International Journal of Modern Science*, 58, article number 5.

Вплив кліматичних змін на санітарний стан соснових лісостанів Полісся

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Анотація. Дослідження було спрямоване на визначення ключових чинників, які впливають на санітарний стан соснових лісостанів у Поліссі в умовах кліматичних змін, а також розробити рекомендації для їх адаптації до нових екологічних викликів. Для аналізу закладено 30 пробних ділянок по 0,1 гектара, на яких досліджували соснові деревостани різних вікових класів. У ході роботи зафіксовано ключові кліматичні тенденції: середньорічна температура за період 1968-2024 років зросла на 1,2°C, кількість опадів зменшилася на 25 міліметрів, а гідротермічний коефіцієнт зволоження знизився з 1,3 до 0,9, що свідчить про посуху. У регіонах із дефіцитом вологи частка суховерхих дерев зросла з 8 % до 20 %, а ураження кореневою губкою – з 5 % до 12 %. Зниження рівня ґрунтової вологи порушило транспірацію, обмежило фотосинтез і знизило приріст деревини на 18 % порівняно зі здоровими деревами. Виявлено, що чисельність соснового пильщика і короїдів збільшилася на 67 % і 150 % відповідно у посушливих умовах. Аналіз показав, що механічні пошкодження, спричинені сильними вітрами, створюють умови для активного поширення шкідників і хвороб. Отримані результати свідчать, що кліматичні зміни спричинили деградацію лісостанів через посилення фізіологічного стресу дерев. Для адаптації запропоновано селекцію стійких сортів сосни, впровадження зрошувальних систем, моніторинг стану лісів із використанням геоінформаційних технологій та збільшення площі лісорозведення у сприятливих зонах. Застосування цих заходів сприятиме збереженню лісових екосистем у регіоні в умовах змін клімату

Ключові слова: посуха; гідротермічний коефіцієнт; суховерхість; екологічні чинники; коренева губка



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Effectiveness of shading sweet pepper for growing in the Forest-Steppe of Ukraine

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Abstract. The purpose of the study was to establish the influence of shading grids of different densities on the growth, development and productivity of sweet pepper plants under irrigation conditions of the Left-Bank Forest-Steppe of Ukraine. The study was carried out at the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine according

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to generally accepted methods using the field research method. The implementation of the research provided for determining the impact of the introduction of shading plants with grids with a density of 45% and 60% on biometric parameters and productivity of sweet pepper plants, economic indicators of cultivation efficiency. It was found that shading provides a significant increase in the diameter of sweet pepper plants for both varieties (by 15.1-23.7%), and only for the Liubasha variety – an increase in plant height (by 17.8-21.5%) and fruit height (by 10.1-15.2%). Shading using a grid with a density of 45% provides a significant increase in the number of fruits on the plant for both varieties (by 11.5% for the Liubasha variety and by 48.5% for the Svitozar variety). Increasing the density parameter of shading nets to 60% leads to a decrease in the number of fruits on plants. It was noted that for the Liubasha variety, the growth of the average fruit weight when using shading is 11.1-25.6%, for the Svitozar variety, this indicator decreases by 17.9-60.2%. A significant increase in the yield of sweet pepper was provided by the use of shading with a grid with a density of 45% only for the Liubasha variety (an increase of 24.3%). According to this technological approach, the economic parameters of growing sweet pepper are increased (profit up to 14.75 UAH/m², profitability up to 103%). The results of the study may be useful for small and medium-sized farmers who grow peppers in the open ground, to reduce the risks associated with heat and temperature changes

Keywords: *Capsicum annuum* L.; density of the shading grid; biometric parameters of plants; productivity; profitability

Introduction

Sweet pepper is a heat-loving crop, but excessive solar radiation can lead to overheating of plants, sunburn, and reduced photosynthetic activity. Optimal shading helps to reduce moisture evaporation, maintain a favourable microclimate, and reduce the temperature of the soil and air around plants, which has a positive effect on moisture retention and nutrient absorption. In addition, shading can help to improve the marketable appearance of fruits, preventing them from burning out in the sun, which is important for the market quality of products. The study of shading efficiency allows determining the optimal shading levels for different climatic conditions, determining the effectiveness of appropriate technological measures, such as the use of nets with different densities, agrofibre or mixed planting with other crops, and developing recommendations for farmers to increase the productivity of sweet pepper.

Sweet pepper (*Capsicum annuum* L.) is one of the most valuable vegetable crops due to its rich chemical composition and high nutritional value. According to L. Pylypenko & O. Shabetya (2020),

its value is determined by the high content of organic acids, salts, nitrogenous substances, and sugars, which makes fruits not only useful, but also an important component of a healthy diet. In addition, the researchers noted that there is a correlation between the morphological characteristics of plants and their economically valuable traits, which is important for breeding and seed production. S. Vdovenko & P.A. Shvydyki (2023) characterised pepper fruits as a multivitamin product because they contain significant amounts of vitamin C (100-300 mg/100 g). The researchers pointed out that ascorbic acid is a powerful antioxidant that helps to strengthen the immune system and increase the body's resistance to adverse environmental factors.

The level of vitamins and biologically active substances in pepper largely depends on the growing conditions, in particular, light, humidity, and temperature conditions. Accordingly, the introduction of technological solutions aimed at regulating microclimatic factors can have a significant impact on the preservation of the quality

characteristics of fruits. Optimisation of growing conditions, including shading systems, is an important area of research that contributes to improving the qualitative and quantitative indicators of crop yield (Vdovenko *et al.*, 2024).

The study by J. Díaz-Pérez (2013) considered that one of the solutions to mitigate the effects of high temperatures in vegetable growing systems is to manipulate plant development and growth using screens or grids. The implementation of this technological measure does not require high financial and resource costs and is very actively used in different countries of the world, but in different soil and climatic conditions, their effectiveness varies significantly and requires research to clarify the most effective parameters of measures to reduce solar insolation. G. Caruso *et al.* (2020) proved that extreme fluctuations in air temperature and solar radiation during the growing season are vital for plant growth and yield. It was noted that the introduction of shading provided an increase in the pigment content in chloroplasts and improved photosynthesis processes.

X. He *et al.* (2021) noted that, on the one hand, ultraviolet radiation increases the development of secondary metabolites in plants, such as flavonoids, phenol derivatives, ascorbic acid, and carotenoids, which affects changes in the colour of leaves, flowers, and fruits, improved taste of products and greater resistance to pests and diseases. On the other hand, this type of radiation can cause DNA damage and inhibit photosynthesis, reducing growth and causing plant compactness. S. Stanghellini *et al.* (2011) noted that most vegetable crops are sun-loving, for which productivity increases almost linearly with the intensity of photosynthetically active radiation. E. Kitta *et al.* (2014) investigated the photosynthetic acclimatisation of sweet pepper plants to protected soil conditions, noting that shading promotes plant adaptation and can improve their water regime. They found that such conditions help to reduce moisture loss and maintain a stable level of productivity even in water scarcity.

Yu.M.Syromyatnikov (2023) analysed the impact of technological measures on soil moisture saturation in sugar beet cultivation and noted that the introduction of certain agrotechnical techniques allowed reducing water evaporation and improving the water balance of agrocoenoses. Thus, both studies confirmed the positive effect of shading on the water regime of crops, especially in conditions of drought and insufficient precipitation.

Findings of O. Mohawesh *et al.* (2022) demonstrated a positive effect of coloured shading grids on a significant decrease in peak daytime air temperatures and light intensity (from 22 to 28°C and 9,992 Lux, respectively) compared to the control (from 32 to 37°C and 24,973 Lux, respectively), which further provided an increase in the productivity of sweet pepper plants (an increase in plant height, leaf area, an increase in the amount of chlorophyll in the leaves and vitamin C in ripe fruits. According to Hungarian researchers H. Darázs Ledóné *et al.* (2017) for growing sweet peppers in tunnels, the use of a green shading grid led to a decrease in yield, while yellow and red grids contributed to an increase in yield and fruit quality of the crop. It was indicated that the intensity of grid shading should not exceed 35-40%.

Thus, it should be noted that the effect of shading on the growth and productivity of pepper plants significantly depends on the soil and climatic conditions of cultivation. Thus, the purpose of the study was to establish the effect of using a shading grid of different densities on the growth, development and productivity of sweet pepper plants in irrigated conditions of the Left-Bank Forest-Steppe of Ukraine.

Materials and Methods

The research was conducted during 2022-2023 at the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine, in typical soil and climatic conditions of the Left-Bank Forest-Steppe of Ukraine. Sweet pepper was grown by seedling method using

drip irrigation. Its predecessor was cucumber. Seedlings were grown in a heated film greenhouse. Sowing was carried out in the second ten days of March. Before selection, the seedlings were tempered for 8-10 days and at the time of planting, the pepper seedlings had a well-branched root system. Seedlings (60-day) were planted in the second decade according to the scheme $(60 + 40) \times 35$ cm. According to the research scheme, the shading grid was installed in the second decade of June, that is, at the beginning of the period of hot weather in given soil and climatic conditions.

Two types of shading grid were used in the studies: with a 45% shading effect and with a 60% shading effect, the effectiveness of which was studied on two varieties of sweet pepper Liubasha and Svitozar. Liubasha is a medium-ripened variety (103-107 days) selected by the Institute of Vegetable and Melon Growing of the National Academy of Sciences, which has broad-cone fruits of light yellow (bright red when ripe) colour, 9-11 cm long, weighing 130-150 g, with a wall thickness of 7-8 mm. The plant is compact, standard. The variety is characterised by resistance to wilting and viral diseases. Potential yield, t/ha: 42-45 t/ha. Svitozar is a medium-late variety (117-125 days) selected by the Institute of Vegetable and Melon Growing of the National Academy of Sciences, which has cuboid fruits of yellow-green (bright red when ripe) colour, 9-10 cm long, weighing 120-130 g, with a wall thickness of 6-9 mm. The plant is compact, standard, short. The variety is characterised by resistance to TMV. Potential yield, t/ha: 36-42 t/ha.

The study was conducted according to the methodology of research in vegetable growing (Bondarenko & Yakovenko, 2001). The area of the registered plot was 25.2 m², repetition – quadruple. In the experiment, biometric parameters of plants (plant height, bush diameter, fruit height and diameter) were considered, elements of plant productivity (number of fruits per plant, fruit weight, plant productivity) and fruit yield (by the method of dividing weighing by the onset of technical ripeness) were determined.

The economic analysis was carried out based on the calculation of net income, production cost, and profitability level. Statistical processing of the findings was implemented by the method of variance analysis. Experimental studies of cultivated plants, including the collection of plant material, were in accordance with institutional, national or international guidelines. The authors adhered to the Convention on Biological Diversity (1992) standards.

Results and Discussion

A certain dependence of the effectiveness of introducing shading in the technology of growing sweet pepper on the plant variety is established (Table 1). For the medium-ripened Liubasha variety, the introduction of shading indicated a significant increase in such biometric parameters of plants as height (by 17.8-21.5% relative to the control), bush diameter (by 18.7-23.7%), fruit height (by 10.1-15.2%), and a positive trend towards increasing the diameter of sweet pepper fruit (by 4.7-6.6%). Different shading options (45% and 60%) did not differ significantly.

Table 1. Influence of shading on biometric parameters of sweet pepper plants (average for 2022-2023)

Shading options	Biometric parameters of pepper plants			
	Plant height, cm	Bush diameter, cm	Fruit height, cm	Fruit diameter, cm
Liubasha variety				
No shading (control)	51.1	43.9	9.9	6.98
Shading by 45%	60.2	52.1	10.9	7.44
Shading by 60%	62.1	54.3	11.4	7.31

Table 1. Continued

Shading options	Biometric parameters of pepper plants			
	Plant height, cm	Bush diameter, cm	Fruit height, cm	Fruit diameter, cm
Svitozar variety				
No shading (control)	50.9	49.1	6.75	6.75
Shading by 45%	51.9	56.5	7.38	7.38
Shading by 60%	54.8	60.0	7.19	7.19
LSD _{0.95}	5.25	5.62	0.81	0.70

Source: compiled by the authors

For the medium-late Svitozar variety, the introduction of shading provides only a significant increase in the diameter of the sweet pepper bush by 15.1-22.2%. According to the effect on the height and diameter of the fruit, shading causes only a positive trend. A positive trend was also noted for the height of plants using 60% shading.

Shading had a different effect on the productivity parameters of pepper plants of the varieties under study (Table 2). It was noted that when using shading by 45% for both varieties,

there was a significant increase in the number of fruits on the plant (by 11.5% for the Liubasha variety and by 48.5% for the Svitozar variety). Increasing the density of shading nets by up to 60% leads to a decrease in the number of fruits on pepper plants. For the Liubasha variety, this decrease is significant. For the Liubasha variety, the use of shading provides an increase in the average weight of the fruit. Fruit weight increased by 11.1-25.6%. For the medium-late Svitozar variety, the use of shading nets leads to a decrease in fruit weight by 17.9-60.2%.

Table 2. Dependence of elements of productivity of sweet pepper plants on shading (average for 2022-2023)

Shading options	Productivity indicators of sweet pepper plants		
	Number of fruits per plant, units/plant	Average fruit weight, g	Plant productivity, g/plant
Liubasha variety			
No shading (control)	5.20	90	469
Shading by 45%	5.80	100	583
Shading by 60%	4.25	113	481
Svitozar variety			
No shading (control)	4.95	117	499
Shading by 45%	7.35	73	536
Shading by 60%	4.80	96	462
LSD _{0.95}	0.54	9.8	45.6

Source: compiled by the authors

The positive effect of shading plants on increasing the productivity of the sweet pepper variety Liubasha was noted. When using 45% shading, the plant productivity was 583 g/plant, while without shading, this figure was 469 g/plant. When using 60% shading, plant productivity does

not increase significantly, which is associated with the formation of fewer fruits on plants.

For the Svitozar variety, 45% shading provides only a positive trend in increasing productivity (the growth relative to control is only 7.4%). The introduction of 60% shading generally leads

to a negative trend in plant productivity; the indicator decreases from 499 g/plant in the control to 462 g/plant.

The yield of sweet pepper plants depends to a certain extent on the productivity of the plants

(Fig. 1). In the conditions of 2022, there was a significant increase in the yield of Liubasha pepper with the use of 45% shading. The yield increase was 0.43 kg/m² or 18.2% relative to the control with a yield of 2.36 kg/m².

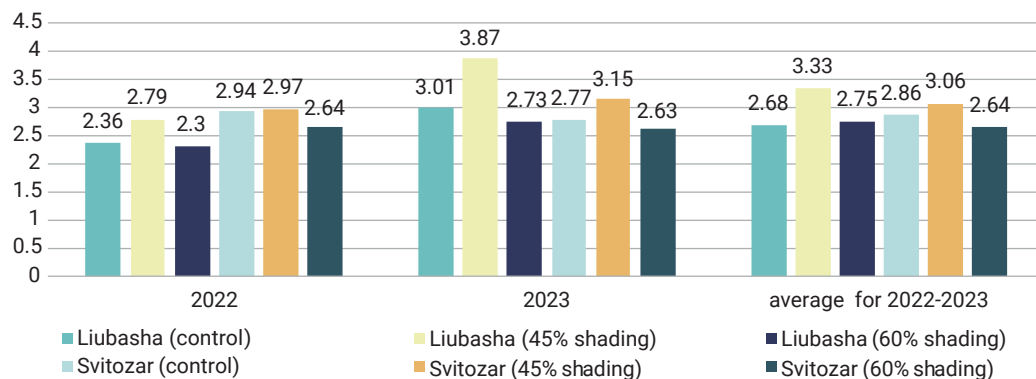


Figure 1. Yield of sweet pepper varieties depending on shading, kg/m²

Note: LSD_{0.95} for 2022 = 0.21 t/ha; LSD_{0.95} for 2023 = 0.26 t/ha

Source: compiled by the authors

In 2023, the yield of the Liubasha variety also increased significantly with the use of 45% shading, providing an increase of 0.86 kg/m² or 28.6%, and Svitozar varieties (increase of 0.38 kg/m² or 12.6%). On average, over two years, there was a significant increase in yield with the use of 45% shading only for the Liubasha variety (an increase of 0.65 kg/m² or 24.3%). The introduction of 60% shading does not provide an increase in the yield of sweet pepper. Despite the increase in the yield of sweet pepper for the use of shading

nets, this technological measure is economically justified due to the payback of the cost of shading nets for three years of operation (Table 3). The maximum economic indicators were noted for options with the maximum increase in the yield of pepper fruits. Even with the payback of the cost of purchasing a grid for one year for growing the Liubasha variety, the use of shading with a 45% grid provides an additional profit of 4.85 UAH/m² but the level of profitability was still less than the control (90.0%) and is 73.0%.

Table 3. Economic efficiency of sweet pepper shading (average for 2022-2023)

Shading	Economic indicators					
	Total yield, kg/m ²	Full expenses, UAH/m ²	Profit, UAH/m ²	Profit from shading, UAH/m ²	Production cost, UAH/kg	Profitability of production, %
Payback of grid purchase costs in one year						
1. Liubasha (control)	2.68	49.40	44.40	-	18.43	90.0
2. Liubasha (45% shading)	3.33	67.30	49.25	4.85	20.21	73.0
3. Liubasha (60% shading)	2.75	74.40	21.85	-22.55	27.05	29.4
4. Svitozar (control)	2.86	50.10	50.00	-	17.52	99.8
5. Svitozar (45% shading)	3.06	68.00	39.10	-10.90	22.22	57.5

Table 3. Continued

Shading	Economic indicators					
	Total yield, kg/m ²	Full expenses, UAH/m ²	Profit, UAH/m ²	Profit from shading, UAH/m ²	Production cost, UAH/kg	Profitability of production, %
6. Svitozar (60% shading)	2.64	75.10	17.30	-32.70	28.44	23.0
Payback of grid purchase costs in three years						
1. Liubasha (control)	2.68	49.40	44.40	-	18.43	90.0
2. Liubasha (45% shading)	3.33	57.40	59.15	14.75	17.23	103.0
3. Liubasha (60% shading)	2.75	59.70	36.55	-7.85	21.71	61.2
4. Svitozar (control)	2.86	50.10	50.00	-	17.51	99.8
5. Svitozar (45% shading)	3.06	58.10	49.00	-1.00	18.99	84.3
6. Svitozar (60% shading)	2.64	60.40	32.00	-18.00	22.88	52.9

Source: compiled by the authors

With the payback of the cost of purchasing a grid for three years of use for shading, 45% of the grid provides an increase in the level of profit for the Liubasha variety up to 14.75 UAH/m², profitability up to the level of 103.0%, which significantly exceeds the economic indicators of growing the Liubasha variety without shading.

The positive effect of using a shading grid with a density of 45% on the biometric parameters of sweet pepper plants was also noted in the study by E. Driesen *et al.* (2020), where the increase in plant growth rates was attributed to positive changes in the stomatal index and increased photosynthetic productivity, and in study by M. Möller & S. Assouline (2007) by reducing the intensity of water evaporation by 38%. According to R. Padrón *et al.* (2015) under optimal irrigation conditions, the use of a shading grid provided the highest plant height, stem diameter and leaf area Index, number of leaves per plant, and high dry matter content in plant leaves.

However, according to D. De la Cruz-Ricardez *et al.* (2023), shading has a positive effect on plant growth and productivity of certain genotypes of sweet pepper plants, especially those where the introduction of shading reduces the ripening period of fruits. For some varieties and

hybrids, the introduction of this technological measure does not ensure the growth of biometric parameters of plants. According to S. Saha *et al.* (2010), different intensity of shading exposure is associated with differential sensitivity of genotypes to heat, which, in turn, depends on the proline content in the leaves of the culture. A decrease in the content of proline in the leaves of plants of sensitive genotypes at high temperatures was also noted, while heat-resistant varieties produce more proline, which indicates the role of proline in the manifestation of heat resistance of the corresponding sweet pepper genotypes.

J. Al-Bakri *et al.* (2013) point out the need for significant changes in the technological processes of crop cultivation under the influence of global warming and climate transformation. Without the introduction of additional protective measures to reduce the adverse effects of critical temperatures, the productivity of agricultural plants may decrease due to the appearance of abiotic disorders (Ilić *et al.*, 2017; Flaishman *et al.*, 2015). A similar situation is observed in the soil and climatic conditions of Ukraine, where extreme weather conditions significantly reduce the productivity of agricultural plants, including sweet pepper.

