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## Global food security: Challenges in achieving the Sustainable Development Goals

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**Abstract.** The aim of this study was to substantiate the peculiarities of the current state of global food security. In the process of writing the article, the following methods were applied: bibliometric analysis (using Google Analytics, Vosviewer v.1.6.18 and SciVal), system-structural analysis and synthesis, historical, dialectical, graphical and descriptive-statistical methods. The article clarifies the essence of the economic category “global food security”, which is considered as a state of the world food system, in which all people in all regions of the world have physical, social and economic access to an adequate volume of safe, high-quality, nutritious and wholesome food to ensure an active and healthy life over the long term. It is noted that advancement toward fulfilling the 2<sup>nd</sup> Sustainable Development Goal “ending hunger” is insufficient and uneven. In 2023, more than 700 million individuals in the world suffered from hunger, and 29% of the world’s population faced food insecurity. Forecasts show that achieving the 2<sup>nd</sup> Sustainable Development Goal by 2030 will be impossible without increased efforts and innovation. It has been established that the dynamics of food insecurity vary greatly between regions. The situation is the worst in Africa, with the food insecurity rate reaching 58% in 2023. Conflict, extreme climate events, economic crises and income inequality are the main factors that worsen the food security situation. These factors create a synergistic negative impact, especially in countries with low and middle incomes, and require the development of comprehensive measures to address food security issues. The study’s practical value is found in the application of the results of the food security monitoring, which will contribute to the adoption of effective solutions to overcome hunger and achieve the goals of sustainable development

**Keywords:** risk of hunger; malnutrition; food affordability; inequality in access to food; access to safe food; conflicts and food crisis

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## INTRODUCTION

One of the primary challenges of modernity is to ensure food security, particularly in the context of global economic and environmental change. Despite the significant progress made in the fight against hunger, millions of people worldwide continue to experience malnutrition and limited access to quality food. In addition, the effects of climate change, dwindling natural resources and economic crises are making it harder to achieve the Sustainable Development Goals, including goal No. 2, which is to end hunger. Scientific research in this area is important for creating effective strategies to ensure food security at the global level and fulfil international commitments. Success in achieving these goals depends on a comprehensive approach that considers economic, social, and environmental factors, which is why analysing the current state and challenges is critical to formulating long-term solutions for sustainable development. This cross-cutting issue remains unresolved in 2024 and meets the most pressing needs of the economy and society.

F. Lin *et al.* (2023) analysed the effect of martial law in Ukraine on global food security trends. The authors developed three forecast scenarios, according to which wheat trade is expected to decline by 60%, prices to rise by 50%, and serious food insecurity, particularly for countries that depend on wheat imports from Ukraine. Given Ukraine's role in the agricultural sector, food prices in some countries could rise by 10-30%, and welfare losses could be 15-25%. The authors X.-Y. Zhou *et al.* (2023) also paid attention to the problem of weakening food security due to martial law in Ukraine. The researchers developed an improved cascading failure model to monitor the effects of war on global food security and stressed the need for international organisations to step up efforts to balance the needs of large and small countries, with a particular focus on the most vulnerable states in Africa and Asia. In the work of A. Molajou *et al.* (2023) proposed a new paradigm that expands the approach to analysis and strategy development for macro-policy to include strategies for managing vital resources, including food, water, and energy.

A. Sridhar *et al.* (2023) analysed that the COVID-19 viral outbreak has caused a large-scale imbalance in all fields of the international economy, a reduction in the workforce, in particular in agriculture and the food industry. The closure of businesses around the world due to quarantine has disrupted the entire supply chain, from producer to end consumer. This study examines the implications of COVID-19 for global food security and its economic aspects. The authors also paid attention to the introduction of sustainable agricultural approaches, such as urban farming, crop rotation,

hydroponic farming, and small-scale family agriculture, conserve natural resources and attain the Sustainable Development Goals. The proposed innovative solutions, such as the use of artificial intelligence, machine learning, and blockchain, are interesting from a scientific point of view as promising tools for developing the agricultural sector and strengthening food security.

M.O. Alabi & O. Ngwenyama (2023) highlighted that the COVID-19 pandemic significantly impacted food security and global food supply chains, resulting in heightened food insecurity in Canada and the United States. The main challenges include a deteriorating economic situation, labour shortages, limited access to food, transportation difficulties and changing consumer preferences. The pandemic has also caused the closure of production facilities and increased uncertainty about product quality and safety. The authors emphasise the need to redesign food supply chains to be resilient to post-pandemic challenges and propose a new framework for creating smarter and more resilient food supply chains in the post-COVID-19 environment. The study by K.A. Abay *et al.* (2023) examines the implications of martial law in Ukraine for both global and regional food security. Particular attention is paid to the Middle East and North Africa region, which is susceptible to trade disruptions due to its high dependence on food imports. The authors point out that the crisis will affect poor and rich households, as well as urban and rural populations differently.

J. Cheng & X. Yu (2024) developed a comprehensive food security assessment system that includes four main aspects: security in terms of quantity, nutrition, environment, and capacity. China's food security index was assessed using the entropy method, and the spatial and temporal dynamics of food security distribution in seven regions was analysed using the Gini coefficient of Dagum and its decomposition, which allowed to confirm the overall and contextual convergence of food security levels in different regions. O. Skydan *et al.* (2020), based on an analysis of current trends in food security, developed a new doctrine that integrates environmental, economic, organisational, social and regulatory aspects into a single governance mechanism. According to the authors, the presented mechanism allows to eliminate shortcomings in the public administration of food security and provides a systematic approach through the introduction of regulatory instruments that affect the process of food security formation.

L. Stuart *et al.* (2024) focused on the fact that food security is one of the key aspects of environmental sustainability in the world, and food insecurity negatively affects human health and well-being, as well as

drives mass migration, jeopardising national security and hindering global sustainable development. It is analysed that ensuring food security requires a balanced approach to numerous issues related to atmospheric and earth sciences, economics, agronomy, agricultural engineering, and social sciences. The authors conclude that the American Meteorological Society community has significant potential to play a more active role in the global food system in the future, which will help to bridge scientific and technological gaps and improve global food security.

The authors R. Dulambayeva *et al.* (2023) examined the potential for implementing a food security management system in the Republic of Kazakhstan, utilising data-driven decision-making to align with the principles of sustainable development. The authors note that an important external factor for Kazakhstan is the current geopolitical situation, in particular the invasion of Ukraine by Russian troops. The paper also outlines various internal and external factors impacting food security in the region and suggests a data-driven decision-making framework for effective management.

Thus, the main aim of this study was to substantiate the peculiarities of the current state of global food security, monitor the progress made in achieving the 2<sup>nd</sup> Sustainable Development Goal, and identify key challenges to food security in the context of global economic and environmental changes.

## MATERIALS AND METHODS

The bibliometric analysis, performed using Google Analytics, Vosviewer v.1.6.18, and SciVal, enabled the identification of research groups that have made significant scientific contributions to the study of global food security and the progress and challenges in achieving the Sustainable Development Goals. The use of Vosviewer v.1.6.18 facilitated the creation of bibliometric networks that encompass researchers and individual publications in the field of global food security monitoring, as well as to justify the feasibility of using different approaches to strengthen it and achieve 2<sup>nd</sup> Sustainable Development Goal. These networks were created based on the analysis of citations and bibliographic links, which allowed to form a list of the main literature sources and authors who have studied the relevant issue.

The basis of this study (theoretical and methodological) was the Food and Agriculture Organization report (2024) and FAOSTAT (n.d.) data, as well as a collection of foundational and applied scientific research by scholars in the field of food security, economic theory, sustainable development, development theory, and international relations. The study used systemic and

structural analysis and synthesis to determine the relationship between the factors of influence (a significant growth in the intensity and frequency of conflicts, extreme climate events, economic downturns and a general slowdown in economic growth) and the level of food security. The issue of the systemic and structural nature of food security arose from the need to find out how changes in various aspects affect changes in the overall system of tax security. Furthermore, the article identified trends in food security levels across various regions of the world.

The historical and dialectical approaches, along with the method of scientific abstraction, were used to clarify the essence of the category “global food security”. Thus, a thorough study of the processes and conditions for ensuring global food security made it possible to identify the basic, most essential features of this category, abstracting from others that were considered secondary in this study. Graphical and descriptive-statistical methods were used to graphically summarise, compare and emphasise the key characteristics of the global food security situation. The abstract and logical method was used at each stage of the study to identify the current state of global food security, monitor progress towards achieving 2<sup>nd</sup> Sustainable Development Goal, and identify key challenges to food security in the context of global economic and environmental change. This study monitors various food security indicators from 2005 to 2023. Different food security indicators are analysed for different periods of time due to changes in the methodology for calculating the Food and Agriculture Organization of the United Nations indicators, the analysis of which formed the basis of this study.

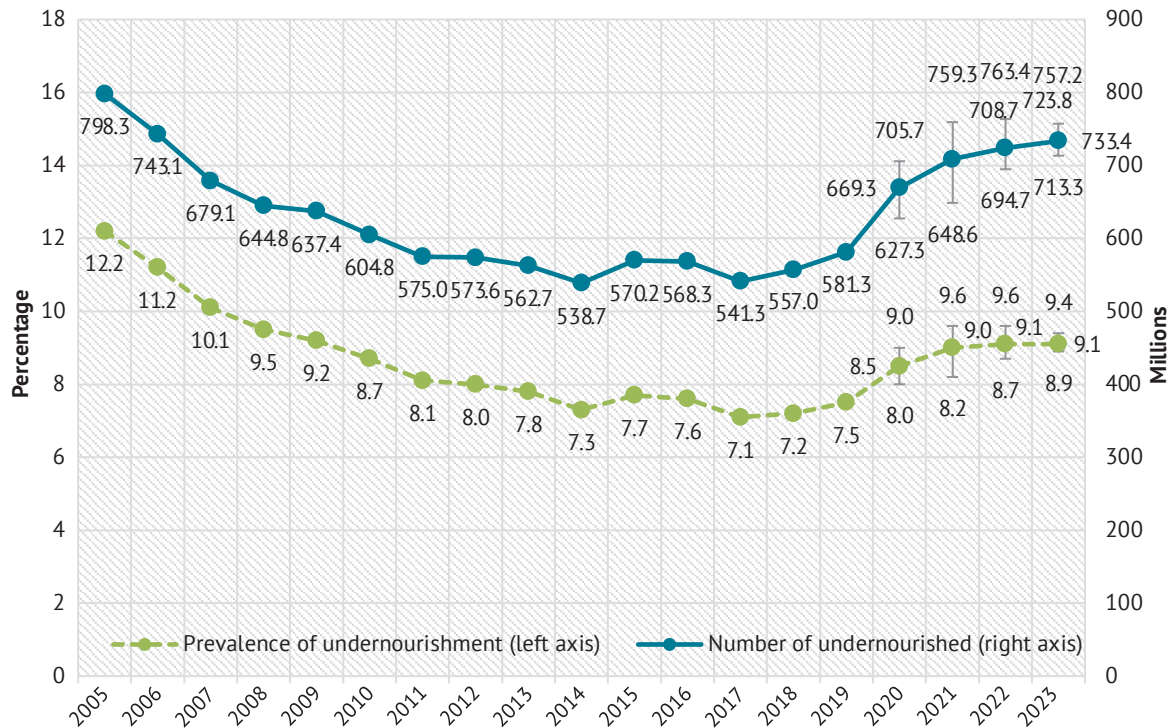
## RESULTS

The fulfillment of the Sustainable Development Goals is a common goal for all countries, which should support comprehensive efforts to create a world free of food insecurity, hunger and all forms of malnutrition by 2030. Progress towards this goal is insufficient and uneven. While there is significant positive momentum in some countries, food insecurity and hunger continue to grow in many regions of the world (especially in rural areas). In general, the factors that exacerbate the problem of malnutrition and food insecurity in the world are conflicts, economic downturns, climate change, insufficiency of access and affordability of nutritious food.

Global food security refers to a comprehensive condition where all people, in every region of the world, have physical, social, and economic access to adequate, safe, nutritious, and high-quality food that supports an active and healthy life over the long term. Global food security includes stability of supply, resilience of

food systems to external influences (such as conflicts, climate change, economic crises) and adherence to the principles of sustainable development, which include preserving resources for future generations. The world is significantly behind the schedule for achieving the

2<sup>nd</sup> Sustainable Development Goal – “ending hunger”. During the COVID-19 viral outbreak, the level of malnutrition went up significantly, and remained almost unchanged in 2021-2023. The main indicators of the scale of hunger in the world are shown in Figure 1.



**Figure 1.** Key indicators of the scale of hunger in the world (2005-2023)

**Notes:** in the line chart, vertical bars show the limits of the calculated range

**Source:** generalised from Food and Agriculture Organization (2024) and FAOSTAT (n.d.)

Thus, Figure 1 shows that in 2023, between 713 million and 757 million people suffered from hunger worldwide, an increase of 152 million people contrasted with 2019. Since 2017, there has been a sharp growth in the incidence of starvation in the world (the “undernourishment” indicator): in 2017, 7.1% of the world’s population suffered from starvation, and in 2023, it was already 9.1%. In addition, progress in ensuring access to safe food has also slowed. In 2023, about 29% of the world’s population faced food insecurity. The issue of inequality in access to food continues to be a particularly pressing concern: more than 71% of people who do not have access to healthy food live in low-income countries. Thus, the state of global food security remains extremely challenging. According to the Food and Agriculture Organization (2024), by the end of the decade, more than 580 million people worldwide will suffer from chronic malnutrition. In 2015-2023, some

progress was made in the fight against various forms of malnutrition, but the problems of childhood obesity and low birth weight remain unresolved. Considering current trends, it is important to note that the world is not on course to achieve any of the seven nutrition-related goals by 2030.

The world needs to introduce comprehensive approaches that will help to improve the effectiveness of the fight against malnutrition, overweight and obesity, and micronutrient deficiencies, addressing the common causes of various forms of malnutrition. It should be noted that the existing problem is exacerbated by the lack of clear data on the available volumes and effectiveness of funding aimed at achieving global food security objectives. Due to the different systems for assessing funding for food security, there are significant discrepancies in estimates, which leads to the inability to fully identify areas with insufficient funding and

ineffective monitoring. There is a need to clearly define the sources and specifics of food security funding and to standardise approaches to its evaluation.

Innovative solutions are needed to increase funding to address global food security challenges in countries with high levels of hunger. However, for low- and middle-income countries, the process of raising affordable resources is quite a challenge. According to the Food and Agriculture Organization (2024), in countries with limited access to finance, malnutrition among children is quite common, while in countries with optimal access to finance, overweight is quite common. The vast majority of countries face food insecurity factors, including extreme climatic conditions.

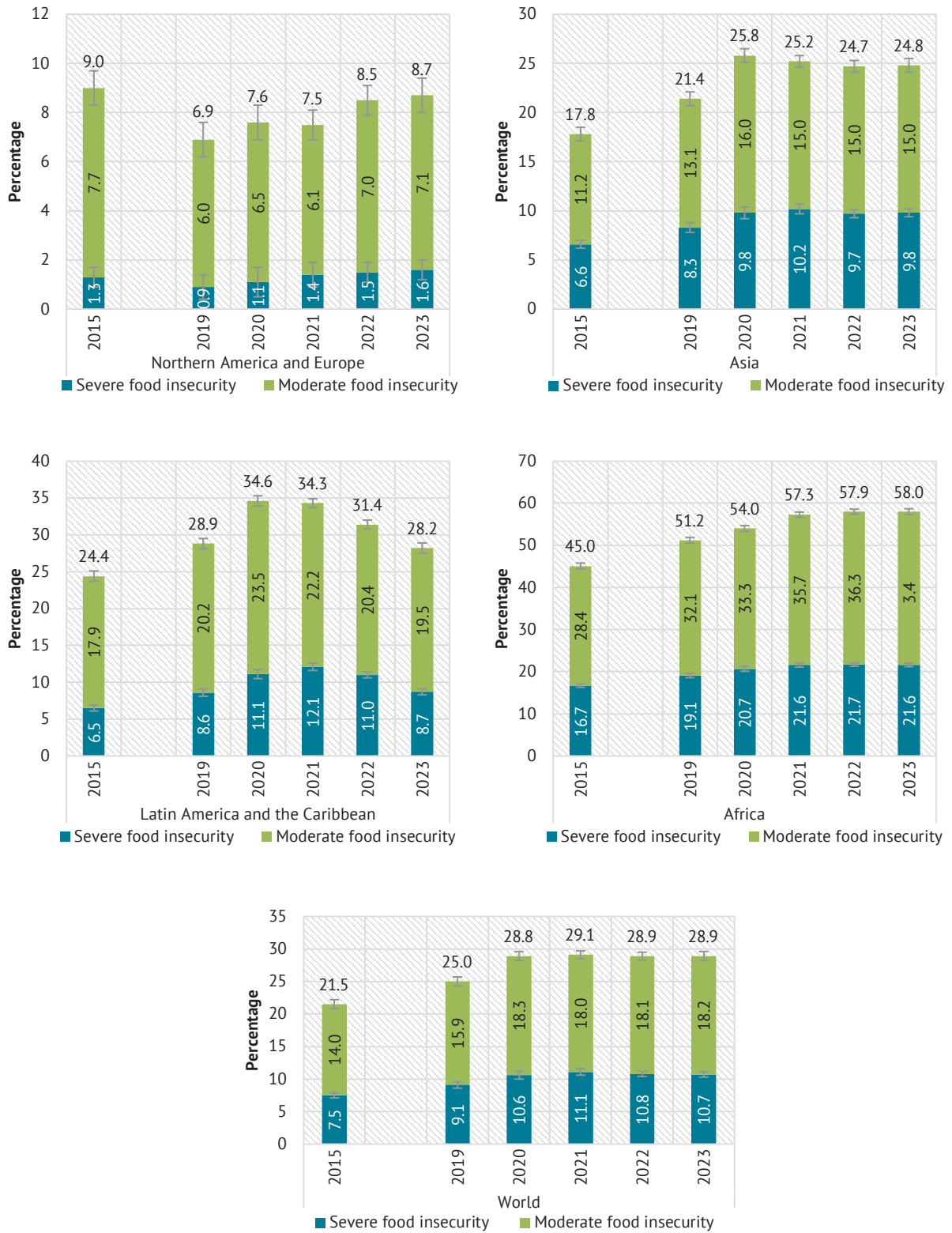
It is worth noting that the task of accelerating the achievement of Sustainable Development Goals was discussed at the “Summit of the Future 2024”, which took place in New York in September 2024. “The Summit of the Future 2024” is a high-level event that brought together world leaders to build an international consensus on how to achieve a better present and preserve the future. It was emphasised that it is necessary to return the world to the path of fulfilling common commitments to achieve the Sustainable Development Goals after a significant deterioration during the COVID-19 pandemic (United Nations, 2024). In addition to improving the mechanisms for responding to global shocks and crises, the transformation of food systems based on the results of the 2021 UN Summit on Food Systems is identified as a common task for all countries. The need to create food systems that will ensure a transition to a healthy diet, promote nature restoration and take into account climate change is emphasised. In addition, recommendations are made to create a fair and sustainable multilateral trading system that will also cover food and agricultural markets. Support for 2<sup>nd</sup> Sustainable Development Goal is being implemented as part of the follow-up to the Food Systems Summit, led by the UN Food Systems Coordination Centre. The dynamics of food insecurity indicators by region of the world is summarised in Figure 2.