T. Dueck *et al.* (2016) noted that manipulating the plant growth environment is a key aspect of improving agricultural productivity and improving the quality of crop production. S. Demotes-Mainard *et al.* (2016) recommended implementing light intensity regulation through the introduction of various photoselective networks. In fact, the maximum assimilation of carbon dioxide for most C3 plant species occurs with relatively low radiation exposure ($600\text{--}900 \mu\text{mol}\cdot\text{m}^{-2} \times \text{s}^{-1}$), which corresponds to 30–40% of total sunlight on a typical summer day. Thus, according to M. Flaishman *et al.* (2015) the resulting excess solar energy causes increased photoinhibition processes, heat stress, and stomatal closure in plants, which leads to a decrease in the net productivity of photosynthesis. In addition, stable high temperatures (35–40°C) due to high solar radiation can impair cell division, leaf growth, and reproductive development.

Since a certain dependence of plant growth processes on the quality, quantity, and frequency of light is established, the use of shading grids is an effective way to reduce solar radiation by regulating the quality of lighting by increasing the relative proportion of scattered light. E. Kitta *et al.* (2014) noted the positive effect of using shading net as a physical protection against birds and insects. Agricultural producers also use shading nets separately, and integrate them with existing greenhouse technologies. The introduction of grids for shading different colours acts as an effective factor in increasing the relative amount of diffused light and absorbing various spectral bands, providing significant changes in the light environment. According to E. Kitta *et al.* (2014), the introduction of shading provides a significant reduction in the effects of stressors (biotic and abiotic), which ultimately leads to improved plant growth.

Z.S. Ilić *et al.* (2012) indicated that the use of coloured shading grids provides an increase in tomato yield in the range of 113–131%. A. Goren *et al.* (2011) reported a 35% reduction in pepper fruit damage when using pearlescent and yellow mesh as a shading material compared to black

and red shading nets. Although black shading nets are most commonly used worldwide, there is growing interest in shading nets of different colours to improve plant growth, yield, and quality. As noted by K. Folta & S. Maruhnich (2007), using different coloured shading grids, it is possible to manipulate plant growth and development by affecting numerous photoreceptors

The positive effect of shading ensures an increase in the yield of sweet pepper, affecting various physiological processes in plants and, in general, the productivity of agroecosystems. The positive impact of using this technological approach, which was noted in the current study, was also noted by S. Alkalai-Tuvia *et al.* (2014) and A. Goren *et al.* (2011), which also noted the positive effect of shading and the use of red, pearlescent, and yellow grids for shading on the biochemical composition of pepper fruits.

According to Z. Nagy *et al.* (2014) the introduction of shading did not contribute to an increase in pepper plant productivity, but a significant increase in the vitamin C content of the fruit was found. The growth of fruit quality indicators without increasing the productivity of pepper plants with the use of shading was indicated by the results of K. Selahle *et al.* (2015), but researchers have also noted a positive effect of shading on increasing fruit resistance to rotting diseases during post-harvest storage.

Both in the current study and in the papers by N. Jeeatid *et al.* (2017) and Y. Jiménez-Viveros *et al.* (2023) proved the fact of a positive effect on the productivity of pepper plants of a moderate level of shading. In the current study, increasing the mesh density to 60% for the medium-ripened Liubasha pepper variety did not cause a change in the yield level, while for the medium-late Svitozar variety, it even caused a tendency to decrease the fruit yield. According to Y. Jiménez-Viveros *et al.* (2023), the introduction of shading nets or plastic coatings to reduce light intensity does not provide a positive consistent response to the phytochemical profile of pepper plants, since the intensity of vegetative mass growth and yield

development depends on many factors. The study by N. Jeeatid *et al.* (2017) noted that the maximum positive effect is provided by the interception of 35% of total sunlight, but under the condition of optimal daily irrigation, that is, controlling the conditions of moistening sweet pepper plants.

The results of the current research are completely different from the findings of G. Timmermans *et al.* (2020) and E. Kesumawati *et al.* (2020), in which shading pepper plants did not provide an increase in fruit yield and an improvement in their quality characteristics. According to E. Kesumawati *et al.* (2020), the use of shading nets with densities of 25% and 50% in basic biometric parameters and yield was inferior to that of pepper in the control without shading. But these studies were conducted on hybrids that were specially created for the appropriate soil and climatic conditions, and, consequently, are characterised by increased resistance to abiotic factors.

Conclusions

The introduction of a grid in the technology of growing sweet pepper to reduce sunlight by 45% and 60% provides a significant increase in the diameter of plants for the medium-ripened Liubasha variety and the medium-late Svitozar variety by 15.1-23.7%. For the Liubasha variety, when using shading, there was a significant increase in plant height by 17.8-21.5% and fruit height by 10.1-15.2%.

A significant increase in the number of fruits on the plant causes only the use of a grid with a density of 45%. With this technological approach, the number of fruits on plants of the Liubasha variety increases by 11.5%, for the Svitozar variety – by 48.5%. With an increase in the degree of shading (using a shading grid with a density of 60%),

a smaller number of fruits are formed on sweet pepper plants of both varieties, even relative to the pepper growing system without shading.

For the Liubasha variety, an increase in the average fruit weight for using all shading options was noted by 11.1-25.6%, for the Svitozar variety – a decrease by 17.9-60.2%.

A significant increase in the yield of sweet pepper was noted only for the Liubasha variety with the use of a 45% shading grid, which provides an increase in yield by 0.65 kg/m² or 24.3% relative to control. For the medium-late Svitozar variety, shading with a grid with a density of 45% causes only a positive trend in increasing yield (the increase was 0.2 kg/m² or 7.0% relative to control).

According to the analysis of economic efficiency, considering that the cost of purchasing the grid will be distributed over three years of its operation, the introduction of shading with a density of 45% leads to an increase in net profit for the Liubasha variety to the level of 14.75 UAH/m², the level of profitability up to 103%, reduction in the cost of production to 17.23 UAH/kg (under control – 18.43 UAH/kg).

In the future, it is advisable to study in depth the effect of different shading levels on the morphophysiological parameters of plants, in particular, on the intensity of photosynthesis, transpiration, leaf surface temperature, and water balance. This would allow determining the optimal shading conditions that will help to increase crop productivity in a variable climate.

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None.

Conflict of Interest

None.

References

- [1] Al-Bakri, J., Salahat, M., Suleiman, A., Suifan, M., Hamdan, M., Khresat, S., & Kandakji, T. (2013). Impact of climate and land use changes on water and food security in Jordan: Implications for transcending “The tragedy of the commons”. *Sustainability*, 3(5), 724-748. doi: [10.3390/su5020724](https://doi.org/10.3390/su5020724).

- [2] Alkalai-Tuvia, S., Goren, A., Perzelan, Y., Weinberg, T., & Fallik, E. (2014). [The influence of colored shade nets on pepper quality after harvest – a possible mode-of-action](#). *Agriculture and Forestry*, 60(2), 7-18.
- [3] Bondarenko, G.L., & Yakovenko, K.I. (Ed.). (2001). [Methodology of research work in vegetable growing and melon growing](#). Kharkiv: Osnova.
- [4] Caruso, G., Formisano, L., Cozzolino, E., Pannico, A., El-Nakhel, C., Roupael, Y., Tallarita, A., Cenvinzo, V., & De Pascale, S. (2020). Shading affects yield, elemental composition and antioxidants of perennial wall rocket crops grown from spring to summer in southern Italy. *Plants*, 9(8), article number 933. [doi: 10.3390/plants9080933](#).
- [5] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.
- [6] Darázsi Ledóné, H., Pék, Z., Helyes, L., & Szuvandzsiev, P. (2017). Influence of colour net shading on quantity and quality of sweet pepper yield. *Acta Horticulturae*, 1170, 359-364. [doi: 10.17660/ActaHortic.2017.1170.44](#).
- [7] De la Cruz-Ricardez, D., Lagunes-Espinoza, L.D.C., Ortiz-García, C.F., Hernández-Nataren, E., Soto-Hernández, R.M., & Acosta-Pech, R.G. (2023). Phenology, yield, and phytochemicals of *Capsicum spp.* in response to shading. *Botanical Sciences*, 101(3), 865-882. [doi: 10.17129/botsci.3234](#).
- [8] Demotes-Mainard, S., Peron, T., Corot, A., Bertheloot, J., Le Gourrierc, J., Pelleschi-Travier, S., & Sakr, S. (2016). Plant responses to red and far-red lights, applications in horticulture. *Environmental and Experimental Botany*, 121, 4-21. [doi: 10.1016/j.envexpbot.2015.05.010](#).
- [9] Díaz-Pérez, J.C. (2013). Bell pepper (*Capsicum annum*) crop as affected by shade level: Microenvironment, plant growth, leaf gas exchange, and leaf mineral nutrient concentration. *HortScience*, 48, 175-182. [doi: 10.21273/HORTSCI.48.2.175](#)
- [10] Driesen, E., Van den Ende, W., De Proft, M., & Saeys, W. (2020). Influence of environmental factors light, CO₂, temperature, and relative humidity on stomatal opening and development: A review. *Agronomy*, 10(12), article number 1975. [doi: 10.3390/agronomy10121975](#).
- [11] Dueck, T., Janse, J., Kempkes, F., Meinen, E., Stanghellini, C., & Marcelis, L. (2016). Light perception, signalling and plant responses to spectral quality and photoperiod in natural and horticultural environments. *Environmental and Experimental Botany*, 121, 1-3. [doi: 10.1016/j.envexpbot.2015.06.012](#).
- [12] Flaishman, M.A., Peles, Y., Dahan, Y., Milo-Cochavi, S., Frieman, A., & Naor, A. (2015). Differential response of cell cycle and cell-expansion regulators to heat stress in apple (*Malus domestica*) fruitlets. *Plant Science*, 233, 82-89. [doi: 10.1016/j.plantsci.2015.01.005](#).
- [13] Folta, K.M., & Maruhnich, S.A. (2007). Green light: A signal to slow down or stop. *Journal of Experimental Botany*, 58(12), 3099-3111. [doi: 10.1093/jxb/erm130](#).
- [14] Goren, A., Alkalai-Tuvia, S., Perzelan, Y., Fallik, E., & Aharon, Z. (2011). Photosensitive shade nets reduce postharvest decay development in pepper fruits. *Advances in Horticultural Science*, 25, 26-31. [doi: 10.13128/ahs-12781](#).
- [15] He, X., Maier, C., Chavan, S.G., Zhao, C.C., Alagoz, Y., Cazzonelli, C., & Chen, Z.H. (2021). Light-altering cover materials and sustainable greenhouse production of vegetables: A review. *Plant Growth Regulation*, 95(1), 1-17. [doi: 10.1007/s10725-021-00723-7](#).
- [16] Ilić, Z.S., Mienković, L., Sunić, L., Baraci, S., Mastilović, J., Kevresan, Z., & Fallik, E. (2017). Effect of shading by coloured nets on yield and fruit quality of sweet pepper. *Zemdirbyste-Agriculture*, 104, 53-62. [doi: 10.13080/z-a.2017.104.008](#).

- [17] Ilić, Z.S., Milenković, L., Stanojević, L., Cvetković, D., & Fallic, E. (2012). Effects of the modification of light intensity by color shade nets on yield and quality of tomato fruits. *Scientia Horticulturae*, 193, 90-95. doi: [10.1016/j.scienta.2012.03.009](https://doi.org/10.1016/j.scienta.2012.03.009).
- [18] Jeeatid, N., Techawongstien, S., Suriharn, B., Bosland, P.W., & Techawongstien, S. (2017). Light intensity affects capsaicinoid accumulation in hot pepper (*Capsicum chinense* Jacq.) cultivars. *Horticulture, Environment, and Biotechnology*, 58(2), 103-110. doi: [10.1007/s13580-017-0165-6](https://doi.org/10.1007/s13580-017-0165-6).
- [19] Jiménez-Viveros, Y., Núñez-Palenius, H.G., Fierros-Romero, G., & Valiente-Banuet, J.I. (2023). Modification of light characteristics affects the phytochemical profile of peppers. *Horticulturae*, 9(1), article number 72. doi: [10.3390/horticulturae9010072](https://doi.org/10.3390/horticulturae9010072).
- [20] Kesumawati, E., Apriyatna, D., & Rahmawati, M. (2020). The effect of shading levels and varieties on the growth and yield of chili plants (*Capsicum annum* L.). *IOP Conference Series: Earth and Environmental Science*, 425(1), article number 012080. doi: [10.1088/1755-1315/425/1/012080](https://doi.org/10.1088/1755-1315/425/1/012080).
- [21] Kitta, E., Katsoulas, N., Kandila, A., González-Real, M.M., & Baille, A. (2014). Photosynthetic acclimation of sweet pepper plants to screen house conditions. *HortScience*, 49(2), 166-172. doi: [10.21273/HORTSCI.49.2.166](https://doi.org/10.21273/HORTSCI.49.2.166).
- [22] Mohawesh, O., Albalasmeh, A., Deb, S., Singh, S., Simpson, C., Alkafaween, N., & Mahadeen, A. (2022). Effect of colored shading nets on the growth and water use efficiency of sweet pepper grown under semi-arid conditions. *HortTechnology*, 32(1), 21-27. doi: [10.21273/HORTTECH04895-21](https://doi.org/10.21273/HORTTECH04895-21).
- [23] Möller, M., & Assouline, S. (2007). Effects of a shading screen on microclimate and crop water requirements. *Irrigation Science*, 25, 171-181. doi: [10.1007/s00271-006-0045-9](https://doi.org/10.1007/s00271-006-0045-9).
- [24] Nagy, Z., Daood, H., Neményi, A., Ambrózy, Z., Pék, Z., & Helyes, L. (2017). Impact of shading net color on phytochemical contents in two chili pepper hybrids cultivated under greenhouse conditions. *Horticultural Science & Technology*, 35(4), 418-430. doi: [10.12972/kjhst.20170045](https://doi.org/10.12972/kjhst.20170045).
- [25] Padrón, R.A.R., Guedes, J.V.C., Swarowsky, A., Nogueira, C.U., Cerquera, R.R., & Nogueira de Moraes, H.M.C. (2015). Supplemental irrigation levels in bell pepper under shade mesh and in open-field: Absolute growth rate, dry mass, leaf area and chlorophyll. *African Journal of Agricultural Research*, 10(42), 3968-3976. doi: [10.5897/AJAR2015.10342](https://doi.org/10.5897/AJAR2015.10342).
- [26] Pylypenko, L.V., & Shabetya, O.M. (2020). Correlational dependences between morphological and valuable economic traits in sweet pepper seed production. *Vegetable and Melon Growing*, 67, 81-88. doi: [10.32717/0131-0062-2020-67-81-88](https://doi.org/10.32717/0131-0062-2020-67-81-88).
- [27] Saha, S.R., Hossain, M.M., Rahman, M.M., Kuo, C.G., & Abdullah, S. (2010). Effect of high temperature stress on the performance of twelve sweet pepper genotypes. *Bangladesh Journal of Agricultural Research*, 35(3), 525-534. doi: [10.3329/bjar.v35i3.6459](https://doi.org/10.3329/bjar.v35i3.6459).
- [28] Selahle, K.M., Sivakumar, D., Jifon, J., & Soundy, P. (2015). Postharvest responses of red and yellow sweet peppers grown under photo-selective nets. *Food Chemistry*, 173, 951-956. doi: [10.1016/j.foodchem.2014.10.034](https://doi.org/10.1016/j.foodchem.2014.10.034).
- [29] Stanghellini, C., Dai, J., & Kempkes, F. (2011). Effect of near-infrared-radiation reflective screen materials on ventilation requirement, crop transpiration and water use efficiency of a greenhouse rose crop. *Biosystems Engineering*, 110(3), 261-271. doi: [10.1016/j.biosystemseng.2011.08.002](https://doi.org/10.1016/j.biosystemseng.2011.08.002).
- [30] Syromyatnikov, Yu.M. (2023). Influence of technological measures on soil moisture saturation in sugar beet growing. *Ukrainian Journal of Natural Sciences*, 4, 125-137. doi: [10.32782/naturaljournal.4.2023.14](https://doi.org/10.32782/naturaljournal.4.2023.14).
- [31] Timmermans, G.H., Hemming, S., Baeza, E., Van Thoor, E.A., Schenning, A.P., & Debije, M.G. (2020). Advanced optical materials for sunlight control in greenhouses. *Advanced Optical Materials*, 8(18), article number 2000738. doi: [10.1002/adom.202000738](https://doi.org/10.1002/adom.202000738).

- [32] Vdovenko, S., Palamarchuk, I., Mazur, O., Mazur, O., & Havrys, I. (2024). Influence of biological preparations on organic cultivation of vegetable plants. *Plant and Soil Science*, 15(1), 9-25. doi: [10.31548/plant1.2024.09](https://doi.org/10.31548/plant1.2024.09).
- [33] Vdovenko, S.A., & Shvydkyi, P.A. (2023). Economic and biological evaluation of sweet pepper varieties in open ground conditions. *Agriculture and Forestry*, 29, 78-89. doi: [10.37128/2707-5826-2023-2-7](https://doi.org/10.37128/2707-5826-2023-2-7).

Ефективність затінення перцю солодкого за вирощування в Лісостепу України

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Анотація. Метою наукової роботи було встановлення впливу затінювальної сітки різної щільності на ріст, розвиток і продуктивність рослин перцю солодкого в умовах зрошення Лівобережного Лісостепу України. Роботу проведено в Інституті овочівництва і баштанництва Національної академії аграрних наук України за загальноприйнятими методиками за допомогою польового методу досліджень. Реалізація досліджень передбачала визначення впливу впровадження затінення рослин сітками зі щільністю 45 % та 60 % на біометричні параметри та продуктивність рослин перцю солодкого, економічні показники ефективності вирощування. Встановлено, що затінення забезпечує істотне підвищення параметру діаметр рослин перцю солодкого для обох сортів (на 15,1-23,7 %), а також тільки для сорту Любаша – підвищення висота рослин (на 17,8-21,5 %) та

висоти плоду (на 10,1-15,2 %). Затінення з використанням сітки зі щільністю 45 % забезпечує для обох сортів істотне підвищення кількості плодів на рослині (на 11,5 % для сорту Любаша та на 48,5 % для сорту Світозар). Збільшення параметру щільності сіток для затінення до 60 % зумовлює зменшення кількості плодів на рослинах. Відзначено, що для сорту Любаша зростання середньої маси плоду за використання затінення складає 11,1-25,6 %, для сорту Світозар даний показник зменшується на 17,9-60,2 %. Істотне підвищення урожайності перцю солодкого забезпечує використання затінення сіткою зі щільністю 45 % тільки для сорту Любаша (зростання на 24,3 %). За вказаного технологічного підходу підвищуються економічні параметри вирощування перцю солодкого (прибуток до 14,75 грн/м², рентабельність до 103 %). Результати дослідження можуть бути корисними для малих та середніх фермерів, які вирощують перець у відкритому ґрунті, з метою зниження ризиків, пов'язаних зі спекою та перепадами температур

Ключові слова: *Capsicum annuum* L.; щільність затінювальної сітки; біометричні параметри рослин; продуктивність; рентабельність



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Assessment of frost and drought resistance in species and cultivars of the genus *Ligustrum* L. for nursery stock production

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Abstract. The relevance of this study is driven by the need to improve the assessment of plants' adaptive potential for urban landscaping, particularly in Kyiv, where factors such as water deficiency and temperature fluctuations are critical in selecting species capable of withstanding environmental stress while maintaining ornamental value. This study aimed to investigate the frost and drought resistance of species and cultivars of the genus *Ligustrum* L., enabling an evaluation of their adaptive capacity for use in urban environments. Physiological methods were employed to assess indicators such as water retention capacity, water deficit, water content, heat resistance, and frost resistance. The findings indicated that *Ligustrum vulgare* L. and its cultivars exhibit high frost resistance, as evidenced by minimal tissue damage at -25°C , averaging 7.0-13.9 points. Other species demonstrated minor tissue damage at -20°C (on average, less than 2 points), suggesting that this temperature is not critical for them. At -25°C , the overall damage score increased significantly. In particular, *Ligustrum ovalifolium* Hassk. and its cultivars exhibited scores ranging from 14.2 to 24.8, while *Ligustrum japonicum* Green Century and *Ligustrum ibota* Musli recorded scores of 30.7 and 26.3, respectively. These values approach critical thresholds; however, during the growing season, cells and tissues demonstrated the ability to

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recover. *Ligustrum vulgare* L., *Ligustrum ovalifolium* Hassk., and certain cultivars displayed considerable drought resistance, as indicated by relatively minor fluctuations in leaf moisture content. The results also highlight the stable waterregulating function of these species, along with high heat resistance, particularly at 50°C. Notably, an increase in temperature to 60°C proved critical for all species, leading to partial browning or complete necrosis of leaf blades. The assessment of these parameters facilitates the selection of initial material for the production of resilient nursery stock suited to urban environmental conditions

Keywords: nursery stock; leaf blade; landscaping; water regime; resilience; frost damage

Introduction

One of the key aspects of developing plant compositions for urban landscaping is the assessment of their condition and resilience to stress factors, which enables the selection of an optimal plant assortment for greening large cities. Therefore, understanding plant sensitivity to stressors, considering the impact of both natural and anthropogenic factors on growth and development, is essential. As a highly urbanised environment, the city of Kyiv is characterised by challenging ecological conditions. As noted by I.O. Sviatohorov (2024), these include temperature fluctuations, limited summer precipitation, and a relatively high level of pollution. Thus, evaluating the adaptive potential of species within the genus *Ligustrum* L. under such conditions is a crucial task in urban landscaping.

S.I. Kuznetsov *et al.* (2020) described *L. vulgare* L. as a hardy plant, capable of withstanding both drought and frost. It is also adaptable to various soil types and tolerates urban conditions, including dust, smoke, and gas pollution. Additionally, this species is noted for its ability to be pruned and shaped, making it versatile for landscaping. *Ligustrum lucidum* W.T. Aiton, on the other hand, is considered moderately frost-resistant, able to withstand temperatures down to -20°C. It requires moderate moisture and is tolerant of smoke and gas pollution. T. Tkaczenko *et al.* (2023) highlight the potential of *L. vulgare* L. to partially purify air by trapping particulate matter, thus improving air quality. T. Pashayev (2024) emphasised the versatility of *L. vulgare* L. in urban landscaping. It is

particularly well-suited for creating hedges and other structured plantings. This species' ability to withstand fluctuating temperatures and moisture levels makes it a valuable asset in urban green spaces. Its resilience and aesthetic appeal allow it to function as both a decorative feature and a functional barrier. Furthermore, *L. vulgare* L. exhibits strong recovery after winter, making it a reliable choice for long-term use in diverse climates.

Evaluating how well plants withstand drought and heat is crucial for determining their suitability in urban environments. In cities, high temperatures and water shortages are significant challenges for plant growth. V. Bessonova *et al.* (2024) have emphasised the importance of studying the heat resistance of trees in the northern steppe region of Ukraine. These factors directly affect the survival and aesthetic appeal of plants exposed to intense sunlight and high temperatures. Similarly, research is being conducted to assess drought tolerance. D.S. Gordienko *et al.* (2021) examined the impact of climate on the resilience of English roses in the forest-steppe zone of Ukraine. L. Leotta *et al.* (2023) have focused on developing new strategies to enhance the resistance of ornamental trees to abiotic stresses (nonliving stresses such as drought or high temperatures) in Mediterranean climates. This research is essential for developing methods to help plants adapt to climate change in urban settings. The use of physiological methods to measure factors like water deficit, water content, water-holding capacity, and heat resistance

provides valuable quantitative data. These measurements can reveal how well plants adapt to harsh temperatures (Demydov *et al.*, 2023; Yavas *et al.*, 2024).

J. Dong *et al.* (2022) have highlighted the critical role of aquaporins, located in cell membranes, in maintaining water balance under various stress conditions. Research has demonstrated that aquaporins directly contribute to a plant's cold tolerance. Specifically, the authors studied the aquaporin gene family in *Ligustrum* × *Vicaryi* Rehd. The use of species and cultivars of the genus *Ligustrum* L. in urban landscaping requires a thorough understanding of their adaptive potential, particularly their frost and drought resistance. This study aimed to evaluate the drought and frost resistance of *Ligustrum* L. species and cultivars within this genus.

Materials and Methods

The study on the potential drought and frost tolerance was conducted between 2023 and 2024. The research took place at the Plant Physiology and Microbiology Laboratory of the Institute of Horticulture, National Academy of Agrarian Sciences of Ukraine. The study involved species and cultivars of the genus *Ligustrum* L., specifically *Ligustrum vulgare* L., *L. vulgare* *Atrovirens*, *L. vulgare* *Aurea*, *Ligustrum ovalifolium* Hassk., *L. ovalifolium* *Aureum*, *L. ovalifolium* *Green Diamond*, *L. ovalifolium* *Vicari*, *Ligustrum ibota* Musli, and *Ligustrum japonicum* *Green Century*. The research adhered to ethical standards outlined in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

To assess drought and frost tolerance, vegetative plant material was collected from mother plants aged 3-5 years. The selected plants were free from any visible damage caused by pests or diseases. These plants were grown in semi-shaded conditions on moderately fertile and moist soils. The frost tolerance of *Ligustrum* L. species and cultivars was evaluated using the methodology recommended by M.O. Bublyk *et al.* (2013).

This involved directly freezing plant shoots in a laboratory setting. During the winter dormancy period, typically the second ten-day period of December to the first ten-day period of February, well-formed, one-year-old shoots (20-25 cm in length) were collected from the middle section of the plant crowns.

The process of determining frost tolerance involved lowering the temperature within a freezer chamber. A DW-40L92 refrigeration chamber (Qingdao Haier Biomedical Co. Ltd., China) was used, which allowed for the cooling of the experimental plant samples down to -40°C. The freezing was conducted using a gradual temperature reduction method, decreasing by approximately 5°C increments until reaching -20°C and -25°C. These specific temperature levels were selected to reflect the average winter temperatures observed in Kyiv between 2019 and 2024. The lowest recorded temperature during this period was -18°C (Meteoblue, n.d.). After freezing the one-year-old shoots of *Ligustrum* L. species and cultivars at -20°C and -25°C, a microscopic analysis was performed to assess tissue damage in comparison to the control samples (unfrozen). Once the desired temperature was reached, the experimental samples were held in the refrigeration chamber for 4 hours. This duration was necessary to allow for nucleation and ice formation processes to occur within the plant tissues. The next step involved determining the extent of frost damage to the shoot tissues. This evaluation was based on the intensity of browning observed in anatomical cross-sections. After freezing, a certain period of time is required for the signs of frost damage to become apparent. As noted by S. Maslovata (2016), it can take up to 7 days at room temperature for signs of frost damage to become visible. The next stage involved partially immersing the shoots in water, followed by the preparation of anatomical sections. Three primary zones were selected for analysis: the shoot apex, the middle section (the centre of the internode, between the buds), and the node itself, with the cut made directly through the bud. These sections

were placed on microscope slides and examined under an MBS-10 microscope (TM MICROmed, Ukraine). During the anatomical-microscopic evaluation of the one-year-old growth, the extent of damage to individual tissues (bark, cambium, wood, and pith) was determined based on the visual browning observed in the cross-section. The degree of tissue damage was assessed using a six-point scale (0 to 5 points) for each anatomical section. The maximum total tissue damage score for the one-year-old growth was 65 points (Bublyk *et al.*, 2013).

The damage assessment followed this scale: 0 – no damage observed; 1 – slight discolouration, damage to up to 20% of the tissue; 2 – moderate tissue damage (40%); 3 – moderate damage with clear browning at the interface with adjacent tissues (60%); 4 – severe damage (complete browning of the affected area, blackened borders with adjacent tissues, 80%); 5 – complete tissue necrosis (100%) (Maslovata, 2016).

To determine the potential drought tolerance, a series of laboratory experiments were conducted. These experiments included measuring water deficit, water content, water-holding capacity, and heat resistance, following the Scientific and Methodological Recommendations for the Study and Conservation of Genetic Resources of Fruit, Berry, Nut-Bearing, and Underutilized Crops (Trokhymchuk & Makarova, 2022). For the drought tolerance assessments, fully grown leaf blades were collected, primarily from the central part of the mother plants' crowns. The leaves were harvested early in the morning, before 8:00, to minimise rapid turgor loss. They were then placed in sealed bags to facilitate long-term transport. The collection period occurred during the first ten-day period of August.

The water deficit was determined as follows: initially, the leaf blades were weighed using precision scales. They were then immersed in a water-filled container, which was covered with glass to create an air chamber. The leaves remained submerged for 24 hours. After this period, they were removed from the water, gently blotted with

paper towels to remove excess moisture, and immediately weighed again. The difference between the pre-saturation and post-saturation weights was then calculated.

To assess the water content, a method involving complete drying of leaf blades was employed. This allowed for the calculation of the total water content within the plant material. For this, previously prepared leaf blades from species and cultivars of *Ligustrum* L. were placed in metal weighing bottles, which had been weighed beforehand. The weighing bottles with the leaf blades were then weighed again. The weighing bottles with the leaf blades were then placed in an oven at 40°C for 24 hours or until the leaves were fully dried. After drying, the weighing bottles with the plant material were weighed again, and the corresponding calculations for the moisture content in the leaves were performed. The total water content (W) as a percentage of the fresh weight was determined using the following formula (1):

$$W = \frac{(b-c)}{(b-a)} * 100\%, \quad (1)$$

where a is the mass of the empty weighing bottle, g; b is the mass of the weighing bottle with the fresh leaf sample, g; c is the mass of the weighing bottle with the dry leaf sample, g. The water retention capacity was determined by measuring the gradual loss of moisture at room temperature. The experiment was conducted in a laboratory setting with a constant temperature of 23.8°C and a relative humidity of 44.5%. At the start of the experiment, the leaf blades were weighed, and subsequent measurements were taken after 2, 4, 6, and 24 hours. The water retention capacity (WRC) is considered higher if the moisture loss from the leaf blades is lower over a specific time period, and it is calculated using the formula (2):

$$WRC = \frac{B}{A} * 100\%, \quad (2)$$

where A is the moisture content at the start of the experiment, g; B is the moisture loss over a specific time period, g. The determination of heat

resistance involved subjecting the leaf blades of the experimental plants to exposure to heat in an oven for 10 minutes at different temperatures: 40, 50, and 60°C. After roasting, the leaf blades were immersed in a 0.2% hydrochloric acid (HCl) solution, which primarily facilitated the faster manifestation of damaged areas on the leaves. The immersion times in the acid were 1, 3, and 5 minutes. Afterwards, the damage was assessed according to the following scale in percentages: 0 – leaves without damage; 0-15 – slight damage; 16-50 – moderate damage; 51-100 – severe damage or complete leaf blade death. The processing and analysis of the results were carried

out in Microsoft Excel (Mezhenskyi, 2017). The measurement results are presented as the mean \pm standard error ($x \pm SE$).

Results and Discussion

The analysis of damage data on shoots revealed that the severity of tissue damage caused by low negative temperatures is influenced by both the species or cultivar and the degree of temperature reduction. Specifically, the control samples, which were not subjected to freezing, showed no damage in any of the tested plants, as illustrated in Figure 1 (a, d, g, j), Figure 2 (a, d, g), and Figure 3 (a, d).



Figure 1. Degree of tissue damage in cultivars of *Ligustrum ovalifolium* Hassk
Note: a, d, g, j – control; b, e, h, k – freezing temperature -20°C; c, f, i, l – freezing temperature -25°C
Source: photos taken by the authors

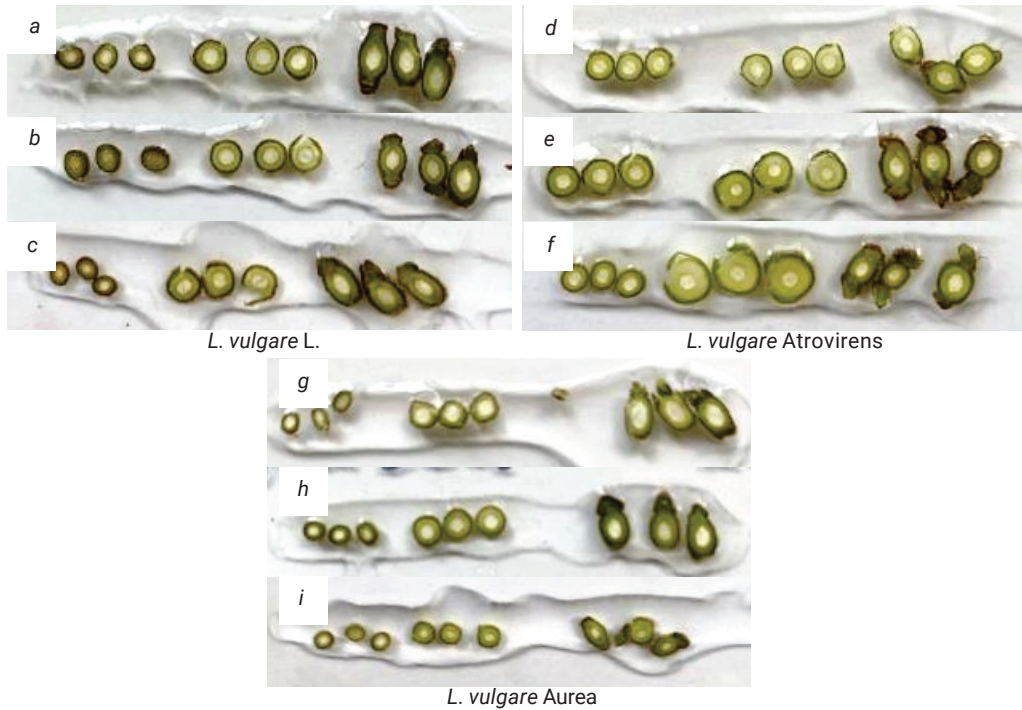


Figure 2. Degree of tissue damage in cultivars of *Ligustrum vulgare* L

Note: a, d, g – control; b, e, h – freezing temperature -20°C ; c, f, i – freezing temperature -25°C

Source: photos taken by the authors



Figure 3. Degree of tissue damage in cultivars of *Ligustrum japonicum* Green Century, *Ligustrum ibota* Musli

Note: a, d, g, j – control; b, e, h, k – freezing temperature -20°C ; c, f, i, l – freezing temperature -25°C

Source: photos taken by the authors

Analysis of the data at -20°C revealed that the majority of the experimental plant samples showed minimal damage, with scores not exceeding 20 points. This suggests a relatively high

tolerance to temperatures down to -20°C . The observed damage primarily consisted of browning in certain areas of the shoot's anatomical sections, as shown in Figure 1 (b, e, h, k), Figure 2 (b, e, h),

and Figure 3 (b, e). *Ligustrum japonicum* Green Century showed the highest damage score at 22 points. Browning was observed in various parts of the shoot (Fig. 3b), with the bud area being particularly affected. All other species and cultivars showed only slight browning. The least amount of damage was observed in *L. vulgare* Atrovirens, with a total damage score of 3.7 points.

Further lowering the temperature to -25°C resulted in more significant damage to almost all the samples. The total damage scores for most species and cultivars increased considerably. This indicates a potential sensitivity of certain plants to this temperature. The lowest level of damage was recorded in *L. vulgare* Atrovirens (7.0 points), while the highest levels were observed in *Ligustrum japonicum* Green Century (29.9 points) and *Ligustrum ibota* Musli (26.3 points).

The freezing process at -25°C revealed that different parts of the *Ligustrum* L. shoot experienced varying degrees of damage. This indicates that the tissues have differing levels of resistance to low-temperature stress. As shown in Table 1, the pith was the most vulnerable to low temperatures

across almost all the tested plants. Notably, *Ligustrum japonicum* Green Century and *Ligustrum ibota* Musli showed maximum pith damage, particularly at the bud and in the middle section of the shoot. For example, in *Ligustrum japonicum* Green Century, the pith damage score at the bud was 10.8 points, the highest recorded (Fig. 3c). The wood tissue also sustained significant damage, especially in the cultivars *L. ovalifolium* Vicari (6.5 points in the middle section of the shoot) and *L. ovalifolium* Aureum (6.5 points in the upper section of the shoot). *L. vulgare* Atrovirens exhibited the least amount of wood damage (1.4 points). The cambium was less susceptible to low temperatures compared to the pith and wood. However, some plants, such as *L. ovalifolium* Green Diamond (5.2 points in the middle section), showed significant cambial damage (Fig. 1f). The lowest level of cambium damage was observed in *L. vulgare* Atrovirens (0.5 points in the middle section). Similar to the cambium, the bark showed relatively less damage, as indicated in Table 1. For instance, *L. vulgare* L. and *L. vulgare* Atrovirens had the lowest bark damage scores, ranging from 0.5 to 0.8 points.

Table 1. Damage to shoots and buds from low temperatures in *Ligustrum* L. species and cultivars, 2024

No.	Species, cultivar	Variant	Object of freezing																
			Apex, points				Middle, points				Through the bud, points				Total Points				
			Bark	Cambium	Wood	Pith	Bark	Cambium	Wood	Pith	Bark	Cambium	Wood	Pith	Bud	Apex	Middle	Through bud	Total
1	<i>Ligustrum</i>	C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	<i>ovalifolium</i>	-20	0.5	0.5	1.2	1.2	0.5	0.4	1.0	1.0	0.8	0.5	1.0	1.0	1.2	3.4	2.9	3.3	9.6
	Hassk.	-25	1.5	1.8	1.8	1.5	0.5	0.5	0.4	2.0	1.2	1.1	1.5	2.2	2.0	6.6	3.4	6.0	16.0
2	<i>L. ovalifolium</i>	K	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.2	
	Green Diamond	-20	0.9	0.8	1.8	1.2	0.8	0.8	1.5	1.0	0.8	0.9	1.5	0.9	1.2	4.7	4.1	4.1	12.9
		-25	1.2	1.1	2.0	1.5	1.1	1.1	1.8	1.2	1.0	1.0	2.5	1.5	4.0	5.8	5.2	6.0	17.0
3	<i>L. ovalifolium</i>	C	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	1.0	0.0	1.0	1.0	2.0
	Vicari	-20	0.0	0.0	1.0	0.0	0.5	0.5	1.0	1.1	0.5	1.1	1.4	2.0	1.0	1.0	3.1	5.0	9.1
4	<i>L. ovalifolium</i>	K	0.0	0.0	0.5	0.0	0.0	0.0	0.5	0.9	0.0	0.0	0.5	0.5	0.5	0.5	1.4	1.0	2.9
	Aureum	-20	0.5	1.5	1.5	1.0	0.5	1.4	1.4	1.2	0.5	1.8	2.2	2.0	2.8	4.5	4.5	6.5	15.5
		-25	1.5	2.5	2.2	2.0	0.8	2.0	2.5	2.0	0.8	1.5	2.0	2.2	3.5	8.2	7.3	6.5	22.0
5	<i>Ligustrum</i>	C	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.6
	<i>vulgare</i> L.	-20	0.5	0.5	0.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.3	2.3	0.0	0.5	2.8
		-25	2.5	2.5	3.0	1.0	0.5	0.5	0.8	0.5	0.5	0.5	1.0	0.6	1.0	9.0	2.3	2.6	13.9

Table 1. Continued

No.	Species, cultivar	Variant	Object of freezing														Total		
			Apex, points				Middle, points				Through the bud, points				Total Points				
			Bark	Cambium	Wood	Pith	Bark	Cambium	Wood	Pith	Bark	Cambium	Wood	Pith	Bud	Apex		Middle	Through bud
6	<i>L. vulgare</i> Atrovirens	K	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.2	0.2	0.2	0.6	
		-20	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.6	0.5	0.8	0.8	1.2	0.5	0.5	2.7	3.7
		-25	0.5	0.5	0.8	0.5	0.5	0.8	0.7	0.5	0.4	0.5	0.7	0.6	1.4	2.3	2.5	2.2	7.0
7	<i>L. vulgare</i> Aurea	C	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.4	
		-20	0.5	0.5	0.4	0.0	0.4	0.4	0.5	0.0	0.4	0.4	0.5	0.0	0.5	1.4	1.3	1.3	4.0
		-25	0.6	0.5	0.8	0.5	0.5	0.5	0.6	0.5	0.6	0.6	1.5	0.5	1.0	2.4	2.1	3.2	7.7
8	<i>Ligustrum japonicum</i> Green Century	C	0.8	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.5	1.2	1.8	0.0	1.3	3.1	
		-20	2.2	2.0	1.5	1.4	1.8	1.8	1.5	1.8	1.8	1.5	2.5	2.2	2.3	7.1	6.9	8.0	22.0
		-25	2.5	2.7	2.5	1.8	2.2	2.4	2.5	2.5	2.2	2.4	3.2	3.0	3.5	9.5	9.6	10.8	29.9
9	<i>Ligustrum ibota</i> Musli	C	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.2	0.2	0.5	0.5	0.9	0.5	0.0	1.4	1.9	
		-20	1.3	1.4	1.8	0.8	1.2	1.3	1.8	0.9	2.2	2.2	2.8	1.0	2.4	5.3	5.2	8.2	18.7
		-25	2.5	2.5	2.0	1.5	2.2	2.6	2.0	2.0	2.5	2.5	2.2	1.8	3.3	8.5	8.8	9.0	26.3

Source: developed by the authors

Thus, analysing all the data, it can be seen that *L. vulgare* Atrovirens is the most resistant to low temperatures. The overall damage level was minimal, with a total of 7.0 points, and the most damaged part was the pith in the middle section of the shoot. In contrast, *Ligustrum japonicum* Green Century and *Ligustrum ibota* Musli showed the highest levels of damage, with the wood and pith being the most affected. The results of the study show that at -25°C, the pith of the shoots sustains the most damage, particularly in the upper part and through the bud. Accordingly, the bark and

cambium suffer less damage, although the extent of the damage also depends on the species and cultivar. Among the plants studied, *L. vulgare* Atrovirens can be considered potentially resistant to low temperatures, while *L. japonicum* Green Century and *L. ibota* Musli are less resistant. Water deficit is a crucial indicator of a plant's ability to retain moisture, which helps determine its potential drought resistance. The analysis of water deficit data for *Ligustrum* L. species and cultivars (Table 2) revealed that the values of this parameter varied significantly depending on the species and cultivar.