In Africa, despite all the world's efforts, the scale of hunger continues to grow (the aggregate level of food insecurity increased from 45% in 2015 to 58% in 2023), in Asia it remains almost unchanged (24.8% in 2023), and in Latin America it is significantly reduced (from 34.6% in 2020 to 28.25% in 2023). Africa is characterised by the highest proportion of the population that suffers from hunger: about 20.4% of the world's population is hungry in this region, 6.2% in Latin

America and the Caribbean, and 8.1% in Asia. According to the Food and Agriculture Organization (2024), by 2030, most of the world's undernourished people will live in Africa. In 2024, Asia will remain the leader in terms of the number of hungry people in absolute terms: the region has more than 384 million hungry people, or more than half of the total number of hungry people in the world. In Africa, 298 million people faced the problem of hunger in 2023, and 41 million in Latin America and the Caribbean.

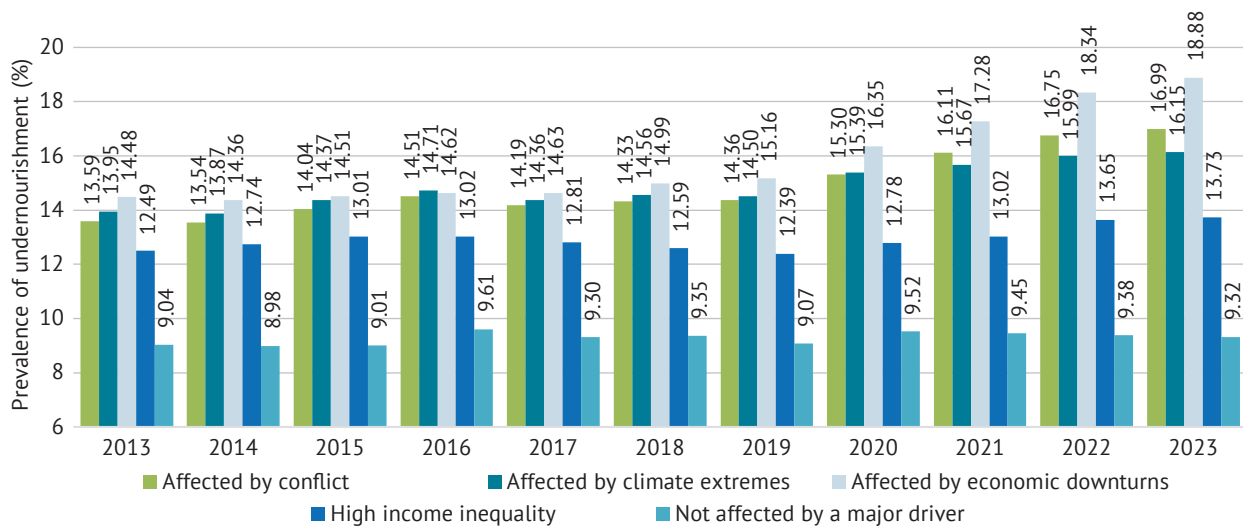
However, hunger is not the only problem with the current state of global food security. In 2024, food insecurity rates are higher than they were before the COVID-19 pandemic, with little change between 2021 and 2024. In 2023, around 28.9% of the global population – approximately 2.33 billion people – experienced food insecurity (either moderate or severe), meaning they lacked consistent access to sufficient food. North America and Europe report the lowest levels of both moderate and acute food insecurity.

In order to develop measures aimed at strengthening food security, it is necessary to analyse the main factors of malnutrition and food insecurity, as well as to identify the countries most often affected by these problems. In the period 2014–2024, there was a significant increase in the intensity and frequency of conflicts, extreme climate events, economic downturns and a general slowdown in economic growth, which weakened the level of food security in the world. The impact of these factors is exacerbated by severe income inequality. The dynamics of undernutrition prevalence in countries affected by certain factors, such as conflicts, extreme climatic events and economic downturns, or countries with high levels of income inequality, are presented in Figure 3. Each of the main factors has its own characteristics, but they are often interrelated and create a synergistic effect, negatively affecting the vast majority of aspects of food security (availability, utilisation, accessibility and stability), as well as other aspects of nutrition. This conclusion is supported by the data on the relationship between food security and nutrition factors and indicators (Fig. 3). Most low- and middle-income countries are affected by at least one of the main factors, with many experiencing several factors simultaneously. This combination contributes to a notable increase in hunger and food insecurity. Figure 4 highlights the difference between the 2019 and 2023 undernutrition prevalence rates in different groups of countries, when different numbers of factors are taken into account.



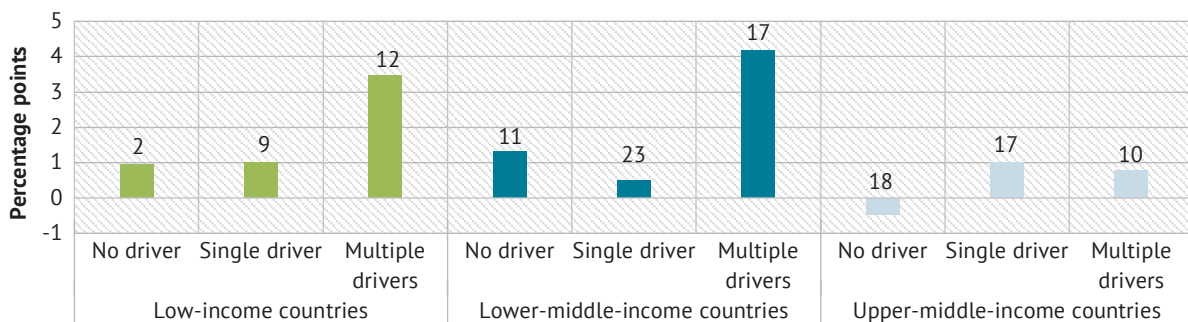
**Figure 2.** Dynamics of food insecurity indicators by regions of the world (2015, 2019-2023)

Source: generalised from Food and Agriculture Organization (2024) and FAOSTAT (n.d.)



**Figure 3.** Changes in the prevalence of undernourishment in countries with high income inequality (2013–2023)

**Source:** generalised from Food and Agriculture Organization (2024) and FAOSTAT (n.d.)



**Figure 4.** Difference between the prevalence of undernourishment in 2019 and 2023 in different groups of countries

**Notes:** the numbers at the top of each column are the number of countries that have been assigned to a particular category

**Source:** generalised from Food and Agriculture Organization (2024) and FAOSTAT (n.d.)

The data presented in Figure 4 suggests that the presence of several factors affecting food security, including the most dangerous ones (conflicts, extreme climatic events and economic downturns), create a synergistic effect, significantly weakening the level of food security in a particular country. Thus, in today's environment, the agricultural sector faces numerous challenges related to climate change, population growth and limited resources. Effective agricultural management is a key factor in protecting plants from weeds, pests and pathogens, increasing crop productivity, and introducing innovative technologies that can significantly affect food security.

One of the main recommendations is to adapt integrated agricultural management systems, which involves the use of crop rotations, post-harvest sowing and optimisation of fertilisation systems. These methods not only increase crop productivity, but also ensure the preservation of soil fertility, which is critical in the

face of increasing food demand. The use of modern management technologies, such as precision farming, enables agricultural producers to effectively control resources, which in turn reduces the cost of cultivation, increases crop productivity and the level of profitability of their cultivation.

Protecting plants from weeds, pests and pathogens also requires new approaches. The introduction of biological control agents and integrated plant protection systems based on environmentally friendly methods can reduce the use of chemical pesticides. This will improve product quality, which in turn will have a positive impact on public health. An important element of food security is also the introduction of innovative minimum tillage technologies. In addition, the use of the latest agricultural technologies, such as hydroponics, vertical farms and precision farming, can significantly increase agricultural productivity, especially in conditions of limited resources, such as water and land.

These approaches ensure the stability of food resources, reducing the risks of hunger and food shortages.

The introduction of new technologies in agriculture allows not only to increase crop productivity but also to adapt production to changing environmental conditions. This is especially important given global challenges like climate change and socio-economic crises, which could disrupt food supplies. Investments in R&D, as well as in farmer training, are needed to introduce new technologies that will make agriculture more sustainable and efficient. Thus, effective agricultural management, plant protection, increasing crop productivity and introducing innovative crop production technologies are important factors that directly affect the food security of the population. These approaches not only ensure the stability of food resources, but also contribute to reducing the risks associated with hunger and food shortages, thus forming the basis for sustainable development of the agricultural sector.

## DISCUSSION

The findings of E. Shahini *et al.* (2024) are confirmed by the results of the authors' research in terms of the fact that war has catastrophic consequences for global food security. These consequences can be long-lasting and even irreversible, so it is important to analyse their impact on ecosystems and look for innovative ways to mitigate them in the future. These methods should form the basis for planning the recovery of areas affected by hostilities, including the restoration of ecosystems and natural resources.

The article by O. Shebanina *et al.* (2024) notes that significant soil contamination is a problem that causes a decrease in the overall state of food security. It is emphasised that the Russian invasion of Ukraine has led to large-scale environmental pollution, the consequences of which will take many years to remedy. In order to comprehensively analyse the scale of pollution and forecast its consequences, the author reviews soil pollution in certain regions of Ukraine. It is emphasised that the level of pollution varies depending on the location and course of hostilities. The disposal of chemical waste and ongoing conflicts in eastern Ukraine have led to soil contamination with heavy metals and petroleum products. In Kharkiv region, cadmium pollution increased by 200%, while in Kherson and Zaporizhzhia regions, oil spills increased by 139 and 156% respectively, causing health problems.

The impact of soil pollution on food security and sustainable development was studied by a group of authors I. Bulba *et al.* (2024), who analysed the state of land in different regions of Ukraine. It was found that in the Dnipro region, soil contamination levels were

three times higher than the maximum permissible concentration for lead and 1.5 times higher for fluoride. In Mykolaiv region, the concentration of lead exceeds the permissible level by five times, while the content of zinc, copper, fluorine and oil products exceeds the permissible levels by 25%. In Zaporizhzhia region, lead exceeds the standard by 11 times, the content of zinc and fluorine is increased by 50%, and that of oil products – by 35% and phosphates – by 30%. The paper emphasises that military operations affect the physical and chemical properties of soils, in particular, they lead to an increase in the acidity and density of the topsoil. The authors stress the importance of analysing the consequences of military operations, as well as developing and implementing eco-friendly technologies to restore the impacted areas.

Expanding on these results, a thorough research paper by V. Shebanin *et al.* (2024) published the results of a study on the introduction of new agrotechnological crop rotations and evaluation of their effectiveness on degraded lands of the Mykolaiv region, where active hostilities took place. The results showed that new crop rotations increase gross output by 1.3 times compared to previous figures. This is extremely important in the context of restoring food security not only in Ukraine but also in the global world. The results obtained can serve as a basis for the development and implementation of programmes aimed at restoring the structure, fertility and quality of damaged land, strengthening food security and achieving 2<sup>nd</sup> Sustainable Development Goal.

The study by O.A. Otekunrin *et al.* (2020) analysed the readiness of African countries to achieve the goal of zero hunger by 2030. The authors conclude that serious problems of hunger in the world are caused by ineffective governance, conflicts, and climate change. The authors emphasise that despite the decline in child mortality in Africa, many challenges remain in ensuring food security. African governments are advised to focus on implementing sustainable agricultural practices and creating effective policies to combat hunger. In addition to these important findings, the study recommends that data on the effectiveness of funding for global food security be adjusted.

The authors of the study N. Rahman & R. Yasin (2022) emphasised that achieving the goal of zero hunger has faced significant challenges due to the economic impact of the COVID-19 pandemic. It was also noted that in order to ensure the survival of vulnerable children, there is a need to provide humanitarian assistance and support agricultural production to ensure a stable food supply. The above study also considers economic crises in countries as a factor affecting food security. In the publication A. Muneeza & Z. Mustapha (2021), the authors analyse the problem of food insecurity in

conjunction with the specifics of Islam and note that it is in line with the basic principles of Shariah, which aim to achieve public welfare through ethical resource management. The researchers concluded that hunger is a problem that requires joint efforts of national governments under the leadership of the UN. In Islam, this cooperation is regarded as a collective responsibility, where both government agencies and affluent individuals must fulfill their duties to society. Interesting results in the field of the studied topic were obtained by E. Mutea *et al.* (2022), who analysed the state of food security in Kenya and concluded that half of the country's population faces problems with access to food. This study also focuses on the significant problems with food security in Africa, which are projected to worsen.

The article by A. Poltorak (2015) assessed the food security indicators for the period 2009-2013 in Ukraine and determined the dynamics of the weighted average food security indicator. The conclusions drawn about the need to adapt state policy to ensure the stability of food security are still relevant in 2024, as the state of food security remains extremely unsatisfactory. Article I. Atamanyuk *et al.* (2019) is devoted to the important economic problem of forecasting grain crop yields, taking into account unstable weather factors, which is extremely important in the process of monitoring the condition of food security. A flowchart of the algorithm is proposed, which illustrates the peculiarities of calculating the parameters of the forecasting model, as well as a formula for estimating the extrapolation error, which helps to determine the amount of information needed to obtain the desired level of forecasting quality.

Thus, the problem of ensuring food security in the world is characterised by a high level of urgency, and the outcomes of scientific research confirm the existence of serious threats to global food security caused by conflicts, environmental pollution and economic crises, in particular in the context of the war in Ukraine. The extent of soil contamination is worsening the situation with access to food, and effective solutions require a comprehensive approach, including innovative agricultural technologies and adaptation of public policies. It is important that national governments make efforts to restore the affected areas, monitor environmental impacts, and implement sustainable practices to ensure food security and achieve global development goals.

## CONCLUSIONS

It is emphasised that the process of ensuring global food security is complicated by numerous challenges, of which climate change, military conflicts, economic crises and pandemics such as COVID-19 are particularly critical. Numerous research studies have pointed to a

significant deterioration in food availability and quality, especially in regions that are dependent on imports. In addition, the impact of armed conflicts causes food prices to rise and increases the risk of famine in vulnerable countries. The authors stress the importance of an integrated approach to monitoring and managing food security, one that considers economic, environmental, and social factors in order to achieve sustainable development goals. The essence of the economic category of "global food security" is clarified, which is considered as a complex state of the global food system, in which all people in all regions of the world have physical, social and economic access to adequate, safe, high-quality and nutritious food to ensure an active and healthy life over the long term.

It is analysed that achievement of the 2<sup>nd</sup> Sustainable Development Goal "ending hunger" by 2030 remains one of the most acute problems in the world. Despite some positive changes, global progress in this direction is insufficient and uneven. In particular, in 2023, more than 700 million people were hungry, and about 29% of the world's population faced food insecurity, especially in low-income countries. The COVID-19 pandemic has made the situation much more complicated, exacerbating food insecurity and disrupting food supply chains. Projected indicators indicate that the world will not be able to achieve the 2<sup>nd</sup> Sustainable Development Goal by 2030 without intensified efforts and innovative solutions. An important aspect is the standardisation of approaches to assessing food security financing, as existing funding gaps and insufficient monitoring make it difficult to identify and overcome problems.

It has been shown that the dynamics of food insecurity in different regions of the world has significant differences and peculiarities. Africa has the worst situation, where the level of food insecurity continues to grow (up to 58% in 2023), while in Asia it remains stable and in Latin America the indicators are decreasing. Africa remains the most vulnerable region, with 20.4% of the population suffering from hunger, and it is projected that starting in 2030, the majority of the world's food-insecure population will reside in that region. Conflict, extreme climate events, economic stagnation and income inequality have been shown to be the main factors that weaken food security, often acting in combination to create a synergistic negative impact on nutrition and access to food. These factors primarily affect low- and middle-income countries, leading to a significant increase in undernutrition. Many countries are simultaneously affected by several of these factors, which complicates the fight against hunger and makes it necessary to develop comprehensive measures to overcome food security problems.

Consideration of new environmental technologies for the remediation of contaminated areas, analysis of the effect of climate change on global food security, and assessment of the effectiveness of existing government policies in the sphere of environment and agriculture will form the basis for further research. Additionally, an important area will be the development of integrated approaches to monitoring soil and water quality, which will allow for an accurate assessment of the effects of military conflicts.