Table 2. Determination of water deficit in *Ligustrum* L. species and cultivars

Species, cultivar	Before saturation, g	After saturation, g	Water deficit, %	Average value, %
<i>Ligustrum vulgare</i> L.	0.702	0.813	13.65	16.25 ^{±2.8}
	0.307	0.38	19.21	
	0.545	0.648	15.90	
<i>L. vulgare</i> Atrovirens	0.538	0.604	10.93	11.77 ^{±1.35}
	0.39	0.45	13.33	
	0.37	0.416	11.06	
<i>L. vulgare</i> Aurea	0.334	0.396	15.66	14.00 ^{±1.47}
	0.38	0.436	12.84	
	0.359	0.415	13.49	
<i>Ligustrum ovalifolium</i> Hassk.	0.927	1.112	16.64	16.14 ^{±0.48}
	0.886	1.056	16.10	
	0.828	0.982	15.68	

Table 2. Continued

Species, cultivar	Before saturation, g	After saturation, g	Water deficit, %	Average value, %
<i>L. ovalifolium</i> Aureum	0.43	0.486	11.52	11.39 ^{±0.74}
	0.414	0.463	10.58	
	0.343	0.39	12.05	
<i>L. ovalifolium</i> Green Diamond	0.343	0.386	11.14	11.34 ^{±0.3}
	0.325	0.368	11.68	
	0.254	0.286	11.19	
<i>L. ovalifolium</i> Vicari	0.17	0.184	7.61	6.16 ^{±1.36}
	0.11	0.117	5.98	
	0.097	0.102	4.90	
<i>Ligustrum</i> <i>ibota</i> Musli	0.227	0.245	7.35	10.65 ^{±3.17}
	0.22	0.247	10.93	
	0.202	0.234	13.68	
<i>Ligustrum japonicum</i> Green Century	0.33	0.352	6.25	6.42 ^{±1.97}
	0.443	0.484	8.47	
	0.442	0.463	4.54	

Source: developed by the authors

Thus, the highest water deficit values were observed in *L. vulgare* L. (16.25%), *L. vulgare* Aurea (14.00%), and *L. ovalifolium* Hassk. (16.14%). Among the other plants, those with a moderate level of water deficit can be highlighted, including *L. vulgare*

Atrovirens (11.77%), *L. ovalifolium* Aureum (11.39%), *L. ibota* Musli (10.67%), and *L. ovalifolium* Green Diamond (11.34%). *L. ovalifolium* Vicari (6.16%) and *L. japonicum* Green Century (6.42%) showed the lowest water deficit levels, as shown in Figure 4.

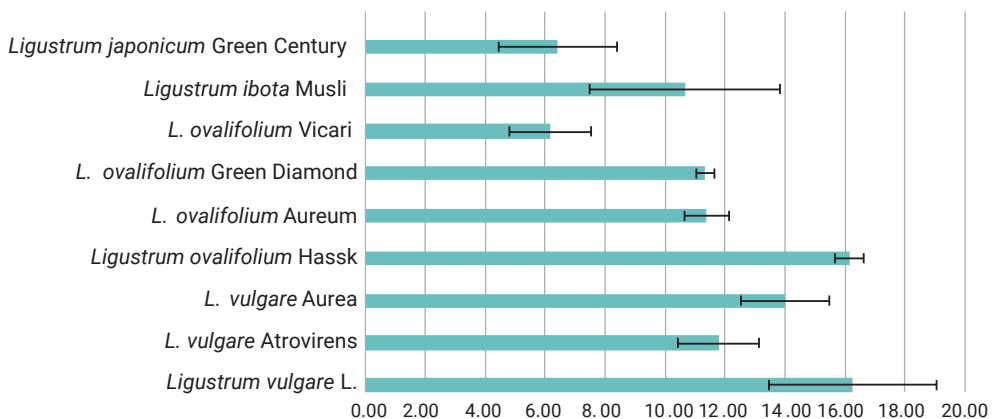


Figure 4. Water deficit values of leaves in Ligustrum L. species and cultivars

Source: developed by the authors

High saturation levels were observed in *L. vulgare* L., *L. vulgare* Aurea, and *L. ovalifolium* Hassk. (Fig. 5). This suggests that these plants may be less adaptable to conditions with limited

moisture. Conversely, *L. ovalifolium* Vicari and *L. japonicum* Green Century exhibited the lowest saturation levels, indicating a potential ability to withstand drought.



Figure 5. Consequences of moisture over-saturation in the leaf blades of *L. ovalifolium* Hassk

Source: photo taken by the authors

Water content is a key parameter that reflects the level of moisture retention in plant tissues, particularly leaf blades. This indicator allows for the assessment of a plant's ability to adapt to its growing conditions, especially drought. In this study, the water content of *Ligustrum* L. species and cultivars was determined. Similar to previous findings, significant variability in results was observed depending on the species and cultivar.

Among the plants with the highest water content, exceeding 70%, *L. vulgare* Aurea (71.3%), *L. ovalifolium* Aureum (77.9%), *L. ovalifolium* Vicari (74.1%), and *L. ibota* Musli (76.3%) stand out. Of these, *L. ovalifolium* Aureum and *Ligustrum ibota* Musli have the highest values, exceeding 75%, indicating their high moisture retention capacity even under potentially unfavourable conditions (Fig. 6). All other plants exhibited moderate water content, suggesting their ability to maintain a stable water balance within their tissues. It is also worth noting that cultivars such as *L. vulgare* Atrovirens and *L. japonicum* Green Century had relatively lower water content, suggesting a lesser adaptive ability to conditions of insufficient moisture.

An interesting observation is that cultivars with variegated leaves, such as white-green or yellow-green (*L. vulgare* Aurea, *L. ovalifolium* Aureum, *L. ovalifolium* Vicari, and *Ligustrum ibota* Musli), tend to have comparatively higher water content than species and cultivars with typical green leaves.

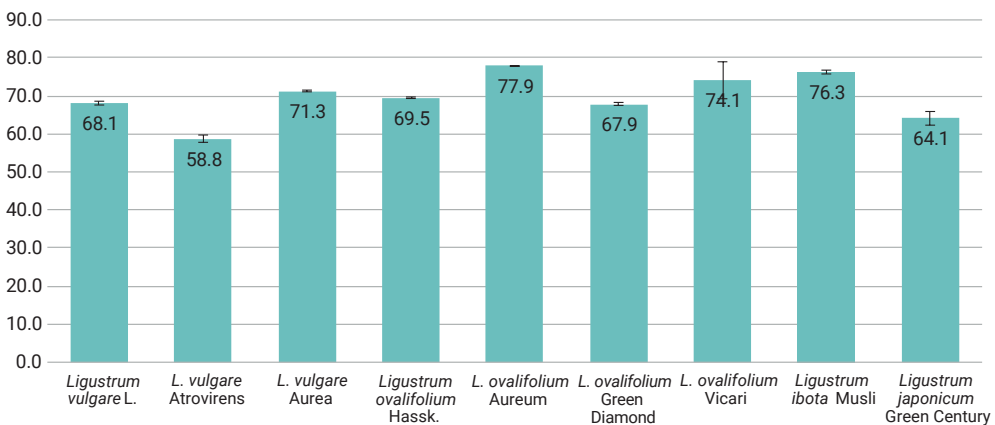


Figure 6. Water content of the leaves of *Ligustrum* L. species and cultivars

Source: developed by the authors

The analysis of water content in the *Ligustrum* L. genus allows for the identification of species and cultivars with a greater ability to retain moisture, such as *L. vulgare* Aurea, *L. ovalifolium* Aureum, *L. ovalifolium* Vicari, and *L. ibota* Musli. It also highlights those with a lower capacity,

including *L. vulgare* L., *L. vulgare* Atrovirens, *L. ovalifolium* Hassk., *L. ovalifolium* Green Diamond, and *L. japonicum* Green Century. The results suggest the potential drought resistance of these plants and their suitability for urban landscaping, particularly in areas with limited water availability.

The study of water retention capacity in the leaf blades of *Ligustrum* L. species and cultivars is a crucial aspect for assessing their potential drought resistance. The experiment was conducted under stable laboratory conditions (temperature 23.8°C, relative humidity 44.5%), allowing for a more accurate evaluation of moisture loss dynamics over 24 hours. Similar to previous

experiments, some variability in results was observed, depending on the species and cultivar of the tested plants. The highest average rate of moisture loss was observed in *L. ovalifolium* Aureum (44.66%) and *L. ibota* Musli (42.71%) (Table 3, Fig. 7). Notably lower moisture loss was observed in *L. ovalifolium* Vicari (37.59%) and *L. ovalifolium* Green Diamond (36.12%).

Table 3. Water retention capacity of *Ligustrum* L. leaves

Plant name	Sample weight by exposure time, g				Average water loss rate, %
	2 hours	4 hours	6 hours	24 hours	
Laboratory results	24°C – 44%	24.2°C – 43%	23.7°C – 49%	22.8°C – 45%	
<i>Ligustrum vulgare</i> L.	10.13	15.95	20.43	47.67	23.26
	11.11	16.78	19.61	42.27	
	9.27	15.12	20.49	50.24	
<i>L. vulgare</i> Atrovirens	12.97	22.87	32.08	57.00	31.26
	11.11	20.94	31.20	53.85	
	14.07	25.48	35.74	57.79	
<i>L. vulgare</i> Aurea	8.93	13.75	17.87	45.70	24.73
	8.28	16.55	21.38	57.93	
	8.97	16.67	21.15	59.62	
<i>Ligustrum ovalifolium</i> Hassk.	2.24	4.17	5.77	19.55	10.22
	3.82	7.64	10.62	36.73	
	1.80	4.09	6.22	19.97	
<i>L. ovalifolium</i> Aureum	19.46	32.89	44.30	79.19	44.66
	21.13	38.03	52.82	78.87	
	17.44	29.65	43.02	79.07	
<i>L. ovalifolium</i> Green Diamond	10.24	27.56	40.16	64.57	36.12
	11.76	27.73	39.50	68.07	
	12.23	26.62	36.69	68.35	
<i>L. ovalifolium</i> Vicari	9.09	25.76	33.33	71.21	37.59
	12.16	39.19	37.84	70.27	
	8.70	27.54	37.68	78.26	
<i>Ligustrum ibota</i> Musli	15.60	31.21	41.13	79.43	42.71
	17.58	36.26	45.05	76.92	
	17.74	29.03	43.55	79.03	
<i>Ligustrum japonicum</i> Green Century	8.12	16.24	18.78	40.44	22.51
	7.86	17.30	21.38	48.74	
	9.69	16.25	19.69	45.63	

Source: developed by the authors

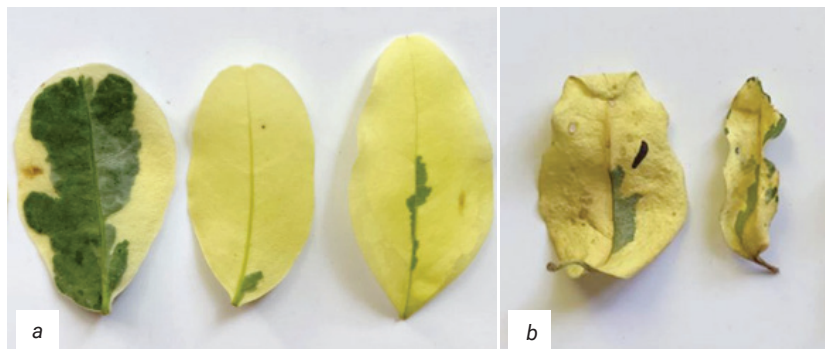


Figure 7. Dynamics of moisture loss from leaves, illustrated by *Ligustrum ibota* Musli.

Note: *a* – before the experiment; *b* – after 24 hours

Source: photos taken by the authors

Significantly lower rates of moisture loss were observed in *L. japonicum* Green Century (22.51%), *L. vulgare* L. (23.26%), and *L. vulgare* Aurea (24.73%). Among these, *L. ovalifolium* Hassk. exhibited the lowest rate of water loss (10.22%). The best water retention capacity was found in *L. ovalifolium* Hassk. and *L. japonicum* Green Century, while the fastest rate of moisture loss was observed in *L. ovalifolium*

Aureum and *L. ibota* Musli. It is also worth noting that in all tested plants, the most intense moisture evaporation occurred between 6 and 24 hours into the experiment. At a temperature of 40°C, all species and cultivars showed no damage to the leaf blades, even after treatment with hydrochloric acid for 5 minutes (Table 4, Fig. 8a). This indicates their high resistance at this temperature.

Table 4. Dynamics of the effect of high temperatures on leaf condition

No.	Plant name	Time of hydrochloric acid treatment, min	Temperature of roasting, °C		
			40	50	60
Percentage of leaf damage, %					
1	<i>Ligustrum vulgare</i> L.	1	0	4	81
2		3	0	5	85
3		5	0	7	97
4	<i>L. vulgare</i> Atrovirens	1	0	8	68
5		3	0	14	74
6		5	0	13	89
7	<i>L. vulgare</i> Aurea	1	0	4	80
8		3	0	6	82
9		5	0	6	88
10	<i>Ligustrum ovalifolium</i> Hassk.	1	0	5	90
11		3	0	2	96
12		5	0	3	100
13	<i>L. ovalifolium</i> Aureum	1	0	7	72
14		3	0	8	84
15		5	0	9	92
16	<i>L. ovalifolium</i> Green Diamond	1	0	0	85
17		3	0	0	90
18		5	0	0	96

Table 4. Continued

No.	Plant name	Time of hydrochloric acid treatment, min	Temperature of roasting, °C		
			40	50	60
			Percentage of leaf damage, %		
19	<i>L. ovalifolium</i> Vicari	1	0	0	73
20		3	0	1	84
21		5	0	2	95
22	<i>Ligustrum ibota</i> Musli	1	0	5	62
23		3	0	6	77
24		5	0	6	89
25	<i>Ligustrum japonicum</i> Green Century	1	0	2	93
26		3	0	5	95
27		5	0	6	100

Note: 0 – no damage; 0-15 – light damage; 16-50 – moderate damage; 50-100 – severe damage or complete leaf death

Source: developed by the authors

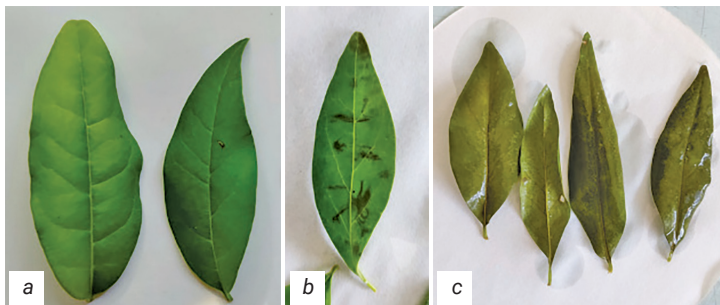


Figure 8. Leaf blades of *Ligustrum vulgare* L. after roasting

Note: a – 40°C, b – 50°C, c – 60°C

Source: photos taken by the authors

At elevated temperatures of up to 50°C, *L. vulgare* L. and its cultivars exhibited slight damage to the leaf blades, which was only 1-5%. When *L. vulgare* Atrovirens (Fig. 8b) was soaked in hydrochloric acid for 3-5 minutes, the damage increased to 20%. In contrast, the cultivars of *L. ovalifolium* Hassk. remained almost undamaged, with the damage percentage ranging from 0-1%, as shown in Figure 9a. Similarly, the leaf blades of *L. ibota* Musli and *L. japonicum* Green Century showed minimal damage, with browning percentages of 5-6%. Increasing the temperature to 60°C resulted in critical leaf damage. High levels of damage were observed in all *L. vulgare* L. cultivars (Fig. 8c), with damage ranging from 80% to 100%. The cultivars of *L. ovalifolium* (Fig. 9b) showed similar

results, with leaf damage between 70% and 100%.

The research demonstrated a significant correlation between temperature and the susceptibility of *Ligustrum* L. species and cultivars to leaf blade damage. While the plants remained resistant to damage at 40°C, a rise in temperature to 50°C, and particularly 60°C, led to increased and critical damage across most cultivars. Similar studies focused on determining frost resistance, with the aim of identifying potentially resilient species and cultivars, provided a foundational basis for this investigation. These studies, such as those conducted by M.S. Kuznetsova & O.I. Kitaiev (2018), assessed the frost and winter hardiness of *Calluna vulgaris* (L.) Hill. and its cultivars. This involved laboratory freezing methods,

as well as visual damage assessments under field conditions. Additionally, O. Babyn *et al.* (2024) detailed a research process examining the poten-

tial frost resistance of *Cercis* L. species and cultivars, which also employed laboratory freezing of experimental plant shoots at -20°C and -25°C.

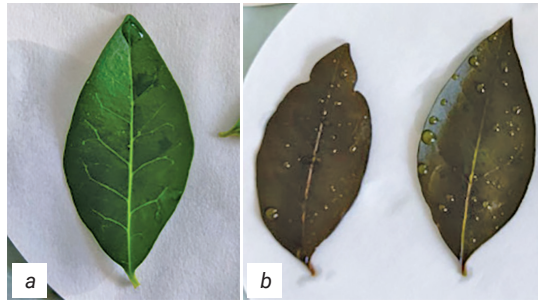


Figure 9. Leaf blades of *Ligustrum ovalifolium* Hassk. after roasting

Note: a – 50°C, b – 60°C

Source: photos taken by the authors

When determining drought resistance indicators, including heat resistance and water retention capacity, the data obtained were similar to those reported by V.M. Novosad (2014). It was established that *L. vulgare* L. exhibits higher resistance to high temperatures. However, when the temperature rises to 60°C, necrosis occurs in 80-90% of the leaf blade. *L. ovalifolium* Aureum showed a significantly lower tolerance to high temperatures, and upon reaching 60°C, the leaf blades discoloured, indicating complete tissue death. Furthermore, the water retention capacity study revealed that *L. ovalifolium* Aureum is less drought-resistant than *L. vulgare* L. After just 30 minutes, the maximum moisture content in the tested leaves was 15%, increasing to 25% after 90 minutes. In contrast, the maximum moisture content in *L. vulgare* L. leaves was 13.4%, and 23.4% at the end of the experiment. The findings of V.M. Novosad (2014) were analysed and expanded to include a wider range of studied plants. Certain aspects of the research were corroborated.

Researchers, including O. Babyn *et al.* (2024), have explored drought resistance indicators such as water retention capacity, water deficit, and heat resistance. Their study, focusing on the *Cercis* L. genus, aimed to determine the plants' ability to withstand dry periods in urban

environments. Y. Telepenko (2018) assessed the drought tolerance of 25 blackberry (*Rubus* L.) varieties in the western Forest-Steppe region of Ukraine. This involved analysing the water-physical properties of leaves using varietal study methods and employing analysis of variance. The study revealed variations in water retention capacity, water deficit, and tissue water content, allowing for the classification of varieties based on their drought tolerance levels. S. Toscano *et al.* (2018) investigated the responses of *Lantana camara* L. and *Ligustrum lucidum* L. to four different water deficit regimes. The results indicated that the water deficit significantly reduced the biomass of both species. However, *Ligustrum lucidum* L. exhibited superior adaptive capabilities and more rapid stomatal regulation.

Research by V.Ya. Zayachuk (2014) indicated that approximately 40 *Ligustrum* L. species exist globally, primarily distributed across Asia, Europe, Australia, and North Africa, with *L. vulgare* L. being native to Ukraine. An examination of the ornamental plant market, particularly the plants cultivated and sold by leading Ukrainian nurseries and garden centres – such as Natalis nursery, Proxima garden centre, and Zelena Kraina ornamental plant nursery – reveals a significant expansion in plant variety to meet landscaping demands.

Consequently, over the past 5-10 years, there has been a notable increase in the range of *Ligustrum* L. species and cultivars. This expansion provides opportunities to utilise not only the indigenous *L. vulgare* L. but also around five other species and numerous cultivars. The *Ligustrum* L. genus is gaining popularity due to its adaptability, evident in both its aesthetic qualities and its tolerance to diverse growing conditions.