## ACKNOWLEDGEMENTS

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## CONFLICT OF INTEREST

None.

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## **Глобальна продовольча безпека: виклики у досягненні цілей сталого розвитку**

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**Анотація.** Основна мета цього дослідження полягала в обґрунтуванні особливостей сучасного стану глобальної продовольчої безпеки. У процесі написання статті були використані такі методи, як бібліометричний аналіз (за допомогою Google Analytics, Vosviewer v.1.6.18 та SciVal), системно-структурний аналіз і синтез, історичний, діалектичний, графічний та описово-статистичний методи. Уточнено сутність економічної категорії «глобальна продовольча безпека», яка розглядається як комплексний стан світової продовольчої системи, при якому всі люди у всіх регіонах світу мають фізичний, соціальний і економічний доступ до достатньої кількості безпечних, якісних та поживних харчових продуктів, що забезпечують активне та здорове життя в довгостроковій перспективі. Зазначено, що прогрес у досягненні 2-ї цілі сталого розвитку «ліквідація голоду» є недостатнім і нерівномірним. У 2023 році понад 700 мільйонів людей у світі страждали від голоду, а 29 % світового населення зіштовхнулося з продовольчою небезпекою. Прогнози свідчать, що досягнення 2-ї цілі сталого розвитку до 2030 року буде неможливим без посилення зусиль та впровадження інновацій. Встановлено, що динаміка продовольчої небезпеки сильно варіюється між регіонами. В Африці ситуація найгірша – рівень продовольчої небезпеки досяг 58 % у 2023 році. Основними чинниками, що погіршують ситуацію з продовольчою безпекою, є конфлікти, екстремальні кліматичні явища, економічні кризи та нерівність доходів. Ці фактори створюють синергетичний негативний вплив, особливо в країнах із низьким і середнім рівнем доходів, і потребують розробки комплексних заходів для вирішення проблем продовольчої безпеки. Практична цінність дослідження полягає у застосуванні результатів проведеного моніторингу стану продовольчої безпеки, що сприятиме прийняттю ефективних рішень для подолання голоду і досягнення цілей сталого розвитку

**Ключові слова:** ризик голоду; недостатнє харчування; економічна доступність продовольства; нерівність у доступі до продовольства; доступ до безпечних харчових продуктів; конфлікти і продовольча криза

## Statistical analysis of pulses harvests and their use in the Ukrainian market

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**Abstract.** The study aimed to assess the state of production of pulses and their use in the Ukrainian market. To achieve this goal, the production, yields, sown areas, export dynamics, and structure of the use of pulses such as beans, soybeans, and peas in 2015-2023 were analysed. The study determined that the production of exports and consumption of pulses in Ukraine from 2015 to 2023 shows significant changes in the industry. Production and area under pulses declined significantly from 2015 to 2022 but began to recover in 2023. The dynamics of pulse yields in the period from 2015 to 2023 are marked by fluctuations. Pea yields ranged from 22.4 cwt/ha in 2015 to 31.3 cwt/ha in 2016, with a further decline to 18.2 cwt/ha in 2018, before recovering to 25.7 cwt/ha in 2023. Bean yields increased from 13.5 cwt/ha in 2015 to 16.3 cwt/ha in 2023, while soybean yields increased from 18.4 cwt/ha in 2015 to 25.8 cwt/ha in 2023. In addition, the structure of pulses used in 2015-2023 also changed: the share of consumption in the food industry decreased from 35 to 27%, while the share of livestock increased from 40 to 48%. The share of the industry remained stable at 25%. The results obtained indicate the need to develop and support the production of legumes in Ukraine, as well as to optimise the structure of their use

**Keywords:** exports; planted areas; soybeans; peas; beans; agricultural production

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## INTRODUCTION

Pulses are important for agricultural development due to their key role in ensuring food security, stimulating agricultural sector development and supporting sustainable rural development. They are an important component of the market with a wide range of applications in various industries. The research relevance is determined by the fact that despite the growing demand for these crops, their production and processing remain insufficient, causing market shortages and rising prices. In addition, the research focuses on preserving and improving soil fertility, as legumes are an important element of the agroecosystem.

According to B. Dessalegn *et al.* (2022), legumes are a highly valuable component of the diet for both humans and animals. These crops contain 20 to 30% of protein on a dry weight basis, which is significantly higher than in other crops. In addition, pulses are a rich source of energy that can be used not only for food but also for industrial purposes. The ecological value of pulses is also high, as they have a positive impact on the environment. According to M. Behnassi & M. El Hai-ba (2022), legumes improve soil structure and increase soil fertility and water permeability, which facilitates the growth of other crops. In addition, legumes are effective in combating soil erosion, as their roots can hold soil, which prevents it from being carried away. A. Freidenreich *et al.* (2022) also note that legumes increase biodiversity by providing food for various species of insects, birds and animals. Studies have also shown that legumes can be used to restore soils that have been damaged by intensive agriculture. They improve soil structure, increase its fertility and reduce degradation (Tibagonzeka *et al.*, 2018). In addition, legumes can be used to create biological fertilisers that can replace synthetic fertilisers and reduce the environmental impact of agriculture (Zhao *et al.*, 2024).

Notably, the energy industry also uses pulses to produce biofuels, which are an alternative source of energy for transport and various industries. According to S. Nath (2024), biofuels have several advantages. For example, it can be produced from local raw materials, which reduces dependence on energy imports from other countries. H. Yatsenko (2020) also noted that biofuels are a cleaner source of energy than traditional sources, as they do not contain sulphur and other harmful substances, rendering them a better option for countries seeking to reduce their environmental impact and increase energy independence. Thus, pulses are an important element of sustainable agricultural development and environmental protection (Fiott, 2022).

In Ukraine, growing pulses open new opportunities for exports and economic growth. Following O. Krupchan & V. Korol (2022), these crops are an important

export commodity that brings foreign exchange earnings to the country and makes them an important component of international trade. This suggests that the development of the pulses industry could become one of the key areas for the development of the Ukrainian economy and increase its competitiveness in the global market. Increased exports of pulses will also contribute to the development of agriculture and the creation of new jobs in this sector. In this regard, A. Bohra *et al.* (2022) believe that the development of pulses production will contribute to increased investment in agriculture, improved infrastructure and the overall economic situation in Ukraine.

In the context of analysing the data from various authors, it should be noted that there is a gap in the collection and analysis of data on pulse production and consumption in Ukraine. Many studies focus on specific aspects of production, such as cultivation technologies, economic efficiency or environmental impact, but do not provide a complete picture of the pulses market in Ukraine. In addition, data on the production and consumption of pulses are often outdated or unrepresentative, making it difficult to conduct a reliable analysis. Therefore, to get a complete picture of the pulses market in Ukraine, it is necessary to conduct a comprehensive study that includes the collection and analysis of data on the production, yields, consumption and trade of pulses. The study aimed to assess the state of pulse production in Ukraine and its role in the market. To achieve this goal, the following objectives were set: to analyse the yields and consumption patterns of pulses in Ukraine and to develop recommendations for improving production efficiency and increasing exports of pulses.

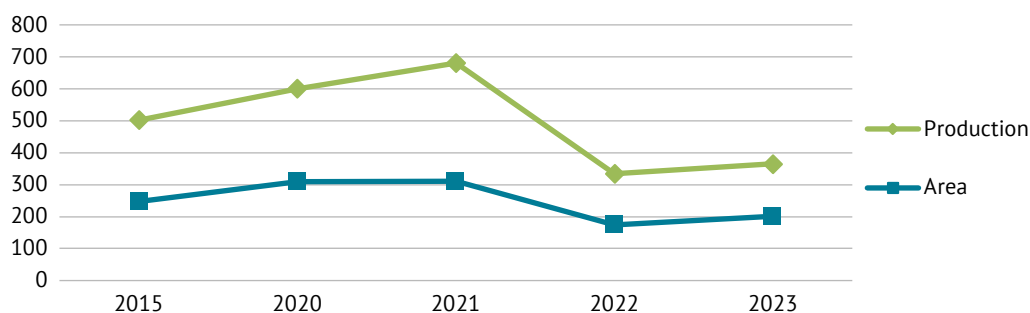
## MATERIALS AND METHODS

To conduct a comprehensive statistical analysis of pulse harvests in Ukraine, including their use and role in the agricultural sector, data from the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.) was used. The study was conducted using a comprehensive approach that included the use of several statistical analysis methods to study in detail the production and use of pulses in Ukraine. To logically combine the statistical data, the information was grouped and patterns alongside prospects of using these crops in Ukraine were analysed. The data obtained were analysed to identify trends and patterns in the production and export of pulses in Ukraine, including production dynamics, production and export structure. The information was also systematised, classified and analysed to identify patterns and trends in the use of pulses.

The study conducted a detailed analysis of several key indicators to get a definitive overview of the current state and prospects of pulses in Ukraine, including soybeans, beans and peas. The focus of this analysis was on the dynamics of production, yields, sown areas, exports and the overall structure of pulses used in the period from 2015 to 2023. The dynamics of pulse production were studied to determine the general trends in production volumes over the period. Thus, general trends in the agricultural sector were analysed, and annual fluctuations were determined. Yields, as an important indicator of the effectiveness of agronomic practices, were analysed to determine the level of productivity of each pulse crop, which included consideration of average yields, their changes over time, and comparison of yields of different crops with each other. The analysis of sown areas determined the scale of pulse cultivation in Ukraine and identified regions where pulses are most developed and promising. Exports were analysed to assess the competitiveness of Ukrainian pulses on the international market. The overall structure of pulses used was analysed to determine their role in the Ukrainian economy. This data was selected due to its completeness and reliability, as it was collected and validated by government agencies.

## RESULTS

An analysis of the production and area of pulses in Ukraine shows important changes in this sector of agriculture. Thus, according to the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.), there is a downward trend in production and area under these crops from 2000-2020. In 2015, the production of pulses in Ukraine amounted to 502.1 thousand tonnes and the area under these crops was 246.7 thousand hectares, which increased to 600 thousand tonnes and 310.3 thousand hectares in 2020. In 2021 production continued to grow, reaching 680.6 thousand tonnes, with a stable area of 310.7 thousand hectares. However, the decline in pulse production to 334.2 thousand tonnes in 2022 is of particular concern. The area under these crops also decreased, reaching 174.1 thousand hectares in the same year. This stagnation can be attributed to various factors, including economic difficulties, changes in agricultural policy, climatic conditions, and war. However, there was some growth in 2023: production of pulses increased to 365 thousand tonnes and the area under them grew to 201 thousand hectares, indicating positive changes and the beginning of the industry's recovery after a period of prolonged decline (Fig. 1).



**Figure 1.** Production (thousand tonnes) and area (thousand hectares) of pulses, 2015-2023

**Source:** compiled by the authors based on the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.)

The analysis of the sown area of pulses for the 2024 harvest in Ukraine shows an overall increase in all regions of the country. The total area under pulses in Ukraine in 2024 is 292.9 thousand hectares, up 41.9% compared to 2023. This significant increase indicates a gradual recovery and expansion of production after a period of decline, which may be due to increased demand for these crops in the domestic and foreign markets.

In most of Ukrainian regions, an increase in sown areas is notable. In particular, the area increased by 11.6% in the Vinnytsia region, by 69.6% in the Volyn region and by 26.9% in the Dnipro region. Zhytomyr region showed an increase of 33.8%, and Zaporizhzhia

region – 64.1%. The increase in planted areas is also observed in Kyiv region (21.1%), Kirovohrad region (40.6%) and Lviv region (25.3%). The largest growth was recorded in Mykolaiv region, where the area under crops increased by 90.2%, and in Odesa region, where the growth was 93.4%. Luhansk region was the only region to record a 9.6% decline in the area under pulses. Data for the Kherson region is not available due to the current situation in the region, which is caused by the fact that in 2023 the Kakhovka Dam, a critical infrastructure facility on the Dnipro River, was destroyed by Russian militants. Overall, the increase in planted areas in most regions indicates renewed interest in pulses and the possibility of their sustainable development

in the future. This positive trend indicates a potential increase in the production of these crops, which is an important factor in ensuring the country's food security and supporting its agricultural economy (Table 1).

**Table 1.** The sown area of pulses for the harvest of 2024 in farms of all categories by region, thousand hectares

	Sown area	
	2024	2024 in % before
Ukraine	292.9	141.9
Vinnitsia region	12.2	111.6
Volyn region	6	169.6
Dnipropetrovsk region	15.9	126.9
Donetsk	2.3	109.4
Zhytomyr region	10.4	133.8
Zakarpattia region	1.6	106
Zaporizhia region	6.2	164.1
Ivano-Frankivsk region	4.9	104.5
Kyiv region	7.2	121.1
Kirovohrad region	23.6	140.6
Luhansk	0.2	90.4
Lviv region	3.9	125.3
Mykolaiv region	37.2	190.2
Odessa region	72	193.4
Poltava region	12.4	108.9
Rivne region	2.5	159.4
Sumy region	8.9	136.3
Ternopil region	9	132.4
Kharkiv region	22.7	111.6
Kherson region	N/A	N/A
Khmelnytskyi region	9.7	110.3
Cherkasy region	9.4	106.8
Chernivtsi region	1.2	105.6
Chernihiv region	9.7	107.2

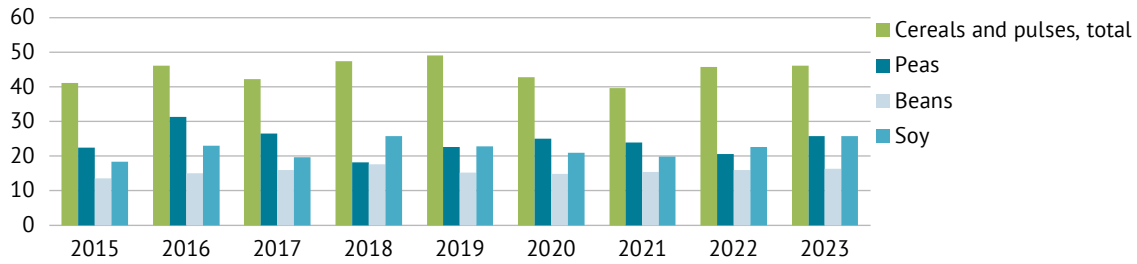
**Source:** compiled by the authors based on the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.)

The analysis of the dynamics of pulse yields, in particular soybeans, beans and peas, for the period from 2015 to 2023 shows instability in the indicators, which may be due to various factors, including weather conditions, growing technologies and agronomic practices. Overall, the yield of cereals and pulses increased from 41.1 cwt/ha in 2015 to 46.2 cwt/ha in 2023. The peak yield was reached in 2019 at 49.1 cwt/ha. This growth reflects an overall improvement in agricultural practices and growing conditions.

Pea yields showed significant fluctuations during the period under review. In 2015, the yield was 22.4 cwt/ha, rising to 31.3 cwt/ha in 2016, but then dropping to 18.2 cwt/ha in 2018. In 2023, yields rose again to 25.7 cwt/ha. The yield of beans increased from 13.5 cwt/ha in 2015 to 16.3 cwt/ha in 2023. The lowest figure was in 2015, and the highest was in 2018 – with 17.7 cwt/ha. Soybean yields are also on the rise, rising from 18.4 cwt/ha in 2015 to 25.8 cwt/ha in 2023. The highest level was reached in 2018 and 2023 – with 25.8 cwt/ha. This relatively stable growth reflects the

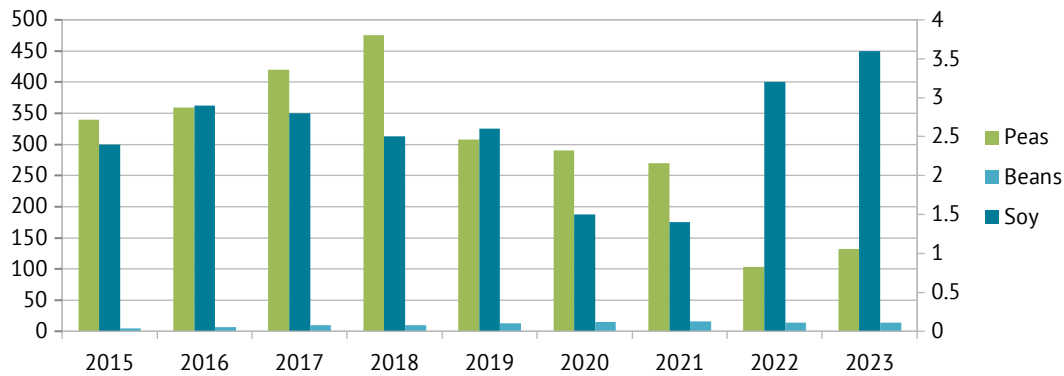
gradual improvement of agricultural practices and technologies (Fig. 2). The results show that Ukrainian exports of soybeans, peas and beans have significant potential, but certain fluctuations could be caused by internal and external factors, such as changes in global market demand and the military and political situation. Thus, in 2015, soybean exports amounted to 2.4 million tonnes, peaked in 2016 (2.9 million tonnes), and then declined to 1.4 million tonnes in 2021. In 2022, soybean exports increased to 3.2 million tonnes, and in 2023 reached 3.6 million tonnes, the highest level for the entire period.

In 2015, pea exports totalled 340 thousand tonnes, with growth continuing until 2018, when exports reached 475 thousand tonnes. After that, there was a decline to 103 thousand tonnes in 2022, but in 2023, exports increased to 132 thousand tonnes. Bean exports grew gradually from 5 thousand tonnes in 2015 to 16 thousand tonnes in 2021. After that, there was a slight decline to 13.4 thousand tonnes in 2022, and in 2023, exports of the crop increased to 14 thousand tonnes (Fig. 3).



**Figure 2.** Yield dynamics of pulses, t/ha (2015-2023)

**Source:** compiled by the authors based on the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.)

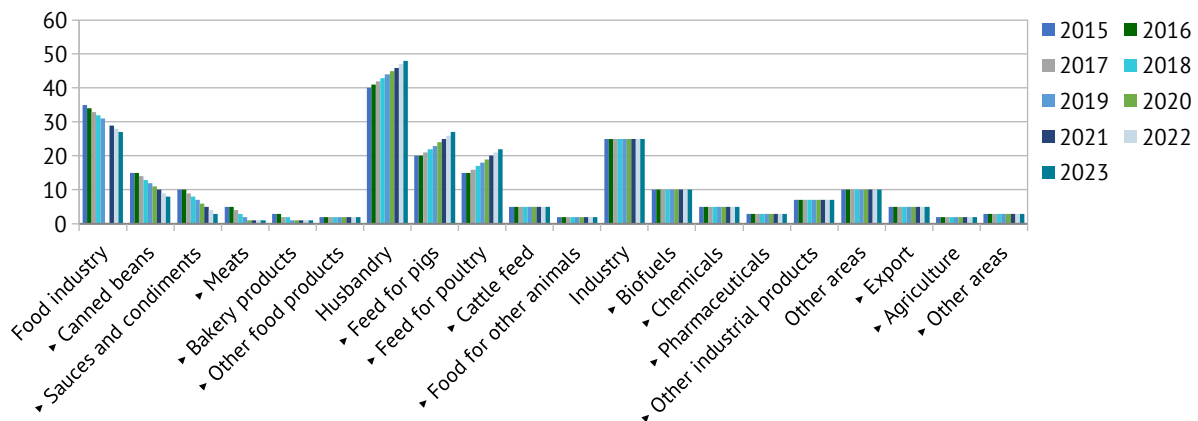


**Figure 3.** Exports of soybeans (million tonnes), peas and beans (thousand tonnes) from Ukraine (2015-2023)

**Source:** compiled by the authors based on the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.)

The study determined that the structure of legume crops used in Ukraine in 2015-2023 is characterised by a variety of purposes and areas of use. The main uses of pulses are in the food industry, livestock and industry. The food industry is the largest consumer of pulses in Ukraine, accounting for about 35% of total consumption in 2015, gradually decreasing to 27% in 2023. Livestock is the second largest industry, with its share increasing from 40% in 2015 to 48% in 2023. This growth was driven by increased demand for pork, poultry and cattle feed.

Industry, including the production of biofuels, chemicals, pharmaceuticals and other products, has maintained a stable share of 25% of total pulses consumption throughout the period. Exports and agriculture account for about 10 and 2% respectively, with no significant changes over the period. In the food industry, the largest sub-sectors are the production of canned beans, sauces, condiments, meat and bakery products, in livestock production – the production of feed for pigs, poultry and cattle, and in the industry – the production of biofuels, chemicals and pharmaceuticals (Fig. 4).



**Figure 4.** The general structure of pulses used in Ukraine in 2015-2023, %

**Source:** compiled by the authors based on the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.)

According to the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.), the market for pulses in 2015-2023 demonstrated several key trends. In particular, the demand for pulses in Ukraine, especially soybeans, beans and peas, was growing due to the increase in the production of feed for livestock and food industry. The development of the domestic pulses market has allowed farmers and producers to sell their products on the domestic market, not just export them. Large trading companies and chains are playing an increasingly important role in the pulses market, which has allowed them to control a significant market share and influence prices.

It is important to note that the development of e-commerce in pulses has allowed farmers and producers to sell their products online and get better prices. The popularity of organic and environmentally friendly pulses products grew and helped farmers to get better prices for their products. The cooperative movement among farmers is developing, allowing them to unite and jointly sell their products on the market. The role of the state in regulating the pulses market is also growing, as is its influence on prices, ensuring supply stability and supporting farmers.

The main actors in the pulses market in Ukraine are farmers and producers of pulses who produce and sell their products on the market, trading companies and networks that buy and sell pulses on the market, the food industry that uses pulses for food production, the livestock industry that uses pulses for animal feed production, and government agencies that regulate the pulses market and support farmers. In Ukraine, pulses are sold through several key distribution channels that ensure their availability on the market. Retail is an important link that allows farmers and producers to offer their products directly to the end consumer through supermarkets, shops and markets. This ensures wide access to pulses for ordinary consumers. Wholesale trade, in turn, is critical to ensuring the availability of pulses on the market. Retailers and chains purchase products in large volumes, which allows them to supply numerous retail outlets and other consumers.

Exports are another important component of the pulses market in Ukraine. It assists Ukrainian producers in entering the international sales market and generating revenue from the sale of their products abroad. The food industry uses pulses to make a variety of products, such as canned beans, sauces, condiments and other food products. This could be used to turn raw materials into finished products, which are then sold to consumers. The livestock industry also uses pulses, to produce feed for pigs, poultry and cattle. This increased the productivity of animals and improved their quality.

Improving production efficiency and increasing exports of pulses in Ukraine requires a comprehensive approach that addresses various aspects of the industry. To achieve this, it is necessary to increase the production of pulses by expanding the area under cultivation, improving yields and improving product quality. The government can support farmers by providing subsidies, training and access to modern machinery and equipment. It is necessary to develop the infrastructure for the processing and storage of pulses, which will allow to produce high-quality products that will be exported to other countries.

Diversification of Ukrainian pulses exports will also be beneficial, with exports to other regions such as the Americas and the Middle East to be expanded. To support exporters, the government can fund export market research to help identify new opportunities and increase exports and organise trade missions to other countries to establish contacts with potential buyers and conclude trade deals. An important step will be to improve the quality of pulse products by implementing a set of control measures. These measures include product certification, labelling and promotion of sustainable agricultural and production practices. This will increase consumer confidence in Ukrainian products, improve their competitiveness in the global market and increase exports. In addition, the implementation of such measures will help reduce risks to consumer health, improve the environment and increase production efficiency.

However, the war in Ukraine significantly impedes the implementation of these recommendations. Hostilities can affect the availability of resources, security and infrastructure. In such circumstances, it is necessary to focus on small but effective steps that can be implemented even in a limited resource environment and unstable situation. Adherence to these recommendations will enable significant progress in the development of pulse production and exports in Ukraine. This will increase production efficiency, improve competitiveness in the global market and take a leading position among the leading players. In addition, it will improve the Ukrainian reputation as a reliable supplier of high-quality products, increase exports and revenues, and create new jobs, stimulating economic growth in the agricultural sector.

## DISCUSSION

Ukraine is a significant link in providing food for the world's population, and growing crops is one of the main areas of the agricultural sector. The country has unique natural conditions, a large land area and a rich history of agricultural development, which creates

favourable opportunities for the successful cultivation of various crops, including pulses. The analysis of the production and area of pulses in Ukraine shows significant changes in this sector of agriculture. During 2015-2020, there was a downward trend in production and area under these crops. Except for 2023, when there was a slight increase in production and area, which indicates positive changes and the beginning of the industry's recovery after a period of decline.

V. Kravchenko *et al.* (2019) noted a decrease in the area and production of pulses, citing economic difficulties and climatic instability as the main reasons for this phenomenon. Similar conclusions were drawn by M. Bacchi *et al.* (2021), which pointed to the negative impact of the political situation and conflicts on the agricultural sector, leading to a decrease in the area under crops and production of pulses. However, the analysis of the sown area of pulses for the 2024 harvest in Ukraine has already shown a general increase in all regions of the country, which indicates a gradual recovery and expansion of production. At the same time, the dynamics of yields of pulses, in particular soybeans, beans and peas, showed a stable performance over the period from 2015 to 2023, which could be caused by various factors, including weather conditions, growing technologies, agronomic practices and war.

The results obtained by S. Kvasha *et al.* (2023) confirm the data obtained. They attribute the gradual growth and recovery of the agricultural sector to positive developments associated with increased demand for pulses and improved agronomic practices. In addition, scholars, including S. Belete *et al.* (2019) and C.K. Walker *et al.* (2023), confirm the upward trend in soybean yields, although note problems with pea and bean yields due to differences in growing technologies and climatic conditions. The study established that Ukrainian exports of soybeans, beans and peas have significant potential, but certain fluctuations may be due to internal and external factors, such as changes in global market demand and the military and political situation.

In terms of export markets, Ukraine has the potential to increase exports of pulses to Asia and Africa, as well as to the European Union. During the 2000s and 2020s, pulses gained significant international demand, which led to an increase in their production and exports. As one of the leading producers of pulses, Ukraine has also increased its participation in global exports. According to the Open Data Portal of Ukraine (n.d.) and State Statistics Service of Ukraine (n.d.), the most exported pulses are soybeans, peas and beans. As a confirmation of the research findings, several scholars, including L.M. Pörtner *et al.* (2022) and Y. Li *et al.* (2024), note that Ukraine is one of the largest producers of

pulses in the world, with a harvest of over 2 million tonnes per year. High harvests allow Ukraine to take a leading position among the largest exporters of these crops on the world market. This provides significant income for agricultural enterprises and farms specialising in pulses. Growing demand for the products encourages farmers to expand the area under these crops and introduce modern growing technologies. This trend is driven by an increase in global protein consumption, which creates new opportunities for Ukrainian farmers (Carton *et al.*, 2022; Yigezu *et al.*, 2024).

M. Behnassi & M. El Haiba (2022) also confirm that Ukraine is one of the leading exporters of pulses in the world. Key export markets include the European Union, India, China and the Middle East. In 2022, Ukraine exported about 1.5 million tonnes of pulses, which brought significant foreign exchange earnings to the national budget. In 2023, exports of pulses showed steady growth, confirming Ukrainian high export potential in this segment. The expansion of production capacities and the active introduction of innovative agricultural technologies have helped to strengthen the Ukrainian position in the global pulses markets.

A study by D. Rawtani *et al.* (2022) showed that pulses are one of the most profitable areas of Ukrainian agriculture. The authors also note that Ukraine has significant potential to increase production and exports of pulses, especially to the European and Asian markets. This is caused by the fact that pulses play a significant role in ensuring food security, replenishing the protein balance and maintaining soil fertility. According to M.T. Roberts (2021), pulse production in Ukraine is not only economically important but also socially important, as maintains employment in rural areas, which is significant for the development of local communities. In addition, the production of pulses stimulates the development of infrastructure, trade and services in rural areas, which helps to improve the quality of life of the population and increase their access to social services.

However, according to I. Salim *et al.* (2019), there is a risk of lower pulse yields caused by adverse weather conditions such as drought or excessive moisture, which could lead to lower pulse exports and income losses for agricultural enterprises and farmers. Low harvests could also lead to higher prices for pulses on the domestic market, which would negatively impact consumers. Following E. Shahini *et al.* (2023), current global changes, economic instability and geopolitical difficulties pose serious challenges to Ukraine's agricultural sector, such as water shortages, rising energy prices, declining soil fertility, biodiversity loss, trade barriers and political crises.

This opinion is also confirmed by H. Zhang *et al.* (2022) and B. Xavier (2023), who believe that climate change is a serious threat to agriculture in general. Adapting to these changes requires strategies that include changing agricultural practices, soil conservation, irrigation and diversification of production. The development and implementation of new technologies, raising awareness among farmers, establishing a system for monitoring and forecasting climate phenomena, and supporting research and development should be implemented to adapt agriculture to climate change.

Therefore, the study confirms the conclusions of C. Shikovets *et al.* (2020), which emphasise that to ensure the sustainable development of plant-based food production in Ukraine, it is necessary to address these challenges through the introduction of innovative technologies, environmental protection, efficient resource management, support for research and education, increased financial sustainability, infrastructure development and government support, and political stability. In addition, the development of the pulses market in Ukraine requires solving the problems associated with the damaged infrastructure of ports and granaries, as well as developing new routes for exporting pulses from Ukraine. This will help to increase the efficiency of pulse exports and reduce transportation costs.

At the same time, C. van der Giesen *et al.* (2022) emphasise that the environmental impact of increasing the production and export of pulses should not be forgotten. Increased pressure on the ecosystem and increased environmental pollution can be serious consequences of such development. Therefore, to address the environmental challenges associated with increasing production and exports of pulses, it is necessary to introduce environmentally friendly technologies and practices. These technologies include organic farming, conservation agriculture, efficient water use, biodiversity conservation, renewable energy, and pollution monitoring and control (Anders *et al.*, 2020). Thus, the results of this study confirm the findings of other researchers regarding the potential of Ukraine to increase production and exports of pulses, and the need for infrastructure development and investment in the agricultural sector to achieve this potential.

### CONCLUSIONS

An analysis of pulse production in Ukraine shows significant changes in the sector. In particular, in 2015, Ukraine produced 502.1 thousand tonnes of pulses in

an area of 246.7 thousand hectares. By 2020, production increased to 600 thousand tonnes, and the area under these crops increased to 310.3 thousand hectares. In 2021, the production of pulses continued to grow and reached 680.6 thousand tonnes, while the area remained at 310.7 thousand hectares. However, in 2022, the production of pulses decreased to 334.2 thousand tonnes and the area – to 174.1 thousand hectares. However, in 2023, there was a positive trend: production increased to 365 thousand tonnes and the area grew to 201 thousand hectares, which may indicate a recovery in the industry. The dynamics of pulse yields from 2015 to 2023 showed fluctuations in performance. Pea yields ranged from 22.4 cwt/ha in 2015 to 31.3 cwt/ha in 2016, with a further decline to 18.2 cwt/ha in 2018 and a recovery to 25.7 cwt/ha in 2023. Bean yields increased from 13.5 cwt/ha in 2015 to 16.3 cwt/ha in 2023. Soybean yields have also increased from 18.4 cwt/ha in 2015 to 25.8 cwt/ha in 2023.

Exports of pulses showed significant potential. Ukrainian soybean exports increased from 2.4 million tonnes in 2015 to 3.6 million tonnes in 2023, reaching a record level. Exports of peas decreased from 340 thousand tonnes in 2015 to 103 thousand tonnes in 2022 but increased again to 132 thousand tonnes in 2023. Bean exports grew gradually from 5 thousand tonnes in 2015 to 14 thousand tonnes in 2023. The structure of pulses used showed a variety of directions. The food industry decreased its share of consumption from 35 to 27%, while livestock increased its share from 40 to 48%. The industry has maintained a stable share of 25%. The main players in the domestic market of Ukraine are farmers, trading companies, the food industry and livestock, which influence the sale of products through retail, wholesale and export.

The limitation of the study is that its period covers only 2015 to 2023, which may not address long-term trends and cycles in the production and consumption of pulses. In addition, the war in Ukraine complicates the accuracy and completeness of statistical data and can significantly affect the production, storage and transportation of pulses. The prospect of further research is to develop strategies to reduce the risks for farmers associated with growing pulses.

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### CONFLICT OF INTEREST

None.

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## Статистичний аналіз врожаїв зернобобових культур і використання їх на ринку України

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**Анотація.** Метою виконаного дослідження було оцінити стан виробництва зернобобових культур та їх використання на ринку України. Для досягнення поставленої мети проаналізовано виробництво, урожайність, посівні площі, динаміку експорту та структуру використання таких зернобобових культур, як квасоля, соя та горох за 2015-2023 рр. Встановлено, що виробництво, експорт та споживання зернобобових культур в Україні з 2015 по 2023 роки показує суттєві зміни в галузі. Виробництво та площа посівів зернобобових культур значно скоротилися у 2015-2022 рр., але почали відновлюватися в 2023 році. Динаміка урожайності зернобобових культур за період 2015-2023 рр. відзначається коливаннями. Урожайність гороху варіювала від 22,4 ц/га у 2015 році до 31,3 ц/га у 2016 році, з подальшим зниженням до 18,2 ц/га у 2018 році, а потім відновилася до 25,7 ц/га у 2023 році. Урожайність квасолі зросла з 13,5 ц/га у 2015 році до 16,3 ц/га у 2023 році, урожайність сої збільшилася з 18,4 ц/га у 2015 році до 25,8 ц/га у 2023 році. Крім того, структура використання зернобобових культур у 2015-2023 роках також змінилася: частка споживання у харчовій промисловості зменшилася з 35 % до 27 %, тоді як частка тваринництва зросла із 40 % до 48 %. Частка промисловості залишилася стабільною на рівні 25 %. Отримані результати свідчать про необхідність розвитку та підтримки виробництва зернобобових культур в Україні, а також оптимізації структури їх використання

**Ключові слова:** експорт; посівні площі; соя; горох; квасоля; сільськогосподарське виробництво

## Review of the main diseases of *Solanum lycopersicum* and methods of chemical control of pathogens

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**Abstract.** This article overviews the major diseases affecting tomato plants (*Solanum lycopersicum*), caused by viral, bacterial, and phytopathogenic microorganisms. Pathogenic microorganisms parasitising tomato plants lead to significant crop losses in agricultural production, reducing the quality of the produce. The study aimed to investigate the impact of microorganisms on tomato plants, the extent of their harmful effects, and methods of controlling disease pathogens. It has been established that the primary diseases of tomato plants are caused by fungi of the genera *Fusarium* (fusarium wilt), *Phytophthora* (late blight), *Botrytis* (grey mould), and *Alternaria* (early blight); viruses such as *tomato spotted wilt virus* and *tomato yellow leaf curl virus*; and bacteria such as *Ascochyta*

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*cucumis* (bacterial canker of tomatoes) and *Xanthomonas vesicatoria* (bacterial spot). Agricultural chemicals are recognised as an essential component in pest and disease management, and the primary means of combating plant diseases include chemical substances such as prochloraz, thiabendazole, propiconazole, carbendazim, benomyl, thiophanate, fuberidazole, and others. Systemic fungicides are crucial in controlling various diseases and exhibit beneficial physiological or growth-stimulating effects on plants, including delaying leaf senescence and increasing chlorophyll content. It has been observed that fungicides (chemical groups: strobilurin and carboxamide) are effective in combating early blight, while the primary strategy for controlling grey mould involves chemical management through the use of synthetic fungicides such as quinone inhibitors, benzimidazoles, carbamates, phenylpyrroles, and succinate dehydrogenase inhibitors. Reviewing diseases and chemical control methods for pathogens is highly valuable for agricultural applications. The practical significance of this research lies in its ability to help agricultural producers manage their crops effectively and maintain fruit quality. Knowledge of the major diseases affecting tomatoes enables the timely identification of symptoms and the implementation of appropriate preventive and treatment measures

**Keywords:** digital technologies; electronic systems; accounting automation; economic efficiency; audit and control

## INTRODUCTION

Knowledge of the diseases that can affect plant health and crop yield is essential for taking timely measures to prevent and control them. The use of fungicides and other chemical agents can be effective in combating diseases and preserving the harvest, particularly for tomatoes. It is important to continually update knowledge on new control methods and protective measures to safeguard agricultural crops from pests. Diseases of *Solanum lycopersicum*, caused by pathogenic microorganisms, are among the most dangerous biotic stresses, negatively impacting yield and causing significant damage in various countries, including Ukraine. Microscopic fungi, in particular, lead to substantial crop losses by parasitising plants, significantly reducing both the quality and quantity of agricultural produce.