Similar research on drought resistance has been carried out by Y.M. Kruhlyak (2010), focusing on various *Salix* L. species and hybrids. Additionally, T. Kopylova (2016) examined the water balance in *Pyracantha* M. Roem. leaf blades and assessed the plants' ability to withstand high temperatures, subsequently evaluating their drought resistance. These methodological approaches were applied in this study to analyse the water regime and drought tolerance of *Ligustrum* L. species, confirming the effectiveness of using physiological parameters to evaluate plant adaptive potential in urban environments.

Conclusions

The ability of *Ligustrum* L. species and cultivars to withstand low temperatures varies significantly. In particular, the *Ligustrum vulgare* Atrovirens cultivar demonstrated the highest resistance to low temperatures, evidenced by minimal damage levels (7.0 points at -25°C). Conversely, *Ligustrum japonicum* Green Century and *Ligustrum ibota* Musli exhibited the lowest resistance, displaying the highest damage scores, especially in the wood and pith regions. The nature of tissue damage indicates that the pith of the shoots is the most vulnerable, particularly at the shoot tip and through the buds, while the cambium and bark proved more resilient to low-temperature effects. Indicators characterising potential resistance to

drought and elevated temperatures, including water retention capacity, water content, water deficit, and heat resistance, also showed considerable variability depending on the species and cultivar. The highest water deficit values were observed in *L. vulgare* L. (16.25%), *L. vulgare* Aurea (14.00%), and *L. ovalifolium* Hassk. (16.14%). Moderately low water deficit values were recorded for *L. ovalifolium* Vicari (6.16%) and *L. japonicum* Green Century (6.42%). Among the plants exhibiting the highest water content, variegated cultivars such as *L. vulgare* Aurea, *L. ovalifolium* Aureum, *L. ovalifolium* Vicari, and *L. ibota* Musli stood out, with levels exceeding 75%. The best water retention capabilities were observed in *L. ovalifolium* Hassk. and *L. japonicum* Green Century, attributed to the denser structure of their leaf blades compared to other varieties.

The heat resistance study revealed that at 40°C, none of the experimental plants suffered leaf blade damage. When the temperature was raised to 50°C, most plants experienced minor leaf blade damage, not exceeding 10-15% of the total leaf area. This suggests that these temperatures do not significantly impact the plants' leaf mass. However, an increase to 60°C resulted in severe damage to the majority of leaf blades across all cultivars or even complete tissue death. Determining resistance to adverse factors enables the selection of resilient *Ligustrum* L. species and cultivars for nursery stock propagation. This, in turn, facilitates the scientifically sound application of these plants for urban landscaping needs in Kyiv.

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Conflict of Interest

None.

References

- [1] Babyn, O., Pinchuk, A., Derii, A., Boiko, O., & Sovakov, O. (2024). Determination of potential drought and frost resistance on the basis of studies with vegetative parts of plants of the genus *Cercis* L. *IOP Conference Series: Earth and Environmental Science*, 1429(1), article number 012019. doi: [10.1088/1755-1315/1429/1/012019](https://doi.org/10.1088/1755-1315/1429/1/012019).

- [2] Bessonova, V.P., Yakovlieva-Nosar, S.O., & Ivanchenko, O.E. (2024). Heat resistance of deciduous woody plants in the northern steppe of Ukraine. *Dnipro State Agrarian and Economics University*, 53, 3-17. doi: [10.15421/442401](https://doi.org/10.15421/442401).
- [3] Bublyk, M.O., Patyka, T.I., Kitaiev, O.I., Makarova, D.H., Kryvoshapka, V.A., Honcharuk, Y.D., & Potanin, D.V. (2013). *Laboratory and field methods for determining the frost resistance of fruit species and crops: Methodological recommendations*. Kyiv: Institute of Horticulture of the NAAS of Ukraine.
- [4] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.
- [5] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1973, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.
- [6] Demydov, O., Blyzniuk, R., Pirykh, A., Yurchenko, T., & Kovalyshyna, H. (2023). Drought resistance of soft spring wheat varieties of different ecological and geographical origins in the Forest Steppe of Ukraine. *Plant and Soil Science*, 14(3), 84-96. doi: [10.31548/plant3.2023.84](https://doi.org/10.31548/plant3.2023.84).
- [7] Dong, J., Niu, S., Zhou, J., Qian, J., Zhao, M., Meng, Y., & Di, B. (2022). Identification of aquaporin gene family in response to natural cold stress in *Ligustrum × vicaryi* Rehd. *Forests*, 13(2), article number 182. doi: [10.3390/f13020182](https://doi.org/10.3390/f13020182).
- [8] Gordienko, D.S., Rubtsova, O.L., Buidina, T.O., Chizhankova, V.I., Rozhok, O.F., & Sokolova, O.A. (2021). Drought resistance of English roses varieties in the conditions of the Right-bank Forest-Steppe of Ukraine. *Plant Varieties Studying and Protection*, 17(1), 60-65. doi: [10.21498/2518-1017.17.1.2021.228212](https://doi.org/10.21498/2518-1017.17.1.2021.228212).
- [9] Kopylova, T. (2016). [Drought resistance of *Pyracantha* M. Roem. representatives under introduction conditions in the Right-Bank Forest-Steppe of Ukraine](#). *Bulletin of Taras Shevchenko National University of Kyiv. Introduction and Conservation of Plant Diversity*, 1(34), 57-61.
- [10] Kruhlyak, Y.M. (2010). Water regime and drought resistance of leaves of species, forms, and hybrids of the genus *Salix* L. *Introduction of Plants*, 1, 85-89. doi: [10.5281/zenodo.2553623](https://doi.org/10.5281/zenodo.2553623).
- [11] Kuznetsov, S.I., Kushnir, A.I., Levon, F.M., Pushkar, V.V., Sukhanova, O.A., Kuznetsova, M.S., & Honcharenko, B.V. (2020). *Assortment of trees, shrubs, and lianas for landscape construction in Ukraine*. Kyiv: CP "KOMPRINT".
- [12] Kuznetsova, M.S., & Kitaiev, O.I. (2018). [Estimation of frost and winter resistance of *Calluna vulgaris* \(L.\) Hull and its cultivars in the conditions of the Right-Bank Forest-Steppe of Ukraine](#). *Introduction of Plants*, 2, 84-91.
- [13] Leotta, L., Toscano, S., Ferrante, A., Romano, D., & Francini, A. (2023). New strategies to increase the abiotic stress tolerance in woody ornamental plants in Mediterranean climate. *Plants*, 12(10), article number 2022. doi: [10.3390/plants12102022](https://doi.org/10.3390/plants12102022).
- [14] Maslovata, S. (2016). Frost resistance of species and forms of *Ulmus* L. genus under the conditions of Uman City. *Scientific Bulletin of UNFU*, 26(5), 109-115. doi: [10.15421/40260516](https://doi.org/10.15421/40260516)
- [15] Meteoblue. (n.d.). *Weather archive Kyiv (2019-2024)*. Retrieved from <https://surl.li/uxdaad>.
- [16] Mezhenyskyi, V.M. (2017). [Fundamentals of research in horticulture. Calculations in Microsoft Excel](#). Kyiv: Lira-K.
- [17] Novosad, V.M. (2014). [Heat tolerance and water-retaining ability of *Ligustrum vulgare* L. and *Ligustrum ovalifolium* "Aureum"](#). *Scientific Bulletin of UNFU*, 24(9), 80-84.
- [18] Pashayev, T. (2024). Study of agroecological features of *Ligustrum vulgare* L. in Nakhchivan Autonomous Republic and prospects for its use in greening. *Bulletin of Science and Practice*, 10(4), 59-63. doi: [10.33619/2414-2948/101/08](https://doi.org/10.33619/2414-2948/101/08).

- [19] Sviatohorov, I.O. (2024). Increased heat stress for the population of urbanized areas against the background of global climate change. *Environmental Safety and Natural Resources*, 49(1), 49-59. doi: [10.32347/2411-4049.2024.1.49-59](https://doi.org/10.32347/2411-4049.2024.1.49-59).
- [20] Telepenko, Y.Y. (2018). Comparative assessment of drought resistance of blackberry (*Rubus* L.) cultivars in the conditions of the Western Forest-Steppe of Ukraine. *Bulletin of Poltava State Agrarian Academy*, 1, 78-82. doi: [10.31210/visnyk2018.01.13](https://doi.org/10.31210/visnyk2018.01.13).
- [21] Tkaczenko, T., Mileikovskiy, V., & Kravchenko, M. (2023). Research of gas exchange and air purification processes by plants of the common privet (*Ligustrum vulgare* L.) species. *Ecological Safety and Balanced Use of Resources*, 14(2), 28-37. doi: [10.69628/esbur/2.2023.28](https://doi.org/10.69628/esbur/2.2023.28)
- [22] Toscano, S., Ferrante, A., Tribulato, A., & Romano, D. (2018). Leaf physiological and anatomical responses of *Lantana* and *Ligustrum* species under different water availability. *Plant Physiology and Biochemistry*, 127, 380-392. doi: [10.1016/j.plaphy.2018.04.008](https://doi.org/10.1016/j.plaphy.2018.04.008).
- [23] Trokhymchuk, A.I., & Makarova, D.H. (2022). *Scientific and methodological recommendations for the study and conservation of genetic resources of fruit, berry, nut-bearing, and underutilized crops*. Kyiv: IS NAAS of Ukraine.
- [24] Yavas, I., Jamal, M.A., Ul Din, K., Ali, S., Hussain, S., & Farooq, M. (2024). Drought-induced changes in leaf morphology and anatomy: Overview, implications, and perspectives. *Polish Journal of Environmental Studies*, 33(2). doi: [10.15244/pjoes/174476](https://doi.org/10.15244/pjoes/174476).
- [25] Zayachuk, V.Ya. (2014). *Dendrology. Textbook*. Lviv: Spolom.

Оцінка морозо- та посухостійкості видів та культиварів роду *Ligustrum* L. при виробництві садивного матеріалу

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Анотація. Актуальність дослідження обумовлена необхідністю вдосконалення оцінки адаптивного потенціалу рослин для озеленення міських просторів, зокрема в умовах Києва, де фактори, як нестача вологи та коливання температур, є ключовими при виборі рослин, здатних витримувати екологічні навантаження та зберігати декоративні властивості. Метою роботи стали дослідження морозо- та посухостійкості видів та культиварів роду *Ligustrum* L., що дозволило оцінити їх адаптивні можливості для використання в умовах урбанізованого середовища. У рамках дослідження були використані фізіологічні методи для оцінки таких показників, як водоутримуюча здатність, водний дефіцит, оводненість, жаростійкість та морозостійкість. За результатами дослідження встановлено, що *Ligustrum vulgare* L. та її культивари мають високі показники морозостійкості. Це проявлялося у найменшій кількості балів ушкодження тканин за температури -25°C , в середньому 7,0-13,9 балів. Інші ж рослини за результатами дослідження при температурі -20°C мали незначний бал ушкодження (в середньому менше 2 балів), це вказує на те що дана температура не є критичною. Водночас сумарний бал при пониженні температури до -25°C значно зростає, зокрема в *Ligustrum ovalifolium* Hassk. та її культивариів сумарний бал коливається в межах 14,2-24,8, тоді як *Ligustrum japonicum* 'Green century' та *Ligustrum Ibota* 'Musli' мали 30,7 та 26,3 бали відповідно, що є близьким до критичного значення, але упродовж вегетації, клітини та тканини здатні відновитись. *Ligustrum vulgare* L., *Ligustrum ovalifolium* Hassk. та деякі культивари мали досить високу посухостійкість, що відображається у відносно невеликих відсотках зміни кількості вологи в листових пластинках. Отримані результати також показують стійку водорегулюючу функцію даних рослин, а також високі показники жаростійкості зокрема за температури 50°C . Слід зазначити, що підвищення температури до 60°C було критичне для всіх рослин. Це відображалось у частковому побурінні або повному відмиранні листових пластинок. Оцінка вищезгаданих показників дає змогу для відбору вихідного матеріалу з метою отримання стійкого садивного матеріалу до факторів урбанізованого середовища

Ключові слова: садивний матеріал; листова пластинка; озеленення; водний режим; стійкість; морозне ушкодження



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Fungal diseases of corn seeds

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Abstract. Corn is a strategic crop with growing demand, which necessitates increased production and the use of healthy seeds to improve yields and product quality. The purpose of the study was to investigate the symptoms of fungal diseases of corn seeds and establish the spread of micromycetes. The study of diseases of corn cobs and seeds was carried out in the Problem Research Laboratory of Mycology and Phytopathology of the Department of Phytopathology of the National University of Life and Environmental Sciences of Ukraine. Samples of plant material (cobs) for diagnostics were taken during route surveys in the Forest-Steppe of Ukraine and during the period of their storage. Seed samples were taken after harvesting. Diagnosis of diseases was carried out by visual examination and biological method (seed germination in wet chambers and on a nutrient medium). Microscopic analysis of their morphological structures was performed to identify micromycetes. The frequency of occurrence of micromycetes was determined during seed germination in petri dishes on filter paper. During the studies, infection of corn cobs and grains with various micromycetes was detected (*Trichothecium* spp., *Fusarium* spp., *Alternaria* spp., *Cladosporium* spp., *Aspergillus* spp., *Mucor* spp., *Penicillium* spp., *Rhizopus* spp.), which caused the variability of disease symptoms. The parasitism of the fungi *Botrytis cinerea*

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and *Bipolaris* spp. on ears of corn was established, which was not disclosed in the national scientific literature. The highest frequency of occurrence on corn seeds was characterised by representatives of the genus *Alternaria* – 18.4%. Fungi of genera *Cladosporium* and *Penicillium* were detected on 4.5 and 4.7% of seeds, respectively. Seed infection with *Fusarium* spp. was 2.7%, *Mucor* spp. – 2.6%. Representatives of the genus *Rhizopus* were identified on 1.1% of seeds. Fungi of genera *Trichothecium* and *Aspergillus* were 0.4 and 0.6%. Therefore, monitoring of fungal pathogens and their phytopathological examination are necessary to assess the quality of corn seeds. Information on the symptoms of mycoses, the species composition of micromycetes should be used in the diagnosis of seed pathologies

Keywords: diagnostic signs; mould; fusarium; micromycetes; grain; germination

Introduction

Research on fungal diseases of corn seeds is necessary because of their impact on germination, plant viability, and overall crop yield. Seeds infected with pathogenic fungi can become a source of primary infection of crops, which leads to a decrease in yield and deterioration of grain quality. Some pathogens, in particular, *Fusarium* spp. and *Aspergillus* spp. and *Penicillium* spp., not only affect seeds but also produce mycotoxins that are dangerous to human and animal health, which reduces the nutritional and feed value of grain. In addition, the affected seed is less resistant to adverse environmental conditions, which can lead to its death even in the early stages of germination or to the appearance of weakened plants with low productivity. In a changing climate and the intensification of agricultural production, the risks of developing fungal diseases increase, which requires a comprehensive approach to monitoring, diagnosing, and controlling these pathogens. The development of effective methods of seed disinfection, introduction of sustainable varieties and improvement of plant protection technologies are important tasks of modern agricultural science, as they contribute to stable corn production, increase its yield, and ensure food security.

Corn is a strategic crop. As noted by O. Erenstein *et al.* (2022), it is the world leader in grain consumption, with annual production exceeding 1 billion tonnes. M.S. Azadi *et al.* (2022) noted the role of corn as a food crop for an estimated

4.5 billion people in 94 developing countries, providing about 30% of their daily calorie needs. In addition, 63% of corn grown worldwide is a significant source of oil, starch, biofuels, and is also used as animal feed. O. Erenstein *et al.* (2022), emphasised that countries such as the United States, Brazil, China, Ukraine, Argentina, India, Mexico, and Indonesia account for 77.4% of global corn production. Overall, its global consumption will grow by an average of 1.1% per year, driven by feed demand (FAOStat, 2021; Spriazhka *et al.*, 2024). In Ukraine, the area on which corn is grown is (on average over the past five years) 4.824 million ha with a yield of 6.98 t/ha.

According to R. Kumar & A. Gupta (2020), to meet the basic nutritional needs of the world's growing population, there is a need to increase agricultural production. The quality of seeds increases the yield by at least 10-15%. As noted by M. Pikovskyi & M. Solomiichuk (2022), infection-free seeds are one of the factors that ensure crop growth, but its infection with micromycetes leads to a decrease in sowing qualities, causing loss of germination, rotting and death of seedlings, and the manifestation of diseases on young plants.

Corn seeds can be infected with various micromycetes. Based on the findings of B. Sreenu *et al.* (2019), external pathogens that are transmitted with seeds (*Aspergillus flavus*, *A. niger*, *Fusarium moniliforme*, *Alternaria alternata* and *Curvularia lunata*) and internal ones, which are represented by micromycetes *Bipolaris maydis* and *Colletotrichum*

graminicola, were identified. The researchers also noted the need for differentiated use of seed testing methods. F.H. Goma (2021) found that corn seeds were infected with many phytopathogenic microorganisms, including *Fusarium*, *Aspergillus*, *Penicillium sp.*, *Nigrospora*, and *Macrophomina*.

In general, phytopathogenic fungi cause a decrease in its sowing qualities of seeds. Along with this, A.M. Gasperini *et al.* (2021) noted that contamination of corn cobs and grains with micromycetes can cause the accumulation of mycotoxins, which negatively affect the health of humans and animals that consume contaminated food. For example, fungi of the genus *Fusarium* can cause the production of fumonisins or trichothecenes of type B in grain, *Aspergillus* section *Circumdati* and *Penicillium verrucosum* species can produce ochratoxins, and the *Aspergillus* section *Flavi* group contaminates corn grain with aflatoxins. The problem of contamination with mycotoxins, which accumulate fungi from the genus *Fusarium*, is also emphasised in the study by O.V. Kaminska *et al.* (2021), which investigated the seasonal dynamics of mycotoxin synthesis in corn grain in Ukraine. All of the above studies indicate the diversity of the species composition of pathogens of fungal diseases of corn seeds, their negative impact on yield, human and animal health. Therefore, there is a need to investigate various aspects of seed pathologies. The purpose of the study was to investigate the symptoms of corn grain mycoses and the spread of micromycetes.

Materials and Methods

The study of the symptoms of corn cob and grain diseases was carried out in the Problem Research Laboratory of Mycology and Phytopathology of the Department of Phytopathology of the National University of Life and Environmental Sciences of Ukraine. The study was in line with the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). Samples of plant material (cobs) for diagnostics were taken during route surveys during

2019-2021 in the conditions of the Forest-Steppe of Ukraine and during the period of their storage. Every year, seed samples (20 pcs.) were selected after harvesting. During field observations, symptoms of fungal damage to cobs with *Fusarium* spp., *Alternaria* spp., *Cladosporium* spp., *Penicillium* spp. and *Trichothecium roseum* Link ex Fries were revealed.

To investigate the symptoms of diseases, corn seeds were sprouted on potato-glucose agar and in wet chambers according to methods provided by E.J. Warham *et al.* (1996). Diagnosis of diseases was carried out by visual method and microscopic analysis of pathogens (Warham *et al.*, 1996; Pikovskiy *et al.*, 2023), using various optical systems (magnifying glass, binocular stereomicroscope and optical microscope). Temporary microscopic preparations were made to identify micromycetes. Based on the morphology of mycelial hyphae, conidiophores and conidia, pathogens were identified and described in the reference literature (Warham *et al.*, 1996; Watanabe, 2002; Leslie & Summerell, 2006). The frequency of occurrence of micromycetes was determined during grain germination in petri dishes on filter paper and calculated by the equation:

$$Fo = \frac{n \times 100}{N}, \quad (1)$$

where Fo – frequency of occurrence, %; n – number of seeds in which this type of micromycete is detected, pcs.; N – total number of seeds studied, pcs. Statistical processing of research results was performed using Microsoft Office® for Microsoft Windows.

Results and Discussion

During the studies, infection of corn cobs and grains with various micromycetes was detected (Table 1), which caused the variability of symptoms of diseases. Seed germination helped to establish diagnostic signs of pathologies on seedlings and identify latent infection. In the field, the cobs were affected by *Fusarium* pathogens (*Fusarium* spp.) and mould (*Alternaria* spp., *Cladosporium* spp., *Penicillium* spp. *Trichothecium roseum* Link ex

Friet Fries.). During the storage period, the development of micromycetes *Botrytis cinerea* Pers. and *Bipolaris* spp. on maize cobs was found. During seed incubation in wet chambers, its mycobiome was represented by fungi of the genera *Trichothecium* Link, *Fusarium* Link, *Alternaria* Nees, *Cladosporium* Link, *Aspergillus* P. Micheli ex Link, *Mucor* Fresen., *Penicillium* Link and *Rhizopus* Ehrenb.