Phytopathogens of *Solanum lycopersicum* produce toxins (mycotoxins), which pose a serious threat to human and animal health, as they can cause diseases and poisoning. This can lead to conditions such as aflatoxicosis and ochratoxicosis. To prevent widespread illness caused by micromycetes, it is essential to implement control and preventive measures, including the selection of resistant varieties, agronomic practices, fungicidal treatments, monitoring, control, chemical and biological remediation, and further research (Suresh *et al.*, 2022). Researchers such as A. El-Nagar *et al.* (2020), Z. Maskova *et al.* (2022) and A. Slama *et al.* (2022) have concluded that pathogenic fungi are the most prevalent microorganisms causing plant diseases, affecting up to 80% of crops. This conclusion highlights the importance of studying and controlling these microorganisms to ensure plant health and productivity. These research findings may prove valuable in developing strategies to combat phytopathogenic micromycetes and improve disease management in agriculture.

M. Attia *et al.* (2020) investigated that tomato plants can be affected by several disease pathogens, which can develop on all vegetative organs of the plants. They also analysed the antagonistic activity of *A. solani* and recorded the plant's metabolic resistance indicators in response to induced systemic resistance. The results showed that the isolates reduced disease development in the plant by 13%, with the plant's protective capacity reaching 84.3%. Y. Nehela *et al.* (2021), while studying the protective potential of benzoic acid and two of its hydroxylated derivatives (hydroxybenzoic acid and protocatechuic acid) against the *Alternaria* pathogen, found that all the compounds significantly reduced pathogen development. Hydroxylated derivatives and benzoic acid enhanced vegetative growth and yield. These findings highlight the physiological and biochemical mechanisms they possess. Researchers S. Panno *et al.* (2021) noted that, due to the genetic characteristics of tomatoes, they are susceptible to numerous pathogens (bacterial, fungal, viral, and phytoplasmal). Therefore, recognising symptoms and understanding the spread of diseases, along with early detection methods for pathogens, are key prerequisites for successful disease treatment. The scale and pace of tomato vegetable production, as well as the degree to which the population's demand for vegetables is met, are determined by the development of horticulture in the country.

Tomatoes (*Solanum lycopersicum* L.) hold a significant position among vegetable crops and are one of the most popular worldwide (FAOSTAT, n.d.). Prior to the full-scale invasion, Ukraine had up to 84.3 thousand hectares under tomato cultivation. By 2022, Ukraine ranked 13<sup>th</sup> globally in tomato production (2.4 million tonnes). However, by 2024, production had decreased to 1.3 million tonnes, placing Ukraine 19<sup>th</sup> globally. The production of fresh market and processed tomatoes

faces numerous challenges caused by diseases stemming from various pathogens. The main groups of pathogens affecting tomatoes include fungi, bacteria, and viruses (FAOSTAT, n.d.). Due to intensive breeding, cultivated tomatoes have reduced genetic diversity, making them more susceptible to over 200 diseases caused by various phytopathogens. This vulnerability has driven researchers to develop new varieties with greater resistance (Panno *et al.*, 2021).

This study aimed to identify and analyse the major diseases affecting tomatoes and to investigate chemical methods for controlling plant diseases and pathogens. To achieve this, the research tasks included analysing the informational basis of the study, as presented in the materials of scientific publications by international authors. These publications, indexed in databases such as Scopus and Web of Science (e.g., *International Journal of Molecular Sciences, Biological Control, Plants, Journal of Plant Biochemistry and Biotechnology, Biocontrol Science and Technology*), provided detailed insights into the chosen topic. The analysis and synthesis of these research enabled a comprehensive understanding of interrelated processes, leading to certain conclusions and the resolution of the research objectives. The abstract-logical method was used to highlight specific features and patterns, facilitating theoretical generalisation based on the obtained data. The object of the study included tomato plants and the pathogenic microorganisms that inhabit them. Over a year, a retrospective analysis of scientific publications on tomato diseases was conducted. No standards, legal acts, or laws were used in the presentation of the material in this article.

### PHYTOPATHOGENIC MICROMYCETES AS DISEASE AGENTS IN TOMATO AGROECOSYSTEMS

One of the most well-known and destructive diseases of tomatoes is fusarium wilt, caused by *Fusarium oxysporum*. This disease adversely affects tomato cultivation, causing significant damage at all stages of plant growth. It infects tomato plants and leads to crop losses ranging from 20% to 60, with some cases reporting losses of up to 90%. Additionally, high infection rates in tomato plants have been observed at temperatures around 27°C (Hassan, 2020). For instance, *Fusarium*-induced crop damage in Egypt reached up to 67% (Srinivas *et al.*, 2019).

Fungi of the genus *Fusarium* spp. can also produce secondary metabolites (mycotoxins) in food products, which can lead to contamination in humans and other animals (Alamri *et al.*, 2018; Lombard *et al.*, 2019). In the study of S. Magar *et al.* (2020), it was reported that the application of tebuconazole, and carboxin thiram effectively suppressed mycelium growth, while captan and azoxystrobin showed minimal inhibition, with

untreated controls revealing pathogen suppression from ridomil. Agricultural chemicals are commonly used for pest and disease management. Seed treatments with fungicides significantly reduce the incidence of tomato diseases. Key chemicals used to control plant diseases include prochloraz, propiconazole, thiabendazole, carbendazim, benomyl, thiophanate, fuberidazole, and others.

It has been reported that benomyl was partially effective against *F. oxysporum* f. sp. *cubense* using the root-dipping method. This method was also applied with carbendazim on tomato seedlings infected with fusarium wilt, increasing yield by approximately 24% (Hagos *et al.*, 2020). It is worth noting that the overuse of broad-spectrum fungicides adversely impacts the environment and increases the resistance of pathogens to chemical treatments (Kabaş *et al.*, 2020). Another of the most prevalent diseases affecting tomatoes, caused by phytopathogenic fungi, is late blight, caused by *Phytophthora infestans* (Hagos *et al.*, 2020). The detrimental effects of this disease on plants lead to significant agricultural losses worldwide each year. According to N. Jiang *et al.* (2018), in Mongolia, China, and the USA, the late blight pathogen caused substantial tomato production losses in the early 2000s. In the 21<sup>st</sup> century, the molecular mechanisms of tomato resistance to *P. infestans* remain insufficiently studied, and methods for controlling late blight in tomatoes are still not sufficiently effective.

Infected tomato plants die rapidly. Under high humidity, a light fungal spore coating appears on the plants. Tomatoes become infected with late blight at air humidity levels around 90% (not less than 76%) and at an air temperature of +20°C (Njoroge *et al.*, 2019). Systemic fungicides play a crucial role in combating late blight; however, in cases of disease and favourable environmental conditions, fungicides may not effectively control this destructive issue. Furthermore, the regular use of fungicides contributes to the development of resistance in *P. infestans*. Increased attention is being paid to biological control of crops in the event of disease as an environmentally safe alternative to chemical pesticides. However, biological control agents alone are not sufficiently powerful to combat the threat of devastating late blight under field conditions (Haveri *et al.*, 2018). These factors suggest a need to formulate an integrated system for disease management. Additionally, researchers have explored the potential of using antagonistic bioagents to suppress late blight in tomatoes (Zhi *et al.*, 2021).

In Cameroon, farmers growing tomatoes reported that outbreaks of disease exacerbated the difficulties in maintaining unaffected areas (Vincent *et al.*, 2023). Combating late blight requires aggressive protective measures, which include a combination of host plant

resistance and the application of fungicides. Gardeners also utilise various fungicides, such as mancozeb, agrolaxyl, metalaxyl, copper, phosphonic acid, and ridomil (Alamri *et al.*, 2018; Arafa *et al.*, 2022). Among the many available alternative measures, the use of resistant varieties is the most crucial and cost-effective approach to managing the disease (Kassaw *et al.*, 2021). The application of fungicides is a common factor in the early control and management of late blight, both in greenhouse cultivation and field conditions. Additionally, some fungicides exhibit beneficial growth-promoting and physiological effects on plants, leading to a delay in leaf senescence and an increase in chlorophyll content (Arafa *et al.*, 2022). This may contribute to higher yields. Similarly, the results of other field trials indicated that fungicides with systemic or translaminar activity were more effective than protective fungicides (Zafar & Shaukat, 2018).

Another dangerous and damaging disease of tomatoes is early blight, primarily impacting the foliage of the tomato plant. High humidity and temperatures ranging from +24 to +29°C, along with frequent rainfall, create favourable conditions for the growth and spread of *Alternaria solani*. Tomato yield losses can reach up to 80%. To prevent infection by this disease, the use of healthy seeds is essential. Additionally, the pathogen *A. solani* can survive in plant debris and soil through conidia and chlamydospores (Matić *et al.*, 2020). The application of fungicides is crucial for effective control of *Alternaria* leaf spot. Researchers J. Marek *et al.* (2018) noted that many fungicides are registered for combating this disease, particularly those from the chemical groups of strobilurins and carboxamides. Strobilurin fungicides inhibit mitochondrial respiration by blocking electron transport, preventing the proper production of adenosine triphosphate. Similarly, the mode of action of carboxamides involves the inhibition of the enzyme succinate dehydrogenase, thereby reducing the respiratory process by blocking its supply to the fungus.

Among the dangerous diseases affecting tomato agroecosystems is grey mould, caused by the pathogen *Botrytis cinerea*. Under favourable conditions (temperatures up to +20°C and humidity levels of 90%), this ascomycete can cause devastating grey mould infections on tomato plants, leading to yield losses of 20-40% (de Vega *et al.*, 2021). The phytopathogen *Botrytis cinerea* can overwinter in the soil (in the form of sclerotia) and in plant debris. The primary strategy for managing grey mould involves the application of fungicides, including benzimidazoles, quinone inhibitors, phenylpyrroles, and carbamates (Yan *et al.*, 2022). Effective control of *Botrytis cinerea* in agroecosystems is critically important for ensuring stable production. As *Solanum lycopersicum* is

a vital crop in the agricultural sector, a successful tomato harvest directly impacts the economic stability of farming enterprises and food security.

### PHYTOPATHOGENIC BACTERIA (BACTERIOSES) AS PATHOGENS OF DANGEROUS DISEASES ON TOMATO PLANTS

Bacterioses, like mycoses, pose a serious threat to tomato crops, causing localised epidemics and widespread crop damage (Njoroge *et al.*, 2019; Borzykh *et al.*, 2022). The most common disease is the bacterial canker of tomatoes (caused by *Clavibacter michiganensis*). This pathogen inflicts substantial damage to tomato crops across various countries. At optimal temperatures (+26°C), the pathogen can lead to extensive infections and yield losses of up to 85%. The phytopathogen *C. michiganensis* can survive on seeds and in plant debris.

Disease symptoms usually appear between the fruit setting period and the beginning of ripening, making disease control critical at all stages of plant growth and development. Biological control of pathogenic bacteria involves the use of composting systems, beneficial fungi or bacteria with antagonistic properties against pathogenic bacteria (certain strains of *Bacillus* or *Pseudomonas*). The introduction of beneficial microorganisms (*Trichoderma* spp. or *Bacillus* spp.) into the rhizosphere can suppress the development of pathogenic bacteria through competition or antagonism (Kulimushi *et al.*, 2021). Additionally, the use of phytopathogenic bacteria (*Pseudomonas fluorescens*, *Bacillus subtilis*), which are natural antagonists of pathogens, is promising. However, these biological control methods have shown moderate effectiveness (Zhou *et al.*, 2021). The most recommended methods for detection, prevention, and control of tomato plant pathogens are based on: isothermal amplification, which allows for rapid and sensitive detection of pathogen DNA; end-point visual analysis (detection of specific antigens or antibodies); limiting excess nitrogen fertilisers (optimising fertiliser dosage helps reduce the risk of infection); and seed treatment using high temperatures to reduce the level of infectious load (Haveri *et al.*, 2018; Njoroge *et al.*, 2019). The use of these methods can reduce environmental risks and enable the production of environmentally friendly products.

Another common bacterial disease affecting tomatoes is leaf spot, caused by *Pseudomonas syringae*. The optimal temperature range for the development of this bacterium is between +13 and +28°C, and high humidity further promotes its spread and proliferation (Zhou *et al.*, 2021). Outbreaks of bacterial leaf spots can result in yield losses of up to 75%. The dissemination of this pathogen occurs through infected seeds. The most

recommended methods for the detection, prevention, and diagnosis of *Pseudomonas syringae* include polymerase chain reaction and isothermal amplification, which effectively identify the DNA of pathogens (Njoroge *et al.*, 2019). To prevent the spread of *Pseudomonas syringae*, it is essential to use healthy seeds, implement measures to reduce humidity in fields and greenhouses and conduct regular monitoring of plants. According to J. Köhl *et al.* (2020), the application of copper-based bactericides can help reduce the level of infection in tomato plants. Additionally, bacterial strains such as *P. aeruginosa*, *P. fluorescens*, *P. syringae*, *B. stratosphericus*, and *Azospirillum brasilense* enhance plant growth and improve resistance to viruses.

### PHYTOPATHOGENIC VIRUSES IN TOMATO AGROECOSYSTEMS

Viruses exhibit a high potential for rapid adaptation to their environment, including within tomato agroecosystems. This adaptability is facilitated by the high population density and the short generation time for reproduction and spread. When they infect tomato plants, these pathogens lead to decreased yields and reduced quality of cultivated crops (El-Garhy *et al.*, 2020). The most prevalent disease in tomato agroecosystems is the *tomato spotted wilt virus*, which can cause losses of up to 95% depending on the severity of the infection and the developmental stage of the plants. Infection occurs primarily through insect vectors, with mites being the main carriers of the disease (Qi *et al.*, 2021). The optimal temperature range for disease development is between +18 and +27°C and higher.

The most effective methods for controlling and preventing *tomato spotted wilt virus* include selecting tomato varieties that are less susceptible to the virus; controlling vectors through monitoring and management of mite populations; employing agronomic practices; using disease-free seeds and managing plant debris. Integrating these methods creates an effective management system that reduces the risk of virus spread and protects yields. Chemical control of *tomato spotted wilt virus* in tomato cultivation is a crucial aspect of disease management. The primary approaches to chemical control of this virus include the use of fungicides, insecticides, growth regulators, and herbicides. Therefore, controlling *tomato spotted wilt virus* requires a comprehensive approach that encompasses not only chemical means but also agronomic practices that help mitigate the risk of infection and virus spread (Haresabadi *et al.*, 2023).

According to F. Hemmati *et al.* (2023), a significant threat in tomato agroecosystems is the *cucumber mosaic virus*. This virus can adapt to changes in its environment, enabling it to damage various plant species. It is

transmitted primarily by insects, particularly aphids, and can result in nearly 100% yield loss in tomatoes (Longe *et al.*, 2022). The *cucumber mosaic virus* can have severe consequences for tomato productivity, including reduced yield; a decrease in both the quantity and quality of fruit; diminished plant vigour and economic losses. Therefore, effective management and control necessitate a comprehensive approach that incorporates both chemical and agronomic methods. The most effective strategies for managing and controlling this virus include the use of chemical and agronomic measures such as insecticides, systemic insecticides, phytosanitary practices, management of agronomic techniques, optimisation of plant care, regular irrigation and fertilisation, sanitation of plants, and the use of resistant varieties. Another dangerous disease posing a serious threat is the *tomato yellow leaf curl virus*. Under favourable conditions for the pathogen, yield losses can reach up to 100%. This plant disease is transmitted by insect vectors and their hosts (Vincent *et al.*, 2023).

Similar to the *cucumber mosaic virus*, the *tomato yellow leaf curl virus* can have severe consequences for tomato yield, including reduced productivity; lower quality and size of fruit; decreased fruit quantity; and economic losses (El-Sappah *et al.*, 2022). Chemical control of the *tomato yellow leaf curl virus* focuses on managing its vectors, as the virus itself cannot be treated with chemical agents. To enhance tomato yield and quality, the following control methods should be employed: phytosanitary measures; vector control (insecticides); crop rotation; and the use of resistant varieties, among others (Kumar *et al.*, 2023). Implementing these methods in conjunction with agronomic practices will aid in more effectively controlling the virus and mitigating its impact on yield.