Fusarium infection occurred in the field and during seed germination (Fig. 1). In the pre-harvest period, a web-like or denser pale pink coat-

ing appeared on the affected cobs in foci. Grains placed in the lesion visually lost their lustre and acquired a dirty brown hue. During germination, corn grains affected by *Fusarium* fungi lost their germination or formed weak sprouts that usually died. Under wet conditions, mycelium and pathogen sporulation organs formed on the seed surface. In some cases, grains affected by *Fusarium* pathogens also showed a coexistence of various micromycetes, which increases the harmfulness of the disease.

Table 1. Visual symptoms, damage to corn cobs and seeds by micromycetes

Micromycete	Symptoms of pathologies	
	on the cobs	on seeds during germination
<i>Fusarium</i> spp.	under the leaves there are one or more foci of web-like, pale pink, light or bright pink plaque colour; the grains lose their lustre, are covered with mycelium to varying degrees	highly infected seeds are covered with fluffy mycelium and sporulation of the pathogen, do not germinate; weakly affected seeds have a slow germination energy, form weak seedlings, underdeveloped roots, which are gradually colonised by the pathogen, covered with plaque and rot
<i>Penicillium</i> spp.	green mycelium is formed between the rows of seeds in the cob, which covers the surface of the seeds to varying degrees	heavily affected grains become mouldy and do not form seedlings, they are completely covered with a well-developed coating, which is light at first and later becomes green; the coating can form in different parts of the seed, seedlings and roots are underdeveloped, deformed, stunted, and eventually die
<i>Alternaria</i> spp., <i>Cladosporium</i> spp.	dark coating forms on the seeds of the cob	on the skin of seeds, a dark coating is formed with sporulation of pathogens; surface infection dominates – normal seedlings and roots are formed; due to a joint infection with fungi of the genus <i>Fusarium</i> seedlings die
<i>Aspergillus</i> spp.	no results were found on cobs in the field during the research period	on the surface of seeds, in the form of small heads, sporulation of pathogens of various shades (light yellow-green, dark yellow-green, olive-brown, brown, brown-black, black) is formed; infected seeds lose their germination, or form weak seedlings and roots, which eventually die
<i>Botrytis cinerea</i>	it was not detected in the field; during storage of cobs, a grey coating forms between the rows of grains and on their surface; infected seeds lose their lustre	seeds are covered with a grey, ashy coating and turn mouldy; weakly affected grains form seedlings that rot over time
<i>Bipolaris</i> spp.	it was not detected in the field; during storage of cobs, a light, and later darkish coating is formed between the rows of grains and on their surface	infected seeds lose their germination and become covered with a light grey, fluffy mycelium, which darkens over time
<i>Trichothecium roseum</i>	develops intensively on the grains of the cob powdery pink coating	infected grains become covered with a powdery pink coating and become mouldy
<i>Mucor</i> spp.	no results were found on cobs in the field during the research period	web-like coating forms on the surface of the seed, among which individual dark heads (sporangia) are clearly visible
<i>Rhizopus</i> spp.	no results were found on cobs in the field during the research period	abundant loose grey mycelium and rounded black sporangia form on the surface of the grains

Source: developed by the authors

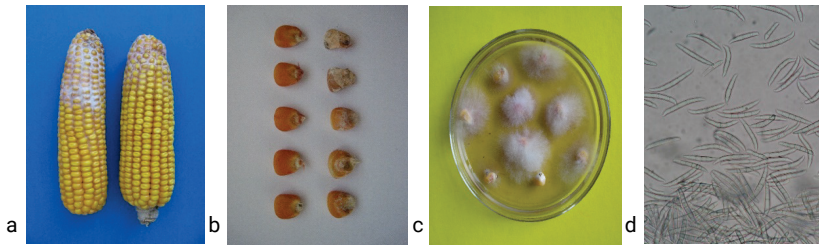


Figure 1. Symptoms of *Fusarium* infection on corn (a, b, c) and macroconidia of *Fusarium* spp. (d)
Source: compiled by the authors based on own research

In conditions of high humidity and late harvesting, fungi of the genus *Penicillium* developed on the cobs in the form of a mouldy coating of green-bluish hue between the rows of grains and on their surface (Fig. 2a, b, c). Highly infected grain lost its sowing qualities. During germination of corn seeds infected with *Aspergillus* spp. (Fig. 2d), small powdery heads (of various shades) formed on its surface. Intensive development of the pathogen led to a decrease in seed germination, death of seedlings, and weakening of plant seedlings. Pathology often developed on grains with mechanical damage. Damage to corn cobs

by micromycetes of genera *Alternaria* Nees and *Cladosporium* Link was observed during crop maturation. Symptoms of pathology were noticeable on the top of the cobs. A black or dark olive coating of varying intensity was formed on the seed shell (Fig. 3). Injured and damaged grains were susceptible to infection. There are also cases of joint development of *Alternaria* spp., *Cladosporium* spp. with fungi of the genus *Fusarium*, which led to a loss of seed germination. As a rule, in apparently healthy, full grain, the micromycetes *Alternaria* spp. and *Cladosporium* were present as a surface infection.

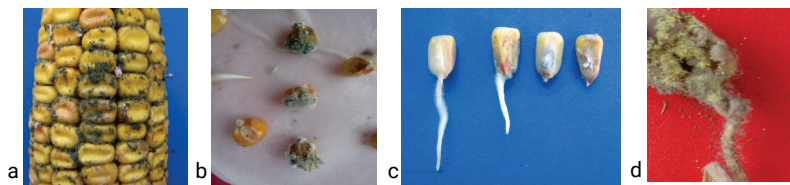


Figure 2. Penicilliosis and corn aspergillosis

Note: a – cob affected with *Penicillium* spp.; b, c – manifestation of penicilliosis during seed germination; d – symptoms of aspergillosis

Source: compiled by the authors based on own research

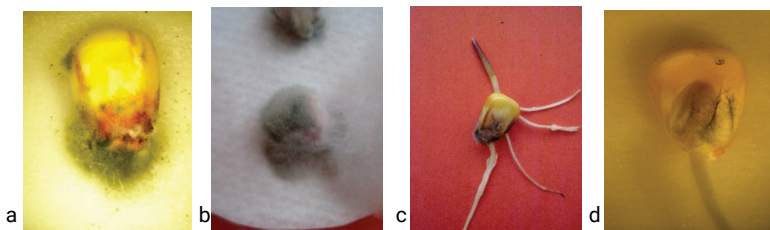


Figure 3. Manifestation of fungal infection during corn seed germination

Note: a, b – *Alternaria* spp. and *Fusarium* spp.; c – *Alternaria* spp. and *Cladosporium* spp.; d – *Cladosporium* spp.

Source: compiled by the authors based on own research

During field monitoring of mycoses of corn cobs, their fungal damage with *Botrytis cinerea* was not observed. The pathogen developed in the post-harvest period. Symptoms of grey rot were characterised by the formation of grey plaque between the rows of grains. As the disease progressed, the micromycete affected the grains, which acquired a lighter shade and were covered with plaque, which consists of the organs of sporulation of the pathogen (Fig. 4a, b). During the germination of diseased seeds, moulding occurred. Seedlings were not formed. In addition, during the storage of corn cobs, their damage with *Bipolaris* spp. was detected (Fig. 4c, d). Parasitisation of fungi *B. cinerea* and *Bipolaris* spp. on the corn cobs was not disclosed in the domestic scientific literature.

Fungus *T. roseum*, infecting corn seeds, caused a thick powdery pink coating to appear on their surface (Fig. 5a, b). During seed germination, its moulding was observed. Heavily contaminated grain lost its germination. Corn mould caused by micromycetes *Mucor* spp. and *Rhizopus* spp. was observed during seed germination. In particular, under *Mucor* spp. parasitism, a web-like plaque with dark sporangia formed on the seed surface (Fig. 5c). The fungus developed intensively on a weak grain with damaged skin. Fungus *Rhizopus* spp. formed sporangia singly or in groups on corn seeds under moist conditions (Fig. 5d). Strong colonisation led to seed mould during germination. Grains with damaged seed skins were more likely to develop the pathogen.

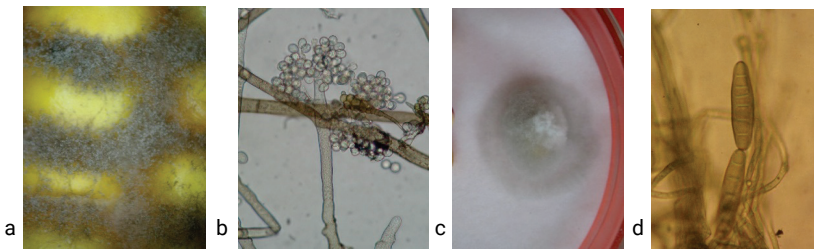


Figure 4. Symptoms of grey mold on the cob of corn (a) and conidial sporulation of the fungus *B. cinerea* (b); the seed is affected by the fungus *Bipolaris* spp. (c) and pathogen conidia (d)

Source: compiled by the authors based on own research

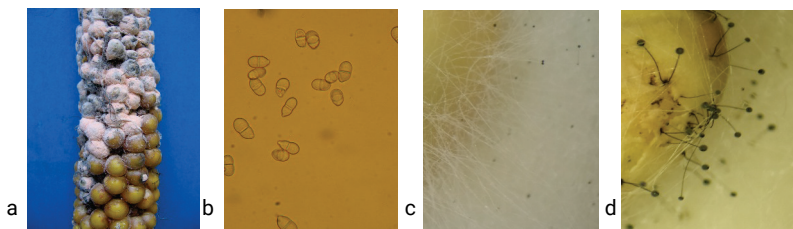


Figure 5. Mould symptoms

Note: a – pink mould on the cob of corn; b – conidia of the fungus *T. roseum*; c – fungal sporulation of *Mucor* spp.; d – *Rhizopus* spp.

Source: compiled by the authors based on own research

Phytopathological examination of corn seeds performed using a biological method showed its contamination with fungi belonging to 8 genera: *Trichothecium*, *Fusarium*, *Alternaria*, *Cladosporium*, *Aspergillus*, *Mucor*, *Penicillium* and *Rhizopus* (Fig. 6).

The highest frequency of occurrence was characterised by representatives of the genus *Alternaria* – 18.4%. Fungi of genera *Cladosporium* and *Penicillium* were detected on 4.5 and 4.7%, respectively. Seed infection with *Fusarium* spp. was 2.7%, while

Mucor spp. – 2.6%. Representatives of the genus *Rhizopus* were identified on 1.1% of seeds. Fungi of genera *Trichothecium* and *Aspergillus* were 0.4 and 0.6%. The proportion of micromycetes

in the pathogenic complex was as follows: *Alternaria* – 52.4%, *Penicillium* – 13.4%, *Cladosporium* – 12.8%, *Fusarium* – 7.7%, *Mucor* – 7.4%, *Rhizopus* – 3.2%, *Aspergillus* – 1.7%, *Trichothecium* – 1.4%.

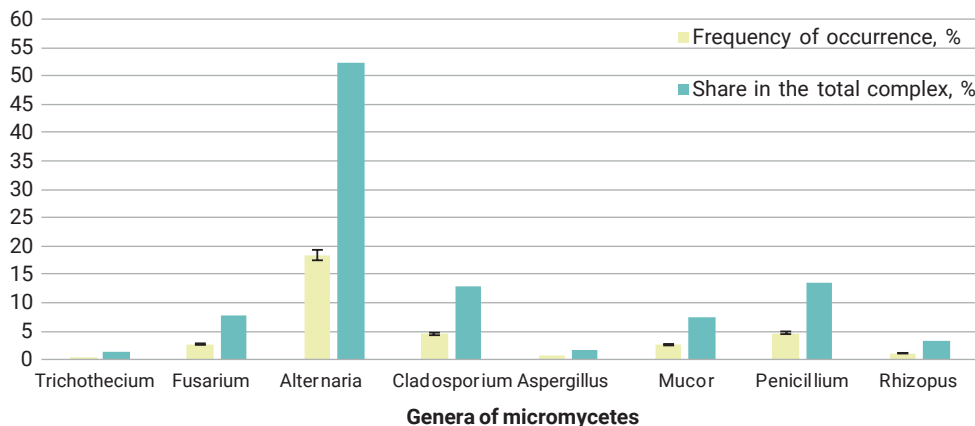


Figure 4. Mycobiota of corn seeds (average for 2019-2021)

Source: compiled by the authors based on own research

According to the analysis of results, seed micromycetes are characterised by significant species diversity in different regions of experiments. In the study by I. Niaz & S. Dawar (2009), corn seed mycoflora was represented by the following species: *Aspergillus flavus*, *A. goesii*, *A. niger*, *Penicillium* spp., *Drechslera* spp., *Cladosporium* spp., *Fusarium* spp., *Curvularia* spp., *Rhizopus* spp., *Arthrinium phaeospermum*, *Aspergillus foetidus*, *A. tubingensis*, *Curvularia clavata*, *C. pallescens*, *C. intermedia*, *Bipolaris maydis*, *Drechslera carbonum*, *Diplodia zea*, *Fusarium crockwellense*, *F. cladosporium*, *F. graminearum*, *F. culmorum*, *F. proliferatum*, *F. nivale*, *Penicillium citrinum*, *P. funiculosum*, *Phoma herbarum*, *Rhizoctonia solani*, *R. oligosporum*, *Syncephalastrum racemosum* and *Trichoderma harzianum*. The researchers also noted that similar types of fungi have been found on corn seeds from different countries around the world, such as the United States, Thailand, India, Canada, Australia, France, Nepal, the United Kingdom, Romania, and Hungary.

M.M. Akonda *et al.* (2016) established infection of corn seeds with nine types of fungi: *Aspergillus flavus* – 27.42%, *A. niger* – 23.47%,

Fusarium oxysporum – 20.55%, *F. moniliforme* – 17.39%, *Penicillium oxalicum* – 18.37%, *Rhizopus stolonifer* – 17.83%, *Curvularia lunata* – 7.87%, *Bipolaris maydis* – 3.50%, and *Alternaria alternata* – 27.4%. According to O.T. Kutsan *et al.* (2021), when analysing corn seed samples taken from farms in Eastern Ukraine, the greatest contamination with micromycetes (from 42 to 74%) was inherent in *Fusarium*, *Aspergillus*, *Penicillium* and from 9 to 29% for *Rhizopus*, *Mucor* and *Alternaria* (2015 harvest). While in the seed samples of the 2020 harvest, the total contamination with grain micromycetes increased to 89% and their ratio to each other changed. M.V. Bogach *et al.* (2024) identified a mycobiota of corn grain in the North-Western Black Sea region of Ukraine during periods of severe drought, which was represented by fungi from genera *Penicillium* (81%), *Aspergillus* (78%), *Fusarium* (42%), *Alternaria* (31%), *Mucor* (16%), and *Rhizopus* (5%). Whereas in growing seasons with sufficient moisture, the spread of micromycetes of genera *Penicillium* and *Aspergillus* decreased by 17% and 14%, respectively, and fungi of the genus *Fusarium* increased by 9%.

Y.M. Shabana *et al.* (2023), studying the distribution and biodiversity of seed pathogenic and toxigenic corn fungi in Egypt and their correlation with weather factors, identified mycobiome and the most common species: *Ustilago maydis*, *Alternaria alternata*, *Aspergillus flavus*, *Aspergillus niger*, *Penicillium* spp., *Cladosporium* spp., and *Fusarium verticillioides*. Moreover, relative humidity, temperature and wind speed, respectively, had the greatest impact on the spread of pathogens. According to I.H. Al-Masoodi *et al.* (2023), corn seed analysis revealed *Aspergillus* spp., *Penicillium* spp., *Fusarium* spp., *Mucor* spp., *Alternaria* spp., *Acremonium* spp. and yeast. Among the fungi of the genus *Fusarium*, the following species were identified: *F. verticillioides*, *F. equiseti*, *F. proliferatum*, *F. sulawenes*, *F. oxysporium* and *F. thapsinum*. W.M. Haggag *et al.* (2024), using molecular identification, identified the most common fungi in corn seeds that were represented by species *Fusarium verticillioides*, *Talaromyces verruculosus*, *Aspergillus niger*, *A. flavus* and *A. terreus*.

New pathogens of corn cobs and grains have been detected in different countries. Thus, A. Pfordt *et al.* (2020) in 2018 observed an intense infection of cobs with the fungus genus *Trichoderma* in Germany. In further research, it was identified as *Trichoderma afroharzianum*. The researchers proposed the name of the disease – trichoderma ear rot. A little later, M. Sanna *et al.* (2022) found infection of corn cobs with the fungus *T. afroharzianum* in Italy, which caused green seed mould. In Hainan province in Southern China, H. Sun *et al.* (2022) were the first to diagnose cob infection with the fungus *Exserohilum rostratum*. The pathogen caused the appearance of dark brown spots, which were covered with a grey-black coating. Severely affected grains had a wrinkled appearance.

Thus, monitoring of fungal pathogens and its phytopathological examination are necessary to assess the quality of corn seeds. Information on the symptoms of mycoses, the species composition of micromycetes should be used in the diagnosis of seed pathologies.

Conclusions

During the study of diseases of corn cobs in the field, their damage by fungi – pathogens of *Fusarium* spp.) and mold (*Penicillium* spp., *T. roseum*, *Alternaria* spp., *Cladosporium* spp.). In the post-harvest period, parasitisation on the heads of micromycetes *B. cinerea* and *Bipolaris* spp. was identified. The variability of symptoms of pathologies characterised by the formation of plaque of various colours, deterioration or loss of the ability of seeds to germinate, and rotting of seedlings was established. Seeds heavily infected with *Fusarium* spp. did not germinate, while weakly affected, formed weak seedlings, underdeveloped roots. *Penicillium* spp. caused seed mould, deformation of seedlings and roots, and their growth lag. Seeds infected by *T. roseum* were covered with a powdery pink coating and mould. Micromycetes *Alternaria* spp. and *Cladosporium* spp. were often in the form of a superficial infection and in most cases did not reduce seed germination rates. *Aspergillus* spp., *Mucor* spp. and *Rhizopus* spp. caused moulding of highly infected seeds, and also made up its epiphytic mycoflora. Fungi *B. cinerea* and *Bipolaris* spp., in the case of infection of corn cobs, led to a loss of germination of corn seeds.

Mycobiom of corn seeds was represented by *Fusarium* spp. *Penicillium* spp., *Aspergillus* spp., *Mucor* spp., *Rhizopus* spp., *T. roseum*, *Alternaria* spp., *Cladosporium* spp. Phytopathological examination of corn seeds has shown that the highest frequency of occurrence was characterised by representatives of the genus *Alternaria* – 18.4%. Fungi of genera *Cladosporium* and *Penicillium* were detected on 4.5 and 4.7% of the tested seeds, respectively. Seed infestation with *Fusarium* spp. was 2.7%, *Mucor* spp. – 2.6%. Frequency of occurrence of micromycetes of genera *Rhizopus*, *Aspergillus* and *Trichothecium* was 1.1%, 0.6%, and 0.4%, respectively. Further research should focus on identifying the species composition of pathogens, determining the content of mycotoxins in grain, and the influence of environmental factors on these processes.

Acknowledgements

None.

Conflict of Interest

None.

References

- [1] Akonda, M.M., Akonda, R., Yasmin, M., & Hossain, I. (2016). [Incidence of seed-borne mycoflora and their effects on germination of maize seeds](#). *International Journal of Agronomy and Agricultural Research*, 8, 87-92.
- [2] Al-Masoodi, I.H., Al-Rubaye, A.F.M., & Hussein, H.J. (2023). [Isolation and diagnosis of the fungi associated with maize seeds collected from local markets in Karbala, Iraq](#). *Caspian Journal of Environmental Sciences*, 21(3), 665-672.
- [3] Azadi, M.S., Shokoohfar, A., Mojdani, M., Lak, S., & Fazel, M.A. (2022). Investigation of changes in corn hybrids grain protein, proline, and micronutrient content under the influence of drought and fertilizers. *Turkish Journal of Agriculture and Forestry*, 46(4), 413-423. doi: 10.55730/1300-011X.3014.
- [4] Bogach, M.V., Paliy, A.P., Bohach, D.M., Kovalenko, L.V., Selishcheva, N.V., Ganova, L.O., Stegnyy, B.T., Pavlichenko, O.V., & Vovk, D.V. (2024). Influence of weather conditions on contamination of grain fodder by micromycetes in the northwestern Black Sea region of Ukraine. *Microbiological Journal*, 86(5), 75-86. doi: 10.15407/microbiolj86.05.075.
- [5] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.
- [6] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1973, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_129#Text.
- [7] Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B.M. (2022). Global maize production, consumption and trade: Trends and R & D implications. *Food Security*, 14, 1295-1319. doi: 10.1007/s12571-022-01288-7.
- [8] FAOStat. (2021). Retrieved from <http://www.fao.org/faostat>.
- [9] Gasperini, A.M., Garcia-Cela, E., Sulyok, M., Medina, A., & Magan, N. (2021). Fungal diversity and metabolomic profiles in GM and isogenic non-GM maize cultivars from Brazil. *Mycotoxin Research*, 37(1), 39-48. <http://dx.doi.org/10.1007/s12550-020-00414-8>.
- [10] Gomaa, F.H. (2021). Detection of maize seed-borne fungi and induced resistance against both *Aspergillus niger* and *Fusarium verticillioides*. *Archives of Phytopathology and Plant Protection*, 54(19-20), 2051-2066. doi: 10.1080/03235408.2021.1969627.
- [11] Haggag, W.M., Diab, M.M., Al-Ansary, N.A., Ibrahim, M.I.M., Khattab, E.-N.A.A., Abdel-Wahhab, M.A., & Ali, M.K. (2024). Molecular identification and management of mycotoxigenic fungi in stored corn grains. *Cereal Research Communications*, 52, 1631-1644. doi: 10.1007/s42976-024-00502-w.
- [12] Kaminska, O.V., Marchenko, T.V., Kyryk, M.M., & Shevchenko, L.V. (2020). Seasonal dynamics of accumulation of mycotoxins in corn grain. *Biological Resources and Nature Management*, 12(1-2), 47-55. doi: 10.31548/bio2020.01.006.
- [13] Kumar, R., & Gupta, A. (2020). *Seed-borne diseases of agricultural crops: Detection, diagnosis & management*. Singapore: Springer. doi: 10.1007/978-981-32-9046-4.
- [14] Kutsan, O.T., Nychyk, C.A., Zakharova, O.M., & Tarasov, O.A. (2021). Mycotoxicological risks of grain feeds. *Veterinary Biotechnology*, 38, 131-144. doi: 10.31073/vet_biotech38-11.
- [15] Leslie, J.F., & Summerell, B.A. (2006). *The fusarium laboratory manual*. Ames, IA: Wiley-Blackwell.
- [16] Niaz, I., & Dawar, S. (2009). [Detection of seed-borne mycoflora in maize \(*Zea mays* L.\)](#). *Pakistan Journal of Botany*, 41(1), 443-451.

- [17] Pfordt, A., Schiwek, S., Karlovsky, P., & von Tiedemann, A. (2020). *Trichoderma afroharzianum* ear rot – a new disease on maize in Europe. *Frontiers in Agronomy*, 2, article number 547758. doi: [10.3389/fagro.2020.547758](https://doi.org/10.3389/fagro.2020.547758).
- [18] Pikovsky, M.Y., Kyryk, M.M., & Konup, L.O. (2023). *Pathology of agricultural seeds*. Kyiv: Editorial and Publishing Department of NULES of Ukraine.
- [19] Pikovskiy, M., & Solomiichuk, M. (2022). Identification of mycobiota and diagnosis of soybean seed diseases. *Plant and Soil Science*, 13(1), 44-50. doi: [10.31548/agr.13\(1\).2022.44-50](https://doi.org/10.31548/agr.13(1).2022.44-50).
- [20] Sanna, M., Pugliese, M., Gullino, M.L., & Mezzalama, M. (2022). First report of *Trichoderma afroharzianum* causing seed rot on maize in Italy. *Plant Disease*, 106(7), article number 1982. doi: [10.1094/PDIS-12-21-2697-PDN](https://doi.org/10.1094/PDIS-12-21-2697-PDN).
- [21] Shabana, Y.M., Ghoneem, K.M., Rashad, Y.M., Arafat, N.S., Fitt, B.D.L., Richard, B., & Qi, A. (2022). Distribution and biodiversity of seed-borne pathogenic and toxigenic fungi of maize in Egypt and their correlations with weather variables. *Plants*, 11, article number 2347. doi: [10.3390/plants11182347](https://doi.org/10.3390/plants11182347).
- [22] Spriazhka, R., Zhemoida, V., Makarchuk, O., Dmytrenko, Yu., & Lehenkyi, B. (2024). Combining ability of inbred maize lines in breeding for grain quality. *Plant and Soil Science*, 15(4), 50-63. doi: [10.31548/plant4.2024.50](https://doi.org/10.31548/plant4.2024.50).
- [23] Sreenu, B., Girish, A.G., & Alice, R.P.S. (2019). Identification and detection of maize seed-borne pathogens using different seed testing methods. *International Journal of Current Microbiology and Applied Sciences*, 8(10), 1460-1466. doi: [10.20546/ijcmas.2019.810.171](https://doi.org/10.20546/ijcmas.2019.810.171).
- [24] Sun, H., Guo, N., Ma, H., Liu, S., & Shi, J. (2022). First report of maize ear rot caused by *Exserohilum rostratum* in Hainan Province in Southern China. *Plant Disease*, 106(1), article number 314. doi: [10.1094/PDIS-01-21-0044-PDN](https://doi.org/10.1094/PDIS-01-21-0044-PDN).
- [25] Warham, E.J., Butler, L.D., & Sutton, B.C. (1996). *Seed testing of maize and wheat – a laboratory guide*. Mexico: Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT).
- [26] Watanabe, T. (2002). *Pictorial atlas of soil and seed fungi: Morphologies of cultured fungi and key to species* (2nd ed.). Boca Raton: CRC Press.

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Анотація. Кукурудза є стратегічною культурою, попит на яку зростає, що зумовлює необхідність збільшення виробництва та використання здорового насіння для підвищення врожайності й якості продукції. Метою роботи було дослідити симптоматику грибних хвороб насіння кукурудзи та встановити поширення мікроміцетів. Вивчення хвороб качанів і насіння кукурудзи здійснювали у проблемній науково-дослідній лабораторії Мікології і фітопатології кафедри фітопатології Національного університету біоресурсів і природокористування України. Зразки рослинного матеріалу (качанів) для діагностики відбирали під час маршрутних обстежень в умовах Лісостепу України та під час періоду їх зберігання. Проби насіння були відібрані після збирання врожаю. Діагностику хвороб здійснювали шляхом візуального огляду і біологічним методом (пророщування насіння у вологих камерах та на поживному середовищі). Для ідентифікації мікроміцетів проводили мікроскопічний аналіз їх морфологічних структур. Частоту трапляння мікроміцетів встановлювали під час пророщування насіння у чашках Петрі на фільтрувальному папері. Під час досліджень виявлено інфікування качанів і зерна кукурудзи різними мікроміцетами (*Trichothecium* spp., *Fusarium* spp., *Alternaria* spp., *Cladosporium* spp., *Aspergillus* spp., *Mucor* spp., *Penicillium* spp., *Rhizopus* spp.), що зумовлювали мінливість симптомів хвороб. Встановлено паразитування на качанах кукурудзи грибів *Botrytis cinerea* та *Bipolaris* spp., яке у вітчизняній науковій літературі не розкрито. Найвищою частотою трапляння на насінні кукурудзи характеризувалися представники роду *Alternaria* – 18,4 %. Гриби родів *Cladosporium* та *Penicillium* виявлялися відповідно на 4,5 та 4,7 % насінин. Інфікованість насіння *Fusarium* spp. становила 2,7 %, *Mucor* spp. – 2,6 %. Представників роду *Rhizopus* ідентифіковано на 1,1 % насінин. Гриби родів *Trichothecium* та *Aspergillus* становили 0,4 та 0,6 %. Тому, моніторинг збудників грибних хвороб та його фітопатологічна експертиза є необхідними для оцінки якості насіння кукурудзи. Інформацію щодо симптоматики мікозів, видового складу мікроміцетів слід використовувати під час діагностики патологій насіння

Ключові слова: діагностичні ознаки; пліснявіння; фузаріоз; мікроміцети; зерно; проростання



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Root intake of ^{137}Cs in pasture grasses

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Abstract. The accumulation of ^{137}Cs in plants can carry risks to animal and human health due to its entry into the body through the food chain. The purpose of the study was to estimate the transition coefficients ^{137}Cs in pasture mixed grasses from the dominant soil types of Ukraine and their dynamics during the growing season. The experiment was conducted on three types of soils, namely: sod-podzolic loam, podzolic chernozem, and typical chernozem. Soils for the experiment were selected in the Kyiv and Zhytomyr oblasts. The density of artificial surface contamination of all soils was the same and amounted to 336 kBq m^{-2} . Radionuclide was applied to the soil surface in a water-soluble form. The plants were grown in a greenhouse in pots with regular watering without fertilisation. The results obtained showed that bioavailability of ^{137}Cs is determined by soil conditions and significantly decreases in the series: sod-podzolic soil > podzolic chernozem > typical chernozem. The obtained average values of the radionuclide transition coefficients to grass for the first mowing ranged from 50 to 4 ($\text{Bq}\cdot\text{kg}^{-1}$) / ($\text{kBq}\cdot\text{m}^{-2}$) and were maximal for sod-podzolic soil. At the end of the growing season, bioavailability of ^{137}Cs significantly decreased by half for sod-podzolic soil and typical chernozem.

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No significant changes in the bioavailability of radionuclide were observed on podzolic chernozem. The accumulation coefficients of the stable isotope of caesium (^{133}Cs) are estimated. Compared to the radioactive isotope, stable caesium is characterised by significantly lower bioavailability for plants, but the nature of its dependence on soil conditions is identical to that of ^{137}Cs . Since stable caesium is in the soil in a state of equilibrium, the coefficients of its accumulation by the mixture of grasses did not change during the growing season. The obtained transition parameters, in accordance with soil conditions, can be used in radiological models for conservative estimation of radiation doses of radiation exposure to the population in the first year after radionuclide entry into the environment

Keywords: ^{137}Cs ; bioavailability; transition coefficient; caesium; radionuclides; soils, vegetation

Introduction

Technogenic radionuclides enter the environment with emissions from nuclear fuel cycle plants and nuclear power plants (NPPs), with global fallouts after nuclear weapons tests, and as a result of accidents at nuclear facilities. Examples of such major radiation accidents were those at the Chernobyl NPP and the Fukushima Daiichi NPP. In both cases, significant caesium radioisotopes were released into the environment. In addition, now there is a real threat of the use of nuclear weapons on the territory of Ukraine, as a result of which certain territories may be exposed to radioactive contamination. After a certain time following soil contamination (usually in the next growing season), radionuclides begin to enter plants via root, including cultivated plants, which are used for food production. With food, radionuclides enter the human body and irradiate it. One of the radiologically significant technogenic radionuclides is long-lived ^{137}Cs (half-life – 30.08 years), which is a fission product of ^{235}U and ^{239}Pu and is characterised by a high fission yield of about 6%. This radionuclide is characterised by high bioavailability and is one of the main dose-forming radionuclides among fission products. An important way for this radionuclide to enter the human body is the pasture-animals-milk (meat) chain. The main part of internal dose from ^{137}Cs to humans is formed in this way. Given that “fresh” deposition of this radionuclide can be nonequilibrium in the soil environment, information about the dynamics of its bioavailability is extremely important. Some of

the radioactive isotopes of caesium are irreversibly absorbed by soil minerals after entering the soil, and their bioavailability decreases over time. This process is called “ageing”. It leads to a decrease in the accumulation coefficients of this radionuclide in the soil over time (Park *et al.*, 2019).

In the natural environment (earth’s crust, clay minerals, etc.), there is only one stable isotope of caesium – ^{133}Cs . The average concentrations of this element are about 1 mg/kg in granites and 4 mg/kg in sedimentary rocks. In soils, the gross concentration of caesium ranges from 0.3 to 25 mg/kg (International Atomic Energy Agency (IAEA), 2009). As for the behaviour in the soil-plant chain, the chemical behaviour of technogenic radioactive isotopes of caesium is considered identical to that of stable caesium. H. Tsukada *et al.* (2023) observed close bioavailability values of stable caesium and a radioactive isotope ^{137}Cs when they enter potatoes from the soil. Stable caesium behaviour analysis is used to understand the long-term behaviour of radiocaesium and its equilibrium distribution in soils. Thus, the naturally occurring stable isotope ^{133}Cs , which is in an equilibrium state in soil, can be a useful analogue for estimating the accumulation rates of its radioactive isotope ^{137}Cs .

V. Kashparov *et al.* (2020) showed that an important factor affecting the plant uptake of radiocaesium is its initial physical and chemical forms in fallout. In the case of the Chernobyl accident, a significant part of radiocaesium in

radioactive fallout in the near-accident zone (10 km) was in the composition of fuel particles and was not available for plant assimilation for some time. The dynamics of the bioavailability of radiocaesium and radiostrontium in this area were determined by the superposition of the processes of their adsorption by soil and leaching from fuel particles.

The soil plays an important role in the root uptake of radionuclides by plants. When plants uptake radionuclides from an aqueous solution, radiocaesium is the most biologically available in comparison with other radionuclides ($^{137}\text{Cs} > ^{90}\text{Sr} > ^{144}\text{Ce} > ^{106}\text{Ru} > ^{95}\text{Zr}$). According to M. Vanheulelom *et al.* (2023), when growing plants on soil, the bioavailability of ^{90}Sr decreases by about 20 times, whereas ^{137}Cs – by 100-1,000 times. The reason for this is the absorption of radionuclides by the soil. In general, the influence of soil is manifested in a decrease in the bioavailability of radiocaesium with an increase in its content of exchange cations, organic matter, physical clay, montmorillonite minerals, and absorption capacity (Kang & Tazoe, 2024). M. Vinichuk *et al.* (2025) observed higher accumulation rates on sandy loam and organic soils, and lower accumulation rates on soils with a high clay content. In addition, this paper shows that the bioavailability of caesium for grasses in the first few years after deposition rapidly decreased with subsequent plateau release.

The bioavailability of caesium and radiocaesium is affected by the presence of other chemical elements in the soil, especially potassium. The average concentration of potassium in the soil solution is about 10^{-3} m/l, whereas the concentration of activity ^{137}Cs in a soil solution of 1 Bq/l approximately corresponds to its concentration of $2 \cdot 10^{-15}$. M. Syaifudin *et al.* (2023) showed that an increase in the concentration of potassium available to plants in the soil leads to a decrease in the intake of caesium into plants.

According to the latest study by Ukrainian researchers, despite almost forty years after the Chernobyl accident, a significant part of the territory of Ukraine remains radioactively

contaminated (Kyrylchuk & Palamarchuk, 2022), and radionuclides enter agricultural products (Snitynskyi *et al.*, 2023). Studies aimed at radiological safety of the population remain relevant. In general, as numerous studies show, the accumulation of caesium by plants is characterised by great variability, which is mainly determined by local soil and climatic conditions. Experimental parameters that consider these local features on a national scale are needed to reduce the uncertainty of predictive estimates. In Ukraine, there are currently no data on the accumulation of ^{137}Cs by grasses in the first growing season after its release into the environment.

The purpose of the study was to estimate the transfer coefficients of ^{137}Cs in pasture mixed grasses from the dominant soil types of Ukraine and their dynamics during the growing season.

Materials and Methods

Scheme of a vegetative experiment. The assessment was carried out in a laboratory experiment simulating “fresh” radionuclide deposition in soluble form before the beginning of the growing season. The study was conducted according to the Convention on Biological Diversity (1992). To investigate the accumulation of ^{137}Cs by a mixture of perennial grasses (ryegrass 60%), 4-litre plastic pots filled with air-dry soil were used. Soil moisture was increased to 60% of their field moisture capacity by adding the appropriate amount of water. The experiment used three types of soils that were selected in Zhytomyr and Kyiv oblasts, namely: sod-podzolic loam; ordinary chernozem; and podzolic chernozem. For each soil type, the experiment included three parallels and a control (without radionuclide application). Grass sowing was carried out on 12.04.2024 with the recommended seeding rate of 3.5 g m^{-2} . After sowing, 9.51 kBq (336 kBq m^{-2}) of ^{137}Cs was applied to the soil surface in each pot. An aqueous solution (50 ml) of radionuclide was evenly distributed over the soil surface using a dispenser. During the experiment, three grass mowing operations were performed. The grass was cut at a height of 1 cm

above the ground. The resulting grass samples were dried at 105°C to a constant mass and homogenised using a laboratory mill. The obtained samples were transferred to sealed plastic vials for storage and subsequent measurement of ^{137}Cs activity and concentrations of stable caesium.

Analytical methods. Specific activity of ^{137}Cs in pre-prepared soil and vegetation samples was measured on gamma-ray spectrometers with semiconductor (GEM-30185, “EG & ORTEC”, USA) and scintillation detectors (SEG-01, “AKP”, Ukraine). The measurements were carried out in polypropylene containers with a volume of 100 cm³ and in Marinelli vessels with a volume of 1,000 cm³. The spectrometers were calibrated using certified secondary radionuclide standards in accordance with the requirements of the standardised method (ASTM E181-10, 2010). Specific activity of ^{137}Cs and the concentration of its stable isotope in grass and soil samples were calculated for absolute dry weight.

The concentration of stable caesium in grass and soil samples was determined on a Nexlon 2000b inductively coupled plasma mass spectrometer (PerkinElmer, USA). The samples were prepared using the Ethos Up microwave decomposition system (Milestone, USA).

Agrochemical properties of soils were determined by standardised methods (DSTU 4405:2005, 2005; DSTU 7863:2015, 2015; ISO 10390:2021, 2021; ISO/TS 22171:2023, 2023) using appropriate equipment.

To determine the quantitative parameters of the dependence of the transfer of radionuclide from soils to a mixture of grasses on soil properties, the aggregated transfer factor (T_{ag}) was used. T_{ag} defined as the ratio of the mass specific activity of ^{137}Cs in grass (Bq·kg⁻¹, dry weight) to the density of the soil radionuclide contamination (kBq·m⁻²) on which it was grown. For the stable isotope, the concentration ratio (CR), defined as ^{133}Cs concentration in the grass (mg·kg⁻¹, dry weight) divided by that in the soil (mg·kg⁻¹, dry weight) on which it was grown, was used.

Results and Discussion

Before the experiment, the main agrochemical properties of soils and their contamination with ^{137}Cs were determined. The ^{137}Cs contamination was formed as a result of nuclear weapons tests and the Chernobyl accident. Soils are characterised by a low level of radioactive contamination (Table 1). Radioactive contamination of chernozems was close to the level of global fallout. Such contamination levels will not affect the experiment, since the introduced activity exceeds them by 2 orders of magnitude. In general, in terms of nutrient supply, sod-podzolic soil is classified as low, podzolic chernozem is close to the middle class, and typical chernozem is to middle class (Table 1). The content of mobile potassium, which affects the accumulation of ^{137}Cs in plants, in this series varies from 70 to 220 mg kg⁻¹.

Table 1. Main agrochemical characteristics of soils and their contamination density with ^{137}Cs (for horizon 0-10 cm)

Soil type	^{137}Cs , kBq m ⁻²	pH (H ₂ O)	pH (KCl)	LOI*, %	Exchange K, mg kg ⁻¹	Exchange Ca, mg kg ⁻¹	Alkaline hydr. nitrogen, mg kg ⁻¹	Mobile phosphorus, mg kg ⁻¹
sod-podzolic gleyed	6.4±1.9	6.6	5.6	2.7	70	420	66	30
podzolic chernozem	1.6±0.5	5.7	4.5	5.9	104	1620	94	99
typical chernozem	0.7±0.2	7.8	7.1	7.1	222	2,250	95	167

Note: * – Loss on Ignition

Source: compiled by the authors

The radionuclide specific activity in samples of grass grown on sod-podzolic soil was the highest and 10 times higher than in grass grown on

typical chernozem. Grass contamination on podzolic chernozem was twice as high as grass contamination on typical chernozem. The maximum

standard deviations between parallels were about 10%. Over time, there was a significant decrease in accumulation of ^{137}Cs in perennial grasses (Table 2). During the growing season, the specific ac-

tivity of radionuclide decreased in grass grown on sod-podzolic soil and typical chernozem by about 2 times. No significant decrease was observed for podzolic chernozem.