According to L.E. González *et al.* (2021), the most prevalent virus affecting tomato plants is the *tomato mosaic virus*. This aggressive pathogen causes disease in tomatoes and can inflict significant damage to yields. When cultivated tomato plants are infected, yield losses can range from 30 to 75%. One of the primary pathways for the virus's transmission is infected seeds. Weather and climatic conditions can also influence the manifestation of the disease symptoms. Furthermore, this virus can remain active in infected seeds for up to ten years (Kesksé *et al.*, 2019). Research on treating tomato plants has been conducted using zinc oxide. The results demonstrated an enhancement in the plant's immunity against this disease. At 45 to 160 days post-sowing, the plants treated with ZnO nanoparticles exhibited improved growth and photosynthetic properties, increased activity of various antioxidant enzymes, and higher levels of proline and protein compared to

untreated plants. The number of fruits and the yield of plants treated with ZnO nanoparticles were also higher (Faizan *et al.*, 2020; Arafa *et al.*, 2022). In contrast to some other viral diseases, there are no effective chemical agents available for the control or treatment of the *tomato mosaic virus*. Therefore, preventive measures and control of infection are crucial.

An analytical review of the scientific and technical literature allows for the summarisation of the main diseases affecting tomatoes both in Ukraine and globally, as well as the identification of their harmful effects. A systematic analysis of chemical methods for controlling phytopathogens in tomato agrocenoses enables the selection of environmentally safe products, which will reduce pesticide contamination in agroecosystems. This, in turn, will significantly enhance biodiversity levels in agroecosystems, restore balance in the microbiota of agroecosystems, and decrease the cost of plant raw materials. Such measures will reduce the risk of epiphytotics and improve the quality of tomato raw materials. Therefore, the integration of effective disease control and the timely implementation of a comprehensive approach will help mitigate ecological risks, protect yields, and cultivate high-quality, environmentally safe products.

## CONCLUSIONS

This review presents a retrospective analysis of the literature, highlighting harmful microorganisms (viruses, bacteria, and fungi) that affect tomato plants and negatively impact the agrocenoses of this crop. Pathogens interact with tomato plants, attacking their vegetative organs, which results in a decline in the quality of plant products, loss of yield, and partial or complete plant death. The influence of pathogens on tomatoes has been analysed, along with the degree of pest intensification in the plants, as well as methods for combating these pathogens. The functioning of fungicides from various chemical groups and origins against phytopathogens is also discussed, as they are a critical

factor in preventing the spread of diseases affecting tomato plants. The main diseases are caused by fungi of the genera *Alternaria*, *Fusarium*, *Phytophthora*, and *Botrytis*. Additionally, viruses (such as the *tomato spotted wilt virus* and the *tomato yellow leaf curl virus*) and bacteria (including bacterial canker of tomatoes and bacterial spot) are also covered.

Chemical control in agriculture plays a crucial role in addressing the challenges posed by pathogens affecting tomatoes. It is essential to utilise appropriate chemical agents, taking into account the type and stage of the disease. This approach will facilitate the effective management of tomato plant diseases and enhance their yield. Understanding the primary diseases that can afflict tomatoes enables the timely identification of disease symptoms and the prompt implementation of preventative and therapeutic measures. Effective plant protection substances against pathogens include chemicals such as thiabendazole, prochloraz, benomyl, propiconazole, thiofanate, and fuberidazole. For the control of plants infected with *Phytophthora*, effective fungicides include agrolyxil, mancozeb, ridomil, copper, and phosphonic acid. In the fight against *Alternaria*, carbamate and strobilurin fungicides are recommended, while for grey mould, the use of benzimidazole, phenylpyrroles, and quinone inhibitors is effective. The information gathered has allowed for an analysis of tomato diseases and their pathogens, as well as a review of the chemical agents used and their impact on these diseases. This knowledge will enable agricultural producers to promptly identify issues and take necessary actions to cultivate high-quality yields with minimal damage and loss.

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## CONFLICT OF INTEREST

None.

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## Огляд основних хвороб *Solanum lycopersicum* та методи хімічного контролю патогенів

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**Анотація.** У статті наведено перелік основних хвороб рослин томатів (*Solanum lycopersicum*), що спричиняються вірусними, бактеріальними та фітопатогенними мікроорганізмами. Патогенні мікроорганізми, паразитуючи на рослинах томатів, викликають великі втрати врожаю в сільськогосподарському виробництві, знижуючи якість продукції. Метою дослідження було з'ясувати вплив мікроорганізмів на рослини томатів, ступінь їх шкодочинності та методи боротьби зі збудниками хвороб. Встановлено, що основні хвороби рослини томатів викликані грибами роду: *Fusarium* (фузаріоз), *Phytophthora* (фітофтороз), *Botrytis* (сіра гниль), *Alternaria* (альтернаріоз); віруси *Omato spotted wilt virus* (вірус плямистого в'янення), *Tomato yellow leaf curl virus* (вірус жовтого скручування листя), бактерії *Ascochyta cucumis* (бактеріальний рак томатів), *Xanthomonas vesicatoria* (бактеріальна плямистість). Проаналізовано, що сільськогосподарські хімікати є важливою складовою для управління шкідниками та хворобами, тому основним засобом боротьби з хворобами рослин є хімічні речовини, такі як прохлораз, тіабендазол, пропіконазол, карбендазим, беноміл, тіофант, фуберідазол та ін. Досліджено, що системні фунгіциди відіграють важливу роль у боротьбі з різними хворобами, виявляють корисну фізіологічну або стимулюючу ріст дію на рослини, включаючи затримку старіння листя, підвищення вмісту хлорофілу. Встановлено, що у боротьбі з альтернаріозом ефективним є застосування фунгіцидів (хімічна група стробілурін і карбоксамід), а основною стратегією боротьби з сірою гниллю є хімічний контроль шляхом застосування синтетичних фунгіцидів: інгібітори хінону, бензімідазолу, карбамати, фенілпіроли та інгібітори сукцинатдегідрогенази. Огляд хвороб та методів хімічного контролю патогенів є надзвичайно корисним для застосування у сільському господарстві. Практична цінність дослідження полягає в тому, що ця інформація допомагає сільськогосподарським виробникам ефективно управляти врожаєм та зберігати якість плодів. Знання про основні хвороби, які можуть уражувати томати, дозволяє вчасно виявляти симптоми та вживати відповідні заходи для їх запобігання та лікування

**Ключові слова:** мікроскопічні гриби; томати; хімічні речовини; бактерії; віруси; агроценоз

## Digitalisation of accounting of agricultural enterprises: National and international experience

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**Abstract.** The study aimed to analyse the peculiarities of the introduction of digital technologies in the field of accounting at agricultural enterprises, in particular, the analysis of national and international experience. The study analysed the process of digitalisation of accounting at agricultural enterprises in Ukraine, which is an important step towards improving management efficiency, reducing operating costs and ensuring compliance with modern regulatory requirements. The analysis of the main trends in the implementation of automated accounting and financial accounting systems demonstrated that such systems allow agricultural enterprises to automate routine processes, reduce the number of errors and reduce the time for preparing financial statements. The study

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also revealed several challenges towards the full digitalisation of accounting, including insufficient technical infrastructure, lack of qualified personnel, and low digital literacy. Insufficient funding and regulatory barriers are also serious challenges for businesses. Particular attention was devoted to cybersecurity issues, which are increasingly relevant due to the growth of digital data. The study compared the Ukrainian experience with the experience of the European Union, the United States, and Canada, where the digitalisation of accounting has reached a high level. The study proposed recommendations for the successful implementation of digital technologies in accounting processes at agricultural enterprises in Ukraine, addressing the existing limitations and opportunities. The study emphasised the importance of auditing the existing digital infrastructure, investing in equipment upgrades, staff training, gradual introduction of new technologies, and partnerships with leading digital solution providers. The findings emphasise the significant potential of digitalisation to increase the efficiency, transparency, and competitiveness of Ukrainian agricultural enterprises, but achieving these goals requires a balanced approach to the introduction of new technologies, government support, and appropriate educational training. The results obtained in this study can be used to improve the digitalisation of accounting at Ukrainian agricultural enterprises, increase the efficiency of financial management and adapt international standards to local conditions

**Keywords:** digital technologies; electronic systems; accounting automation; economic efficiency; audit and control

## INTRODUCTION

Digitalisation in the modern world has become an indispensable part of any part of the economy, including the agricultural sector. Changes in financial and accounting processes management are caused by global digital transformation, affecting all aspects of enterprises. Accounting, being central in enterprise management, is also affected by these changes. As such, the issue of digital technology implementation into accounting becomes especially relevant. The agricultural sector is one of the most dynamic and yet highest-risk sectors of the economy, where proper accounting is critical in the stability and efficiency of an enterprise. However, due to the specifics of agricultural enterprises, especially seasonal nature, dependency on natural conditions and high competition, traditional accounting approaches are often insufficiently effective. Therefore, the implementation of digitalisation is required for proper accuracy, speed and transparency of accounting processes. One of such key issues is lacking most agricultural enterprises from overall digital transformation processes. This is caused by several reasons, such as insufficient funding, improper personnel training, lack of required infrastructure and cybersecurity concerns. In addition, there is an issue of integrating new digital solutions with existing accounting systems, which requires additional resources and time.

Digitalisation of accounting involves the integration of modern information systems that automate accounting and reporting processes. This includes employment of software to manage financial flows, maintain electronic documents and ensure timely reporting. National and international experience in this area is also an important aspect. Countries that are actively implementing digital technologies in accounting are showing significant progress in increasing the efficiency

of agricultural production and reducing operating costs. The use of automated accounting systems helps to unify processes and ensure high accuracy and reliability of financial reporting. At the same time, the experience of advanced countries can be useful for adapting these practices in the national context.

Thus, the study of Ukrainian and international experience in the field of digitalisation of accounting at agricultural enterprises is important for developing effective strategies for the introduction and adaptation of new technologies, which will help to increase the competitiveness and sustainability of the agricultural sector. Several authors described the trends, challenges and prospects for the introduction of digital technologies. F. Costa *et al.* (2023) analysed the impact of digital technologies on the efficiency of financial accounting in the agricultural sector. As determined, businesses that implement automated accounting systems have fewer errors in their financial statements and can reduce their accounting services costs. K. Poppe *et al.* (2023) reviewed the experience of agricultural companies in the digitalisation of accounting, focusing on the importance of compliance with regulatory requirements. As demonstrated, automation of accounting processes increases the transparency of financial reporting and reduces the risk of financial sanctions. V. Goi *et al.* (2023), in turn, investigated the role of cybersecurity in the process of digitalisation of accounting. The authors highlighted that data protection is critical to maintaining the confidentiality of financial information. D.M. Coman *et al.* (2022) also analysed the digitalisation of accounting, finding that one of the main problems is the lack of sufficient infrastructure.

M. Petchenko *et al.* (2023) studied the impact of digitalisation on the financial statements of enterprises

and concluded that enterprises that implement artificial intelligence technologies demonstrate increased efficiency in resource management. A.M. Ciruela-Lorenzo *et al.* (2020) addressed peculiarities of introducing digital technologies into the accounting systems of agricultural enterprises. The authors identified that agricultural companies are actively integrating software solutions to automate financial processes, but face difficulties due to the lack of adaptation of the software to local conditions. D. Radicic & S. Petković (2023) analysed the impact of accounting digitalisation on small and medium-sized businesses in the agricultural sector. The authors noted that small businesses have difficulty implementing digital systems due to limited financial resources and a lack of qualified specialists.

I. Lomachynska *et al.* (2023) concluded that digital technologies can help improve environmental performance through more accurate resource planning and accounting. M. Eulerich *et al.* (2024) determined that automation of accounting processes contributes to an increase in the level of internal control and a reduction in financial fraud. H.J.P. Marvin *et al.* (2022) addressed the role of artificial intelligence in the digitalisation of accounting in the agricultural sector. Their results show that the use of AI technologies can significantly improve accounting accuracy and reduce the time required to prepare financial statements.

Previous research confirms that the digitalisation of accounting is an important and complex process that requires a comprehensive approach, accounting for national peculiarities and international experience. However, the analysed studies insufficiently address the specifics of the digitalisation of accounting at small and medium-sized agricultural enterprises, especially in the context of their impact on competitiveness and long-term sustainability. There is also a lack of research on the integration of artificial intelligence into agricultural accounting systems, considering regional peculiarities and legislative requirements.

The study aimed to analyse the impact of accounting digitalisation on the competitiveness of agricultural enterprises, considering regional peculiarities and legislative requirements. Moreover, the study analysed the impact of accounting digitalisation on the productivity of small and medium-sized agricultural enterprises, as well as assessed the opportunities and challenges of integrating artificial intelligence into accounting systems in the agricultural sector, considering regional peculiarities.

## MATERIALS AND METHODS

A comprehensive methodology that included both primary and secondary sources of information was employed. The main materials of the research were

legislative and regulatory acts of Ukraine, analytical reports, studies, and a review of software products implemented by agricultural enterprises for accounting automation. The first step was to study the legal framework governing accounting in Ukraine. In particular, the Law of Ukraine No. 996-XIV (1999), which is the main document defining the principles of accounting and financial reporting, and the Law of Ukraine No. 851-IV (2003), which regulates the use of electronic documents in commercial activities, were analysed in detail. In addition to these laws, several bylaws and regulations address specific aspects of digitalisation, such as electronic reporting standards, data protection requirements and other regulations that affect the process of transition to digital accounting methods (Tax Code of Ukraine, 2010; Order of the Ministry of Finance of Ukraine No. v0433201-13, 2013; Law of Ukraine No. 2155-VIII, 2017). Legislation governing state support for the agricultural sector, including financing and subsidy programmes, as well as rules defining agricultural insurance mechanisms, were also reviewed in detail (Law of Ukraine No. 1877-IV, 2004; Law of Ukraine No. 4391-VI, 2012).

Particular attention was also devoted to the analysis of software products used by agricultural enterprises to automate accounting. Such solutions as MASTER, BAS ERP, QuickBooks, Xero, M.E.Doc, and other software products that are most common on the market were addressed. The analysis covered the functionality of these programmes and the level of adaptation to the needs of Ukrainian agricultural enterprises. The functionality of these systems, the level of their adaptation to the needs of Ukrainian agricultural enterprises, and their effectiveness in different conditions, such as limited Internet access in rural areas or the need to work with large amounts of data, were assessed. The current state of digitalisation of accounting globally was also addressed, emphasising the comparison of Ukrainian achievements with international standards. Analysis of digitalisation practices in countries such as Estonia (Dubinina *et al.*, 2022), Germany (Tiberius & Hirth, 2019), Sweden (E-Invoicing in Sweden, 2023), Italy (SDI Italy..., 2021), USA (McCumiskey & Wolfson, n.d.), Canada (Dhaliwal *et al.*, 2023) and Ukraine (Koval & Lyshak, 2024) has revealed important aspects and new approaches in the field of accounting. The study of practices in these countries helped to identify opportunities for adapting these approaches to the Ukrainian context. The study determined which of these international practices can be effectively used to improve the digitalisation of accounting at Ukrainian agricultural enterprises, accounting for the specific conditions and requirements of the local market.

## RESULTS

At a time when digital technologies are increasingly penetrating all spheres of life, the agricultural sector remains on the sidelines of the digitalisation process. This is especially true in Ukraine, where agricultural enterprises are one of the key sectors of the economy. The digitalisation of accounting at such enterprises is becoming an integral part of their operations, as it can increase management efficiency, reduce operating costs, and ensure compliance with modern regulatory requirements (Knudsen, 2020). One of the main trends in the digitalisation of accounting in the agricultural sector of Ukraine is the introduction of automated accounting and financial management systems. These systems can be used to automate routine accounting processes, reduce errors and shorten the time required to prepare financial statements in agricultural enterprises. The use of specialised software around the world, such as MASTER, BAS ERP and other solutions, was used to integrate all financial processes into a single system, ensuring transparency and control over all aspects of accounting.

Another important aspect of the Ukrainian experience is the active introduction of electronic document management. The transition from paper to electronic documents greatly simplifies financial information processing, speeds up the exchange of data between different departments of the enterprise and ensures more reliable data storage. This is especially true for agricultural enterprises, where large amounts of information require efficient management and quick access to data. Another trend is the integration of accounting with other enterprise information systems, such as production, logistics and human resources management systems. This integration allows for the creation of a single information ecosystem where all processes are interconnected and can be effectively managed (Syrtseva *et al.*, 2022). This contributes to more accurate planning and analysis of financial flows, which is key to the successful functioning of an agricultural enterprise in a constantly changing market environment.

The digitalisation of accounting at agricultural enterprises has significant potential to increase efficiency, transparency and competitiveness. However, there are several problems and challenges on the way to full integration of digital technologies that need to be addressed. One of the most pressing issues is the lack of technical infrastructure, especially in rural areas where most agricultural enterprises are located. Insufficient access to high-speed internet, outdated computers, and limited opportunities to upgrade equipment pose serious obstacles to the effective implementation of digital technologies in accounting. Without modern infrastructure, businesses cannot

fully use software solutions that automate accounting processes and integrate them with other business systems. In addition to technical limitations, the problem of staff shortages and low levels of digital literacy is acute. Implementation of new accounting systems requires specialists who are well-versed in digital technologies and able to manage automation processes. However, many agricultural enterprises, especially small ones, do not have sufficient resources to train employees or hire IT specialists. This limits opportunities for full digitalisation and increases the risk of errors in financial accounting.

Another obstacle to digitalisation is the inadequacy of the legal framework and regulatory barriers. The rapid development of digital technologies is outpacing legislative updates, which creates legal conflicts and complicates the work of businesses. Existing accounting standards are often not adapted to the digital environment, making it difficult to apply them in practice. In addition, regulatory requirements for the storage and protection of electronic data may be overly complex or not fully defined, creating additional challenges (Gonçalves *et al.*, 2022). As the volume of digital data increases, another serious problem arises – cybersecurity concerns. Agricultural enterprises that switch to digital accounting become more vulnerable to cyberattacks, which can lead to the loss or compromise of confidential financial information. Implementing effective cybersecurity systems requires significant investment, which is not always affordable for small and medium-sized enterprises. Many companies are not sufficiently aware of modern cyber threats, which increases risks in this area (Sontowski *et al.*, 2020).