Table 2. Specific activity of ^{137}Cs in grass samples (for completely dry weight)

Soil type	Repeatability	^{137}Cs , Bq kg $^{-1}$		
		Cutting 29.05.24	Cutting 16.07.24	Cutting 01.09.24
sod-podzolic gleyed	control	29 ± 17	24 ± 15	33 ± 16
	1	15,390 ± 920	15,040 ± 750	8,400 ± 750
	2	17,050 ± 1,200	13,610 ± 820	7,070 ± 710
	3	18,040 ± 1,260	11,900 ± 830	7,150 ± 720
	Mean ± SD	16,830 ± 1,340	13,520 ± 1,570	7,540 ± 750
podzolic chernozem	control	<4	<5	<4
	1	2,940 ± 270	4,290 ± 390	2,950 ± 470
	2	3,000 ± 270	3,880 ± 310	3,450 ± 520
	3	2,860 ± 140	4,710 ± 380	5,300 ± 850
	Mean ± SD	2,930 ± 70	4,290 ± 420	3,900 ± 1,240
typical chernozem	control	28 ± 16	18 ± 8	21 ± 9
	1	1,650 ± 130	1,420 ± 140	730 ± 90
	2	1,250 ± 150	910 ± 90	810 ± 160
	3	1,540 ± 150	760 ± 40	650 ± 110
	Mean ± SD	1,480 ± 210	1,030 ± 340	730 ± 110

Source: compiled by the authors

The results showed a significant difference in accumulation of ^{137}Cs in perennial grasses from different soils (Fig. 1). The highest values of aggregated transfer factors were obtained for the first mowing on sod-podzolic soil. This soil is characterised by the lowest content of exchangeable potassium, organic matter (Table 1), and the dispersed composition is dominated by coarse fractions of physical sand. Such characteristics are favourable for high bioavailability of caesium (Sinchenko, 2021). The value of the average T_{ag} value for sod-podzolic soil was 50 (Bq kg $^{-1}$)/(kBq m $^{-2}$) and exceeded the value obtained in 1987 for the sown grasses hay by averaging a large array of data, by ten times (Ukrainian Institute of Agricultural Radiology (UIAR), 1998). Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments (International Atomic Energy Agency (IAEA), 2010) recommends using a concentration ratio of 0.084 to estimate the transfer of

radiocaesium from sandy soil to grasses, which is approximately equal to a T_{ag} of 0.750 (Bq kg $^{-1}$)/(kBq m $^{-2}$). This recommended value is significantly lower than the parameters obtained, and its use for forecasting may lead to an underestimated evaluation of the radionuclide uptake by vegetation. The average value of the ^{137}Cs aggregated transfer factor for the grass obtained for typical chernozem in the first mowing was at the level of 4 (Bq kg $^{-1}$)/(kBq m $^{-2}$), which also differs by an order of magnitude from the data of 1987 (Ukrainian Institute of Agricultural Radiology (UIAR), 1998). Y. Khomutinin *et al.* (2022) presented current results on the accumulation of ^{137}Cs in pasture vegetation in natural meadows (meadow-swamp soils). In such landscapes, this radionuclide is still characterised by high bioavailability (T_{ag} 5 (Bq kg $^{-1}$)/(kBq m $^{-2}$)). But even this value of the transition coefficient is significantly lower than those obtained in the experiment for sod-podzolic soil.

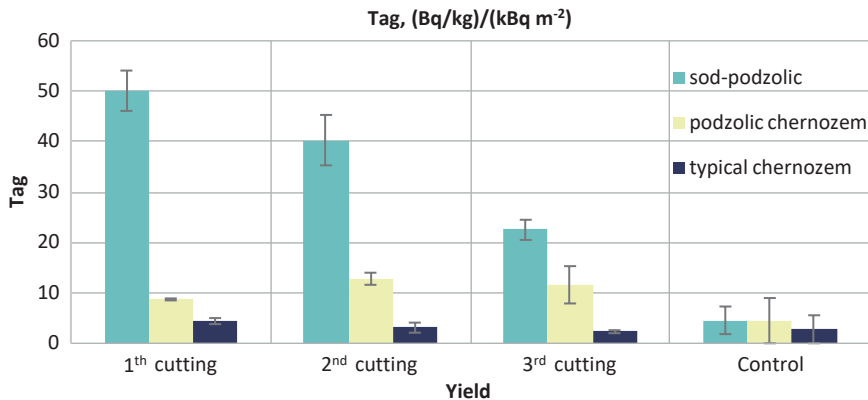


Figure 1. Dynamics of ^{137}Cs intake into a mixture of grasses from different soils in a laboratory experiment during the growing season

Note: surface contamination of the soil after sowing grass ($336 \pm 34 \text{ kBq m}^{-2}$)

Source: compiled by the authors

During the growing season, T_{ag} values for sod-podzolic soil and typical chernozem significantly decreased by half. The results of the experiment for podzolic chernozem showed that the average T_{ag} value in the first cutting for podzolic chernozem was $9 \pm 4 \text{ (Bq kg}^{-1})/(\text{kBq m}^{-2})$ and in the future, its decrease was not observed (Fig. 1). This behaviour of ^{137}Cs in the soil-plant chain may be related to the acidity index of this soil (Table 1). T_{ag} values were also calculated for the control variants. They characterise the bioavailability of the radionuclide (its ageing), which has been in the soil for about 40 years. Unfortunately, these values are characterised by great uncertainty, as grass contamination was very low for all soils. But even this information indicates that the process of absorption of fresh deposition occurs quite slowly (Fig. 1), especially for soils of light mechanical composition. M. Vinichuk *et al.* (2025) assessed the dynamics of ^{137}Cs transfer coefficients from different soils in Sweden to natural and cultivated grasses. According to the researchers, in loamy soils, T_{ag} values decreased from units to plateaus below $0.01 \text{ (Bq kg}^{-1})/(\text{kBq m}^{-2})$ approximately 3-5 years after radioactive fallout, whereas in soils with an intermediate clay content, this process took approximately 12-15 years. These data correlate well with the results obtained.

The concentration of the stable isotope of caesium ^{133}Cs was also determined in soil and grass samples. The gross concentration of ^{133}Cs was the lowest (0.6 mg kg^{-1}) in sod-podzolic soil, and in podzolic chernozem – the highest (2.2 mg kg^{-1}). Stable element transfer parameters are usually used when radionuclide data are not available. For example, if it is necessary to determine the values of transport parameters in areas of low radionuclide contamination, where radionuclide concentrations in food or wildlife are beyond detection. C.L. Barnett *et al.* (2020) conducted a study in this area and showed that the intake of ^{137}Cs and stable Cs in plants are characterised by a good correlation, but has some differences. A number of studies have shown that the ^{137}Cs accumulation coefficients were several times higher than for stable ^{133}Cs , despite a fairly long presence of ^{137}Cs in the soil (Guillén *et al.*, 2022). Stable Cs is mainly retained in primary and clay minerals, so the coefficient of its accumulation by plants may be lower than that of ^{137}Cs , which is of man-made origin. To correctly compare the bioavailability of radioactive and stable caesium, it is necessary to use not their gross concentrations in the soil, but the concentrations of their exchange forms. H. Tsukada *et al.* (2023) proposed an approach based on the following relations for

estimating accumulation parameters: $^{137}\text{Cs}/\text{Cs}$ in the exchange fraction of soil and concentrations of stable Cs in plants and showed that the approach allows more accurately predicting the concentration of ^{137}Cs activity in cultures compared to methods based on accumulation coef-

ficients. The main disadvantage of this method is that it cannot be used with a low level of soil contamination with ^{137}Cs . Using the concentrations of this isotope in grass samples and the corresponding values of soil concentrations, its bioavailability was estimated (Fig. 2).

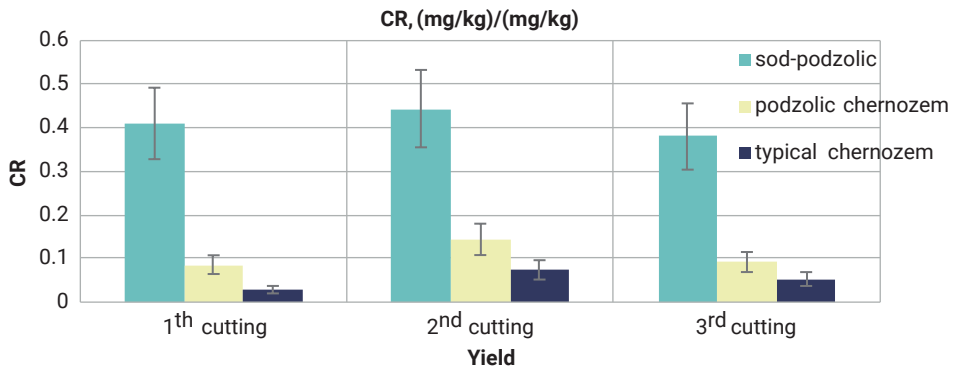


Figure 2. Dynamics of ^{137}Cs (stable) intake into a mixture of grasses from different soils in a laboratory experiment during the growing season

Source: compiled by the authors

In this case, the concentration of ^{133}Cs acid-soluble forms in soils was used to calculate the concentration ratios. The concentration ratios correlate with the aggregated transfer factors for the radioactive isotope depending on soil type – for sod-podzolic soil, they are maximal, and for typical chernozem, they are minimal. The finding does not contradict the studies by C.L. Barnett *et al.* (2020) and J. Guillén *et al.* (2022). The parameters obtained at the end of the growing season for the transfer of radiocaesium from soils to grasses are more than 10 times higher those obtained for its stable isotope. Moreover, such differences were observed for all soils (Fig. 1, 2). Since stable caesium is in the soils in a state of equilibrium, the values of the concentration ratios do not change significantly during the experiment (Fig. 2). It was these data that were necessary to confirm the absence of external factors during the experiment that could affect the bioavailability of caesium.

The results of the experiment on the bioavailability of caesium reflect the features of the

behaviour of this element in the soil-plant chain in relation to the dominant soils of Ukraine. Numerical values of transfer factors can be used for conservative assessment of ^{137}Cs contamination of pasture vegetation, and, accordingly, contamination of livestock products in the first year after radionuclide enters the environment.

Conclusions

Experiments have shown that the bioavailability of ^{137}Cs and its stable isotope is determined by soil properties and fall significantly in the following series: sod-podzolic soil > podzolic chernozem > typical chernozem. Differences in the accumulation of ^{137}Cs by a mixture of perennial grasses between contrasting soils under experimental conditions reached one order of magnitude. The data obtained showed that during the growing season, the bioavailability of ^{137}Cs in sod-podzolic soil and typical chernozem significantly decreased by half. The values of aggregated transfer factors of ^{137}Cs for the grass mixture at the end of the growing

season significantly exceeded the corresponding parameters recommended by the International Atomic Energy Agency for predictive estimates of radionuclide contamination of vegetation. This finding confirms the fact that the bioavailability of ^{137}Cs depends on its residence time in the soil. The use of the radionuclide transfer parameters, which were obtained in the distant period after a radiation accident, for predictive estimates of plant contamination in the first vegetation period will lead to underestimated results.

For more information on the behaviour of caesium in the soil-plant chain, the accumulation rates of the stable isotope caesium in perennial grasses were estimated. The gross concentration of this trace element in soils varied in the range of 0.6-2.2 mg/kg. Compared to the radioactive isotope, stable caesium was characterised by significantly lower bioavailability for plants, which did not significantly change during the growing season. This confirms that stable caesium is in

a certain equilibrium state in the soil. A strong linear relationship was observed between the parameters of vegetation accumulation of stable and radioactive caesium isotopes, but the proportionality coefficient was different from one.

Research on studying the dynamics of radionuclide intake from fresh radioactive fallout into pasture vegetation will continue with the extension of the observation period to 2-3 vegetation periods. In addition to ^{137}Cs , the experiment is planned to include another long-lived and radiologically significant radionuclide ^{90}Sr .

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Conflict of Interest

None.

References

- [1] ASTM E181-10. (2010) *Standard test methods for detector calibration and analysis of radionuclides (ASTM E181-10)*. Retrieved from <https://www.astm.org/e0181-10.html>.
- [2] Barnett, C.L., Beresford, N.A., Wood, M.D., Izquierdo, M., Walker, L.A., & Fawkes, R. (2020). Element and radionuclide concentrations in soils and wildlife from forests in north-eastern England with a focus on species representative of the ICRP's Reference Animals and Plants. *Earth System Science Data*, 12(4), 3021-3038. doi: 10.5194/essd-12-3021-2020.
- [3] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.
- [4] DSTU 4405:2005. (2005). *Soil quality. Determination of mobile phosphorus and potassium compounds by Kirsanov's method modified by NRC ISSAR*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=60252.
- [5] DSTU 7863:2015. (2015). *Soil quality. Determination of readily hydrolyzable nitrogen by Kornfeld's method*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=62745.
- [6] Guillén, J., Beresford, N., Baigazinov, Z., Salas, A., & Kunduzbaeva, A. (2022). Can stable elements (Cs and Sr) be used as proxies for the estimation of radionuclide soil-plant transfer factors? *Environmental Pollution*, 299, article number 118897. doi: 10.1016/j.envpol.2022.118897.
- [7] International Atomic Energy Agency (IAEA). (2009). *Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments*. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/te_1616_web.pdf.
- [8] International Atomic Energy Agency (IAEA). (2010). *Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Technical Reports series No. 472*. Retrieved from <https://surl.li/dyalgx>.

- [9] ISO/TS 22171:2023. (2023). *Soil quality – determination of potential cation exchange capacity (CEC) and exchangeable cations buffered at pH 7, using a molar ammonium acetate solution*. Retrieved from <https://www.iso.org/standard/80891.html>.
- [10] ISO-10390:2021. (2021). *Soil, treated biowaste and sludge – determination of pH*. Retrieved from <https://www.iso.org/standard/75243.html>.
- [11] Kang, D., & Tazoe, H. (2024). Impacts of soil type and drought stress on growth and cesium accumulation in Napier grass. *Environmental Geochemistry and Health*, 46(7), article number 235. [doi: 10.1007/s10653-024-02023-1](https://doi.org/10.1007/s10653-024-02023-1).
- [12] Kashparov, V., Salbu, B., Simonucci, C., Levchuk, S., Reinoso-Maset, E., Lind, O., Maloshtan, I., Protsak, V., Courbet, C., & Nguyen, H. (2020). Validation of a fuel particle dissolution model with samples from the Red Forest within the Chernobyl exclusion zone. *Journal of Environmental Radioactivity*, 223-224, article number 106387. [doi: 10.1016/j.jenvrad.2020.106387](https://doi.org/10.1016/j.jenvrad.2020.106387).
- [13] Khomutinin, Y., Kosarchuk, O., Polishchuk, S., Lazarev, M., Levchuk, S., & Pavliuchenko, V. (2022). Assessment of the possibility of a return to the original use of pastures and hayfields abandoned after the Chernobyl accident. *Nuclear Physics and Atomic Energy*, 23(1), 47-56. [doi: 10.15407/jnpae2022.01.047](https://doi.org/10.15407/jnpae2022.01.047).
- [14] Kyrylchuk, A., & Palamarchuk, R. (2022). Dynamics of ¹³⁷Cs and ⁹⁰Sr content in the soil cover of agricultural lands in Zhytomyr region. *Agroecological Journal*, 4, 84-92. [doi: 10.33730/2077-4893.4.2022.273254](https://doi.org/10.33730/2077-4893.4.2022.273254).
- [15] Park, S.-M., Alessi, D.S., & Baek, K. (2019). Selective adsorption and irreversible fixation behavior of cesium onto 2:1 layered clay mineral: A mini review. *Journal of Hazardous Materials*, 369, 569-576. [doi: 10.1016/j.jhazmat.2019.02.061](https://doi.org/10.1016/j.jhazmat.2019.02.061).
- [16] Sinchenko, V. (2021). Methodological aspects of beta-spectrometric method of control over radiation safety of agricultural and fishing products. *Ecological Safety and Balanced Use of Resources*, 12(1), 60-72. [doi: 10.31471/2415-3184-2021-1\(23\)-60-72](https://doi.org/10.31471/2415-3184-2021-1(23)-60-72).
- [17] Snitynskyi, V., Razanov, S., Hnativ, P., Bakhmat, O., Kutsenko, M., & Kolisnyk, O. (2023). Phytoremediation of ¹³⁷Cs contaminated sod-podzolic soil in Northern Polissia white sweet clover (*Melilotus albus*). *International Journal of Environmental Studies*, 81(1), 223-229. [doi: 10.1080/00207233.2023.2270305](https://doi.org/10.1080/00207233.2023.2270305).
- [18] Syaifudin, M., Suzuki, M., Maruyama, H., Kubo, K., Watanabe, T., & Shinano, T. (2023). Potassium applications reduced cesium uptake and altered strontium translocation in soybean plants. *Soil Science & Plant Nutrition*, 69(2), 88-98. [doi: 10.1080/00380768.2023.2166776](https://doi.org/10.1080/00380768.2023.2166776).
- [19] Tsukada, H., Takeda, A., Takahashi, T., Fukutani, S., Akashi, M., Takahashi, J., Uematsu, S., Chyzhevskiy, I., Kirieiev, S., Kashparov, V., & Zheleznyak, M. (2023). Transfer of ¹³⁷Cs and ⁹⁰Sr from soil-to-potato: Interpretation of the association from global fallout in Aomori to accidental release in Fukushima and Chernobyl. *The Science of the Total Environment*, 899, article number 165467. [doi: 10.1016/j.scitotenv.2023.165467](https://doi.org/10.1016/j.scitotenv.2023.165467).
- [20] Ukrainian Institute of Agricultural Radiology (UIAR). (1998). *Management of agriculture in the conditions of radioactive contamination of the territory of Ukraine due to the accident at the Chernobyl NPP for 1999-2002. (Methodological recommendations)*. Kyiv: UIAR.
- [21] Vanheukelom, M., Sweeck, L., Van Hees, M., Weyns, N., Van Orshoven, J., & Smolders, E. (2023). Quantitative clay mineralogy predicts radiocesium bioavailability to ryegrass grown on reconstituted soils. *The Science of the Total Environment*, 873, article number 162372. [doi: 10.1016/j.scitotenv.2023.162372](https://doi.org/10.1016/j.scitotenv.2023.162372).

[22] Vinichuk, M., Simonsson, M., Larsson, M., & Rosén, K. (2025). Long-term transfer of ^{137}Cs in sensitive agricultural environments after the Chernobyl fallout in Sweden. *Journal of Environmental Radioactivity*, 282, article number 107621. doi: [10.1016/j.jenvrad.2025.107621](https://doi.org/10.1016/j.jenvrad.2025.107621).

Кореневе надходження ^{137}Cs у пасовищні трави

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Анотація. Накопичення ^{137}Cs у рослинах може нести ризики для здоров'я тварин і людей через його надходження в організм по харчовому ланцюжку. Метою роботи була оцінка коефіцієнтів переходу ^{137}Cs у пасовище різнотрав'ям з домінуючих типів ґрунтів України та їх динаміки на протязі вегетаційного періоду. Експеримент проводився на трьох типах ґрунтів, а саме: дерново-підзолистому суглинистому, чорноземі опідзоленому та чорноземі типовому. Ґрунти для експерименту відбирались в Київській та Житомирській областях. Щільність штучного поверхневого забруднення усіх ґрунтів була однаковою і склала 336 кБк м^{-2} . Радіонуклід вносився на поверхню ґрунту у водорозчинній формі. Рослини вирощувались в теплиці в горщиках з регулярним поливом без внесення добрив. Отримані результати показали, що біологічна доступність ^{137}Cs визначається ґрунтовими умовами і достовірно спадає в ряду: дерново-підзолистий ґрунт > опідзолений чорнозем > типовий чорнозем. Отримані середні значення коефіцієнтів переходу радіонукліда в траву для першого укусу коливались в межах від 50 до 4 ($\text{Бк}\cdot\text{кг}^{-1}$)/($\text{кБк}\cdot\text{м}^{-2}$) і були максимальними для дерново-підзолистого ґрунту. В кінці вегетаційного періоду біологічна доступність ^{137}Cs достовірно зменшилась в два рази для дерново-підзолистого ґрунту та типового чорнозему. На опідзоленому чорноземі достовірної зміни біологічної доступності радіонукліду не спостерігалось. Оцінено коефіцієнти накопичення стабільного ізотопу цезію (^{133}Cs). У порівнянні з радіоактивним ізотопом стабільний цезій характеризується значно нижчою біологічною доступністю для рослин, але характер її залежності від ґрунтових умов тотожний такій для ^{137}Cs . Оскільки стабільний цезій знаходиться у ґрунті в стані рівноваги коефіцієнти його накопичення сумішшю трав протягом вегетаційного періоду не змінювались. Отримані параметри переходу, відповідно до ґрунтових умов, можуть використовуватись в радіологічних моделях для консервативної оцінки радіаційних доз опромінення населення в перший рік після надходження радіонукліду в оточуюче середовище

Ключові слова: ^{137}Cs ; біологічна доступність; коефіцієнт переходу; цезій, радіонукліди; ґрунти; рослинність

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