An equally important challenge is the unwillingness to change and organisational barriers that arise in the process of digitalisation. Changes to familiar workflows, the transition to new technologies and the need to train employees are often met with distrust and resistance. Many managers and employees prefer traditional accounting methods, which slows down the digital transformation process. In addition, the high cost of implementing digital solutions is a significant obstacle for many agricultural enterprises. Software licences, the purchase of new equipment and staff training require significant financial investments (Scholkmann, 2021). For many enterprises, this becomes a critical barrier, forcing them to postpone the introduction of new technologies or limit themselves to minimal investments in digitalisation.

The level of digitalisation of accounting for agricultural enterprises in Ukraine varies depending on the scale of the enterprises, their financial condition, regional characteristics and access to modern

technologies. At large agricultural enterprises, especially those that export or cooperate with international partners, the digitalisation of accounting has already reached a high level. Such companies actively employ specialised software solutions, such as Enterprise Resource Planning (ERP) systems, which allow them to integrate accounting with other business processes, ensuring automation of routine operations and transparency of financial reporting.

The level of digitalisation in small and medium-sized agricultural enterprises is much lower. The main reason for this is limited financial resources that do not allow investing in the implementation of modern IT solutions. Many small agricultural enter-

prises still use traditional accounting methods, such as paper-based documentation and local computer programs, which significantly reduces the efficiency of accounting processes and increases the risk of errors. This also creates difficulties when integrating with other management systems or when it comes to complying with new regulatory requirements. The digitalisation of accounting at agricultural enterprises in Ukraine is a complex and multifaceted process that requires consideration of numerous regulations (Table 1). These acts create a legal framework for the introduction of digital technologies, define accounting standards, regulate the exchange of electronic data, and ensure the protection of financial information.

**Table 1.** The main legal acts regulating the process of digitalisation of accounting of agricultural enterprises in Ukraine

Legal act	Content
Law of Ukraine No. 996-XIV "On Accounting and Financial Reporting in Ukraine" (1999)	Defines the basic principles of accounting, and the obligations of companies to keep records and prepare financial statements. Allows the use of electronic documents in accounting and sets out the rules for the use of electronic signatures.
Law of Ukraine No. 851-IV "On Electronic Documents and Electronic Document Management" (2003)	Regulates the procedure for creating, storing and using electronic documents and establishes their legal force. Allows agricultural enterprises to use electronic document management to exchange financial data with counterparties and government agencies.
Law of Ukraine No. 2155-VIII "On Electronic Identification and Electronic Trust Services" (2017)	Establishes the legal framework for the use of electronic signatures, seals and other means of electronic identification. Ensures the security and authenticity of electronic documents used in the process of digitalising accounting.
Tax Code of Ukraine (2010)	Enables the submission of tax reports digitally, which simplifies the interaction of agricultural enterprises with the tax authorities. This is relevant for companies with a complex taxation system related to different types of activities.
Order of the Ministry of Finance of Ukraine No. v0433201-13 "On the Approval of Methodological Recommendations for Filling Out Financial Reporting Forms" (2013)	Approves the Methodological Recommendations for the preparation of financial statements, accounting for the possibility of using electronic accounting systems. Determines the specifics of reflecting financial transactions in the reporting concerning digital technologies.
Law of Ukraine No. 1877-IV "On State Support of Agriculture of Ukraine" (2004)	Establishes provisions on the accounting of agricultural activities that should be addressed during the digitalisation of accounting at agricultural enterprises.
Law of Ukraine No. 4391-VI "On the Peculiarities of Insurance of Agricultural Products with State Support" (2012)	Includes provisions affecting the accounting of agricultural activities, in the context of the digitalisation of accounting processes at agricultural enterprises.

**Source:** compiled by the authors

Digitalisation of accounting is one of the key trends transforming modern businesses, particularly in the European Union (EU). In this area, European countries demonstrate advanced approaches to the introduction of digital technologies that increase transparency, efficiency and accuracy of accounting (Dubinina *et al.*, 2022). The experience of EU countries can be used as an example for other countries seeking to modernise accounting systems. One of the leading examples is Estonia, which is known for its advanced digital infrastructure. Estonia was one of the first countries to implement a full electronic document management system at the state level, including accounting. All businesses can submit financial statements and other documents exclusively in electronic format through special

platforms such as X-Road. This simplifies accounting procedures and interaction with government agencies, ensuring efficiency and convenience for business. This approach reduces administrative costs and speeds up inspection and audit processes.

Germany also demonstrates successful experience in the field of digitalisation of accounting. One of the most important initiatives is the introduction of electronic reporting through the Elektronische Steuererklärung (ELSTER) system, which allows for the submission of tax returns electronically. This system is widely used by businesses and individuals, which helps to increase the efficiency of tax administration and reduce errors associated with manual data processing. In addition, Germany is actively developing electronic

data interchange standards, such as ZUGFeRD, which are used to automate invoice processes (Tiberius & Hirth, 2019).

In Sweden, a country with one of the most developed digital economies, the digitalisation of accounting is also at a high level. Sweden actively supports the electronic submission of accounting reports and uses systems for automated data exchange between businesses and government agencies. For instance, using the Pan-European Public Procurement On-Line (PEPPOL) platform, businesses can exchange electronic invoices and other financial documents, which simplifies accounting and reporting management processes (E-Invoicing in Sweden, 2023). Italy also introduced mandatory e-reporting for businesses through the Sistema di Interscambio (SDI) system, which is used to submit invoices electronically. This system provides for the automatic exchange of data between businesses and tax authorities, which contributes to the efficiency of accounting processes and reduces opportunities for tax evasion (SDI Italy..., 2021).

The United States of America is a leader in the adoption of digital technologies in accounting due to the widespread use of cloud-based platforms and automated financial management systems. Systems such as QuickBooks and Xero are widely used in the US to help small and medium-sized enterprises automate accounting processes, reduce human errors and ensure the accuracy of financial reports. Another important aspect is the introduction of eXtensible Business Reporting Language (XBRL) standards, which provide

a standardised format for financial reports and their automated processing. In the United States, this process is guided by the Sarbanes-Oxley Act, which requires transparency and accuracy of financial reports, as well as the Gramm-Leach-Bliley Privacy Act, which regulates the protection of financial information (McCumiskey & Wolfson, n.d.). Canada also has significant advancements in the field of accounting digitalisation. This country actively uses platforms for electronic filing of financial statements and tax returns, such as the CRA's My Business Account, which simplifies the interaction between businesses and tax authorities. In addition, Canada supports initiatives to develop standards for the automated exchange of financial data, such as CPA Canada's Accounting Technology Framework. The regulatory framework includes the Canadian Corporate Financial Reporting Act and the Information Privacy Act, which govern the processing and protection of financial data (Dhaliwal *et al.*, 2023).

In Ukraine, the main systems for digitalising accounting are InfoTAX, iFin, and MASTER: Accounting, which are widely used by enterprises. These solutions automate the accounting of financial transactions, electronic document management and integration with government systems, such as the tax reporting system. Considerable attention is paid to the use of electronic signatures for the legal authenticity of documents, as well as cloud technologies for data storage and exchange (Koval & Lyshak, 2024). Table 2 compares the experience of different countries in the development of the digitalisation of accounting.

**Table 2.** Comparison of accounting digitalisation features in different countries as of 2024

Country	Key systems and technologies	Source	Main features
Estonia	X-Road	M. Dubinina <i>et al.</i> (2022)	Full electronic document management, including interaction between government agencies and businesses, reduction of paperwork through integration of the system with central registries, access to all public services online, and a high level of data protection through cryptographic technologies.
Germany	ELSTER, ZUGFeRD	V. Tiberius & S. Hirth (2019)	Electronic reporting with the ability to file tax returns and other reports online, electronic data exchange standards that automate the exchange of information between businesses and government agencies, and integration with banking systems to simplify financial transactions.
Sweden	PEPPOL	E-Invoicing in Sweden (2023)	Automated data exchange between companies and government agencies, electronic invoices to reduce paperwork, e-commerce standards that provide a unified data format for interaction, and widespread adoption of e-government for business convenience.
Italy	Sistema di Interscambio (SDI)	SDI Italy: The E-Invoicing Regulations (and what it means for businesses) (2021)	Mandatory electronic reporting for all companies, including automatic data exchange with tax authorities, electronic invoices, and the mandatory use of a special platform for submitting tax documents, ensures real-time monitoring of tax transactions.

Table 2, Continued

Country	Key systems and technologies	Source	Main features
USA	QuickBooks, Xero, XBRL	M. McCumiskey & A. Wolfson (n.d.)	Cloud-based platforms for financial and accounting management, XBRL standards for automating financial reports, which allow for uniform formats for presenting financial information, integration with various third-party applications and systems to improve business process management, and a high level of automation of accounting processes.
Canada	CRA's My Business Account, CPA Canada's Accounting Technology Framework	S.B. Dhaliwal <i>et al.</i> (2023)	Electronic filing of reports through the CRA's My Business Account platform, standards for automated data exchange that integrate tax systems with cloud platforms to simplify accounting and reporting, and support for various forms of electronic documents and payment transactions.
Ukraine	InfoTAX, iFin, MASTER: Accounting	O. Koval & O. Lyshak (2024)	Implementation of systems for electronic document management and accounting automation, integration of accounting systems with government services for reporting and tax payment, support for electronic signatures for the legal force of documents, use of cloud solutions for data exchange and information storage, specific adaptation to the needs of the agricultural sector in Ukraine.

**Source:** compiled by the authors

The introduction of artificial intelligence and automation is one of the main trends in the digitalisation of accounting. Artificial intelligence (AI) can significantly improve the accuracy of financial data processing, automate routine tasks and predict financial performance based on large amounts of data. For instance, AI can automatically analyse invoices, detect errors or fraudulent transactions, and provide detailed financial reports (Hasan, 2021). However, the implementation of such technologies requires large investments in software and hardware, as well as specialised knowledge to set up and maintain the systems. Moreover, agricultural enterprises may face problems integrating new technologies into existing accounting systems, which may require additional effort and time. Ukraine is characterised by a large agricultural sector, with the majority of businesses located in rural areas with limited access to high-quality internet and modern IT infrastructures. This poses additional challenges for AI and automation implementation, as even the most advanced technologies require a stable and fast internet connection to work with cloud services, update software, and maintain uninterrupted data exchange. For instance, in areas with poor internet connectivity, agricultural enterprises may face difficulties integrating AI into their accounting systems, which can lead to delays in automation processes and reduced efficiency.

Accounting outsourcing is substantial in the modern business environment, especially for agricultural enterprises, providing effective management of financial processes without the need for an in-house accounting department. Businesses can focus on core functions by outsourcing accounting to professional companies that

ensure a high level of accuracy and compliance with legal requirements. Accounting outsourcing can also reduce the cost of managing accounting processes, provide access to the latest technology and expertise, and increase flexibility in adapting to changing market and regulatory conditions (Asatiani *et al.*, 2019). However, all these challenges are also accompanied by opportunities. Investments in modern technology can significantly increase the efficiency of accounting processes, reduce human errors, and provide greater transparency in financial transactions. Agricultural enterprises that successfully implement these technologies can gain competitive advantages, such as higher accuracy of financial forecasts and optimisation of resources (Li & Gao, 2022). Thus, although the process of digitalisation of accounting is accompanied by certain challenges, its potential benefits make it an important step towards modernising the agricultural sector and ensuring its sustainable development.

In the context of active digitalisation of business processes, Ukrainian agricultural enterprises can significantly improve their financial reporting, management efficiency and market competitiveness. However, these goals require a balanced approach to the introduction of new technologies. Based on the above information, the following recommendations are made, which can help agricultural enterprises successfully adapt to digital transformation. The first step towards digitalisation is to assess the current state of the IT infrastructure. Agricultural enterprises should conduct a detailed audit of their information systems, including assessing the condition of servers, network devices, workstations and software. For instance, if a business uses outdated

versions of accounting software, this can make it difficult to integrate new technologies. An audit can identify weaknesses and be used to plan for necessary upgrades.

After the audit, IT investments are required. This includes purchasing modern accounting software that supports process automation and integration with other business systems. For instance, platforms such as Debit Plus, IT-Enterprise, and Bookkeeper provide comprehensive solutions for automating accounting and financial processes. They offer tools for digital document management, which significantly reduces paperwork and increases accounting efficiency. These systems can also be used to integrate accounting with other enterprise management systems, such as ERP systems, which help better coordinate financial and production processes. IT Enterprise supports the large amounts of data required by large agricultural companies, while Debit Plus and Bookkeeper are particularly useful for medium and small enterprises, offering user-friendly interfaces and tailored solutions for a variety of industries, including the agricultural sector. Increasing reliance on digital technologies increases the risk of cyberattacks, therefore effective cybersecurity is essential. This includes using data encryption, installing anti-virus software, setting up firewalls and implementing multi-factor authentication for access to accounting systems. The introduction of new technologies requires skilled personnel who can use modern tools effectively. Agricultural enterprises should invest in employee training, providing them with the necessary knowledge and skills. For instance, organising courses on the use of accounting automation software or the basics of cybersecurity can significantly increase work efficiency and reduce the risks associated with human error.

Cloud technologies can significantly simplify accounting management by providing access to data from anywhere and increasing the flexibility of business processes. Cloud-based platforms such as QuickBooks or Xero can be used to automate accounting, store financial data in a secure environment, and reduce the cost of maintaining local infrastructure. For agricultural businesses operating in remote regions or with limited IT resources, cloud-based solutions may be the best choice. Agricultural enterprises are advised to introduce new technologies gradually, testing them on individual business processes. This will help identify potential problems at an early stage and avoid significant financial losses. For instance, a company may initially automate only a part of accounting operations, such as cost accounting or invoicing, and after successful testing, extend automation to other processes.

Cooperation with leading IT solution providers can provide access to the most advanced technologies and

expert support. This will allow agricultural enterprises to implement new technologies faster and with less risk (Hedvall *et al.*, 2019). For instance, partnerships with companies specialising in ERP systems or cybersecurity can facilitate the digitalisation process and ensure its success. Government programmes and grants can be an important source of funding for the digitalisation of agricultural enterprises. Ukraine already has support programmes for small and medium-sized businesses that can cover part of the costs of implementing new technologies. Agricultural enterprises should actively engage in such programmes to get the necessary resources for modernisation. These recommendations will help Ukrainian agricultural enterprises to successfully adopt international experience in digitalising accounting, increase their efficiency and competitiveness, and ensure the sustainability and security of their financial systems.

## DISCUSSION

The results obtained indicate significant prospects for the digitalisation of accounting in the agricultural sector of Ukraine, but the process has its challenges that require attention and solutions. The main trends identified in the study indicate the active implementation of automated accounting and financial management systems that help reduce errors and increase the efficiency of financial flow management. Specialised software such as MASTER and BAS ERP can integrate financial processes into a single system, ensuring transparency and control over all aspects of accounting. M.A. Dayioğlu & U. Turker (2021) investigated the impact of digital transformation on increasing the productivity of agricultural enterprises in different regions. The authors argued that the introduction of Industry 4.0 technologies increased productivity. The current results partially coincide with the authors' findings, as productivity growth was also recorded, which may be due to different conditions and the degree of technology adoption in different regions.

M. Lezoche *et al.* (2020) studied the impact of digital technologies on grain supply chains. The authors noted that the use of blockchain technologies can increase the transparency and efficiency of these chains. The current results did not reveal such a significant impact of blockchain. Instead, the focus was on the efficiency of logistics process automation. Despite the obvious benefits of digitalisation, agricultural enterprises face several significant challenges that slow down this process. One of the key challenges is the lack of technical infrastructure, especially in rural areas where most agricultural enterprises are located. Inadequate access to high-speed internet, outdated equipment and limited opportunities for upgrading it pose serious obstacles to the effective implementation of digital technologies.

This confirms the need to develop technical infrastructure in the regions as one of the priorities of state policy.

Another significant problem is the shortage of qualified personnel and the low level of digital literacy. The introduction of new accounting systems requires specialists who are well-versed in digital technologies and can manage automation processes. However, many agricultural enterprises, especially small ones, do not have sufficient resources to train employees or hire IT specialists. This limits opportunities for full digitalisation and increases the risk of errors in financial accounting. L. Xie *et al.* (2021), on the other hand, focused on the challenges of digitalising accounting in small agricultural enterprises. Authors emphasised that the main obstacles to digital transformation are insufficient staff qualifications and limited access to the necessary software. D.F. Setiawan *et al.* (2024) noted that many small businesses do not have the financial means to purchase modern software solutions and, therefore, cannot effectively integrate new technologies into their accounting processes. The current results partially confirm the authors' conclusions, as these problems were also identified, but in the current study, more emphasis was placed on the need to modernise IT infrastructure, which was less prominent in the authors' work.

H. Guo *et al.* (2020) addressed the impact of digitalisation on small and medium-sized agricultural businesses, noting the positive effect of digital solutions on their competitiveness. In contrast to the current findings, where digitalisation had a more uniform impact on enterprises of different sizes, authors argued that small enterprises gained the greatest efficiency gains due to greater adaptability and flexibility in adopting new technologies. I. Zambon *et al.* (2019), in turn, analysed the implementation of Industry 4.0 in the agricultural sector in terms of reducing dependence on human resources. The authors found that automation has a significant effect on reducing operating costs, but its results showed lower efficiency compared to other technologies, such as drones or sensor systems, which significantly improve resource management. This is different from the current results, where it was noted that automation is a key factor in improving the overall efficiency of agricultural enterprises.

In addition to technical and human resource constraints, inconsistencies in the legal framework and regulatory barriers are also relevant. The rapid development of digital technologies is outpacing legislative updates, which creates legal conflicts and complicates the work of businesses. For instance, existing accounting standards are not always adapted to the digital environment, making it difficult to apply them in practice. This requires not only updating the legal framework

but also raising awareness of new requirements and standards among businesses. J. MacPherson *et al.* (2022) studied the role of state support in the process of digitalisation of the agricultural sector. As argued without active government support, the process of digital transformation is much slower, especially in small and medium-sized enterprises. R. Abbasi *et al.* (2022) also emphasised the need for incentive programmes to help these enterprises introduce new technologies. The current findings confirm these conclusions but also indicate that large agricultural enterprises, with their resources, were able to advance in the digitalisation process even without significant state support.

The issue of cybersecurity, which is becoming increasingly relevant in the context of digitalisation, is notable. The introduction of digital technologies increases the vulnerability of enterprises to cyberattacks, which can lead to the loss or compromise of sensitive financial information. Implementation of effective cybersecurity systems requires significant investments, which are not always affordable for small and medium-sized enterprises. This underscores the need not only for technical solutions but also for the development of a cybersecurity culture in enterprises. X. Yang *et al.* (2021) studied cybersecurity in the agricultural sector in the context of rapid digitalisation. The study highlighted that with the introduction of new digital technologies in agriculture, cyber threats have increased dramatically. Z. Angyalos *et al.* (2021) noted that most agricultural companies are not prepared for such challenges, as they do not have adequate protection against cyber threats, and there is a lack of understanding of the importance of cybersecurity among management and employees. The authors also emphasised that the agricultural sector is becoming an increasingly attractive target for cybercriminals since most of the systems being implemented are interconnected and automated, which opens new attack vectors. The current results are consistent with their findings, showing a similar increase in cyber threats, but also highlighting the need for more cyber security training. This highlights the importance of not only implementing technology but also ensuring its security through training and competence development in this area.

Organisational barriers and unwillingness to change arising from digitalisation are also noteworthy. The transition to new technologies and the need to train employees are often met with distrust and resistance from management and employees. The high cost of implementing digital solutions is also a significant obstacle for many agricultural enterprises, forcing them to postpone the introduction of new technologies or limit themselves to minimal investments in digitalisation.

The results of the study highlight the complexity and multifaceted nature of the digital transformation of the agricultural sector. Comparison with other studies shows that while many challenges are common, especially in terms of cybersecurity, digitalisation of accounting, and the role of government support, there are also unique aspects that require additional attention. In particular, the successful digitalisation of agricultural enterprises requires not only the introduction of modern technologies but also the development of human capital through staff training and the modernisation of IT infrastructure, which is particularly relevant for small and medium-sized enterprises. In summary, the digitalisation of accounting in the Ukrainian agricultural sector has great potential but requires a comprehensive approach that includes the development of technical infrastructure, staff training, adaptation of legislation and cybersecurity. Only under such conditions successful implementation of digital innovations that will help increase the competitiveness of the agricultural sector in the modern economy is possible.

### CONCLUSIONS

The study of the digital transformation of accounting in the agricultural sector of Ukraine identified key trends, challenges and opportunities along the way. The analysis showed that the digitalisation of accounting is critical to improving management efficiency, reducing costs and ensuring compliance with modern regulatory requirements. The introduction of automated accounting systems such as MASTER and BAS ERP have become a major trend that helps agricultural enterprises automate routine processes, reduce errors and speed up the preparation of financial statements. The use of specialised software was used to integrate all financial processes into a single system, which ensures transparency and control.

Active implementation of electronic document management is another important component of digitalisation. The transition from paper to electronic documents simplifies the work with financial information, speeds up the exchange of data between different business units and ensures more reliable data storage. Integration of accounting with other enterprise information systems, such as production, logistics and HR, can be used to create a single information ecosystem where all processes are interconnected and can be effectively managed. However, there are substantial issues on the way to full digitalisation. Insufficient technical in-

frastructure and outdated equipment are substantial problems. In addition, the lack of qualified personnel and low level of digital literacy significantly complicate the implementation of new accounting systems. Other challenges include the inadequacy of legislative support for the rapid development of digital technologies and the increased risk of cyber threats.

In Ukraine, the regulatory framework governing the digitalisation of accounting includes legislation on electronic documents and electronic document flow, accounting and reporting standards, and acts regulating the activities of agricultural enterprises. Legislation on electronic signatures and their use in electronic document management creates the basis for automating accounting processes. International experience, including that of the European Union, the United States, and Canada, demonstrates successful practices of digitalisation that can serve as a guide for Ukraine. Technologies such as electronic document management, automated financial systems and artificial intelligence are already being actively used in these countries to improve accounting and management efficiency.

To improve the digitalisation of accounting in the agricultural sector of Ukraine, it is recommended to conduct a detailed audit of the IT infrastructure, invest in upgrading technical equipment, implement cybersecurity systems, train staff and consider the use of cloud technologies. It is also important to actively use government programmes and grants to support digital transformation. These steps will help to increase the efficiency, transparency and competitiveness of agricultural enterprises, which is key to their sustainable development in the modern market.

The study did not address the impact of regional peculiarities of the Ukrainian agricultural sector, which may limit the applicability of the results to all regions. No in-depth analysis of the environmental aspects of digitalisation was conducted, which requires a separate study. Further research could focus on analysing regional differences in the adoption of digital technologies, as well as on the integration of environmental and social aspects into the process of digitalisation of accounting in the agricultural sector.

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### CONFLICT OF INTEREST

None.

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## **Діджиталізація бухгалтерського обліку підприємств аграрного сектору: національний та міжнародний досвід**

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**Анотація.** Мета дослідження – аналіз особливостей впровадження цифрових технологій у сфері бухгалтерського обліку на підприємствах аграрного сектору, зокрема на аналіз національного та міжнародного досвіду. Проаналізовано процес цифровізації бухгалтерського обліку на аграрних підприємствах України, який є важливим кроком для підвищення ефективності управління, зниження операційних витрат та забезпечення відповідності сучасним нормативним вимогам. Аналіз основних тенденцій у впровадженні автоматизованих систем бухгалтерського та фінансового обліку показав, що такі системи дозволяють аграрним підприємствам автоматизувати рутинні процеси, зменшити кількість помилок та скоротити час на підготовку фінансової звітності. Дослідження також виявило низку проблем, які виникають на шляху до повної цифровізації обліку, серед яких недостатня технічна інфраструктура, брак кваліфікованих кадрів та низький рівень цифрової грамотності. Недостатнє фінансування та нормативно-правові бар'єри також створюють серйозні виклики для підприємств. Особливу увагу приділено питанням кібербезпеки, які стають все більш актуальними у зв'язку із зростанням обсягів цифрових даних. Порівняно український досвід із досвідом країн Європейського Союзу, США та Канади, де цифровізація обліку досягла високого рівня. В дослідженні запропоновано рекомендації для успішного впровадження цифрових технологій в облікові процеси на аграрних підприємствах України, враховуючи наявні обмеження та можливості. Зокрема, зазначається важливість проведення аудиту існуючої цифрової інфраструктури, інвестування в оновлення обладнання, навчання персоналу, поступового впровадження нових технологій та партнерства з провідними постачальниками цифрових рішень. Отримані результати підкреслюють значний потенціал цифровізації для підвищення ефективності, прозорості та конкурентоспроможності аграрних підприємств України, проте досягнення цих цілей потребує збалансованого підходу до впровадження нових технологій, підтримки з боку держави та відповідної освітньої підготовки. Отримані у дослідженні результати можна застосувати для вдосконалення цифровізації бухгалтерського обліку на українських аграрних підприємствах, підвищення ефективності управління фінансами та адаптації міжнародних стандартів до місцевих умов

**Ключові слова:** цифрові технології; електронні системи; автоматизація обліку; економічна ефективність; аудит і контроль

## Oscillatory spatial and temporal variability of precipitation in Polissia and Forest-Steppe and the impact of agricultural landscape transformation

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**Abstract.** The territories of Polissia and Forest-Steppe are of great importance to Ukraine, offering significant potential for the advancement of agriculture and forestry. In light of the pressing issue of global climate change, it is imperative that the active economic utilisation of these territories be guided by a commitment to the maintenance of ecological systems and the sustenance of ecosystem functions. The objective of this article was to ascertain the patterns of both spatial and temporal precipitation variability and to establish the impact of anthropogenic land transformation as a consequence of agricultural production. Within the study area, the average precipitation level was  $625 \pm 68$  mm and ranged from 535 to 1,160 mm. During the study period (1960-2023), there was a trend of increasing and decreasing precipitation. The southeast of the region was characterised by a decreasing trend in precipitation, while in the northwest and north, the time trend showed an increase in precipitation. Precipitation in the Carpathian region is much higher than in other parts of the territory. The presence of an oscillatory regularity in precipitation rhythm allows for consideration of two practical aspects: the possibility of forecasting future precipitation dynamics based on available information from previous years, and accounting for the fluctuating precipitation dynamics when recommending optimal crop rotations and selecting the most suitable range of crop varieties for cultivation

**Keywords:** climate; spatial pattern; temporal dynamics; landscape diversity; land cover

### INTRODUCTION

Increasing crop yields is a critical requirement to ensure food security in the face of a steadily growing global population. Climate change is increasing the frequency and intensity of extreme weather events, such as droughts, floods, storms, and forest fires, all of which can affect agricultural production. The loss of agricultural production is expected to progress in most

European territories during the 21<sup>st</sup> century as a result of heatwaves, droughts, and an increased risk of water shortages. The water is the most important factor for growing various crops. Crop water requirements are highly vulnerable to the impacts of climate change. Water availability significantly affects all physiological and ecological processes in the plant world. The study

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of the spatial and temporal variability of precipitation, to ensure the conditions for sustainable agricultural production, represents a significant scientific challenge.

Precipitation is a critical factor in climate and hydrometeorology, and a major driver of hydrological processes, as well as the structure and function of terrestrial ecosystems, which determine the conditions for agricultural production, as discussed by M. Hernández-Rodríguez *et al.* (2023). Precipitation patterns are highly variable, with significant differences in frequency, duration, intensity, and overall trends over time, directly influencing the rhythm of water use by humans and ecosystems. Changes in precipitation significantly affect the hydrological cycle and human life, potentially leading to floods, droughts, biodiversity loss, reduced agricultural productivity, and soil erosion. According to T.T. Nguyen *et al.* (2019), an increase in extreme precipitation events will lead to a higher risk of flooding, especially with the rapid pace of urbanisation. High temperatures have a negative impact on yields due to heat stress and soil moisture deficits, and similarly, low precipitation leads to stomatal closure, reduced carbon uptake, and lower yields, as highlighted by E.P. Hendri & S. Fadhli (2024). Modern statistical procedures provide powerful tools for predicting crop yields under global climate change, even when the model is based solely on climate variables such as temperature and precipitation (Leng & Hall, 2020).

According to S. Benziene (2024), precipitation forecasting is the process of using a range of models and data sources to accurately predict the amount and timing of precipitation, such as rain or snow, in a given area. Subsequent forecasts are based on historical data regarding precipitation dynamics. The author also explains that mathematical and statistical methods allow for the accurate prediction of future precipitation trends, enabling the identification of patterns, changes, and relationships in the data. Y.-F. Sang *et al.* (2020) highlight that the most common statistical methods are trend analysis, frequency or spatial analysis, regression models, and time series models. Additionally, they emphasise that identifying periodic rainfall fluctuations is the most important aspect of rainfall modelling and forecasting. According to O. Lobachevska & L. Karpinets (2024), the seasonality of the precipitation regime and the amount of precipitation allow for the identification of clear spatial structures, which have significant implications for livestock producers and future climate change assessments.

Precipitation is a distinct field of study within climatology and meteorology. However, precipitation constitutes an aspect of climate that affects biological systems and is therefore a climatope (Kyyak *et al.*, 2023).

A climatope is a specific climatic regime that allows for the formation of a spatially regular fragment of landscape cover. Together with the edaphotope, it forms an ecotope. It must be emphasised that, just as an edaphic environment is not equivalent to soil, a climatological environment is not equivalent to climate. An edaphotope is how living organisms perceive soil. Similarly, the climatope is an aspect of how living organisms perceive climate. The system is becoming more complex. It is no longer sufficient to consider only the climatic component; the biotic component must also be taken into account. Conversely, a specific list of purely climatic issues recedes into the background. For example, this approach does not require an explanation of the mechanisms and processes of the dynamics of climatic phenomena. Climate can be considered purely phenomenologically or formally. This approach can be interpreted as ecological within the framework of ecological climatology. Thus, this study aimed to test the hypothesis that the climate of the area under investigation exhibits spatial and temporal regularity, which is hierarchically ordered. This enables the prediction of the state of the climate in the coming decades.

## LITERATURE REVIEW

Effective water management is crucial for maximising crop yields, particularly in areas with varying rainfall patterns. Different crops have specific water requirements that are vital for their growth, with some being more drought-resistant, such as rye, and others requiring more moisture during key growth stages, such as potatoes and rapeseed. Understanding these seasonal water needs helps optimise crop production, as evidenced by the varying water demands across crops like soybeans, sugar beet, and sunflower.

The article by G. Bodner *et al.* (2015) suggests that seasonal crop water needs are essential for crop management, especially in dry years. For maximum tuber yield, potatoes require 500-700 mm of water per season. Rapeseed evaporates a large amount of water, with its transpiration coefficient in the range of 500-700 mm, and it needs 400-500 mm of rainfall during the growing season. High humidity during flowering is necessary for high yields. Excessive rainfall and low temperatures during the reproductive stage are unfavourable, as they reduce the number of flowers, the number and size of the capsules, and the seeds inside them (Moteva *et al.*, 2018). Rye grows well with annual rainfall of 600 to 1,000 mm and is relatively drought-resistant: it can tolerate dry conditions with annual rainfall as low as 400 mm (Basche *et al.*, 2016). Soybeans are water-efficient, depending

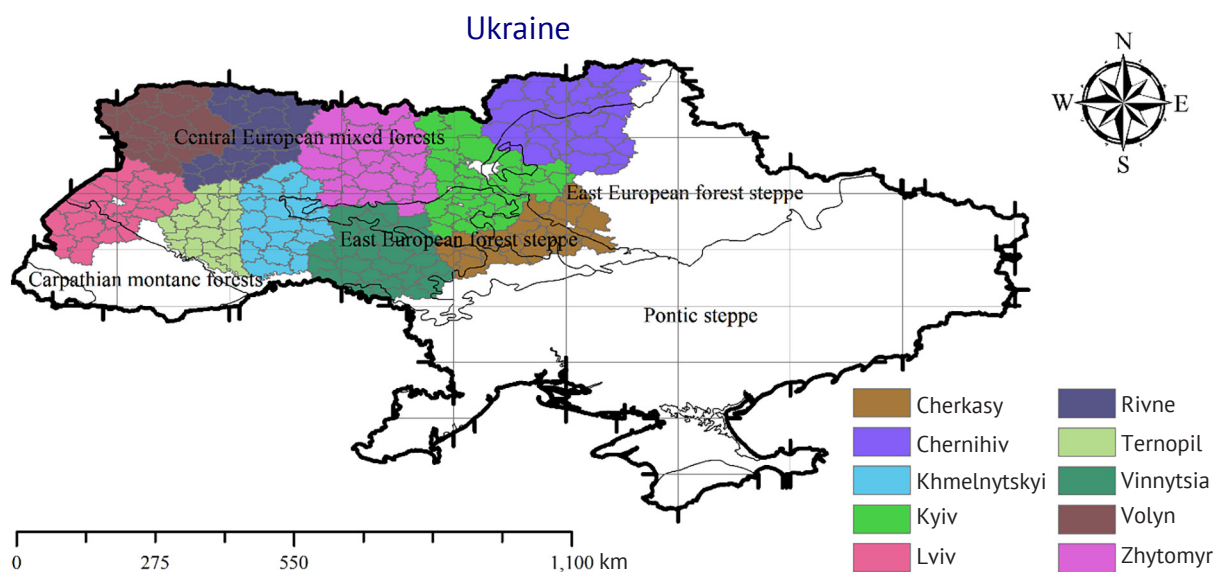
on the weather and soil type, they use 400-700 mm of water, either from rainfall, irrigation, or the soil, to produce sufficient yields (Tacarindua *et al.*, 2013). Water is essential for many vital functions of sugar beet, which has a relatively low water consumption of between 500 and 800 mm, making it a suitable crop for regions with limited water resources. Sunflower is cultivated in a multitude of geographical regions worldwide, whether as a rain-fed, arid, or irrigated crop (Sposaro *et al.*, 2010). Sunflower requires about 500-670 mm of water during the growing season. According to FAO (Food and Agriculture Organization), guidelines for crop water requirements and drought sensitivity indicate that cabbage, walnut, and onion require 350-500 mm of water and are moderately sensitive to drought. Tomatoes require 400-800 mm of water and are moderately sensitive to drought, while peppers require 600-900 mm of water and are also moderately sensitive to drought. The quantity of water required by wheat varies depending on several factors, including the climate, the length of the growing season, soil conditions, and irrigation. In general, wheat

requires between 400 and 650 mm of water for optimum yield (Tripathi & Mishra, 1986).

The regions of Polissia and Forest-Steppe represent significant areas of Ukraine with considerable potential for the advancement of agricultural and forestry activities. The active economic utilisation of these territories must be undertaken in a manner that ensures the sustainability of ecological systems and the maintenance of ecosystem functions. The issue of evaluating the impact of precipitation dynamics on crop yields at the regional level remains unresolved. Accordingly, the objective of this study was to identify patterns of spatial and temporal variability in precipitation and to ascertain the influence of anthropogenic landscape modification resulting from agricultural production.

## MATERIALS AND METHODS

The spatial variability of annual precipitation within 10 administrative regions in the north and northwest of Ukraine between 1960 and 2023 was investigated (Fig. 1). The region encompasses both Polissia and Forest-Steppe geographical zones.



**Figure 1.** The study area with the administrative regions of the country covered

**Source:** authors' development

Prior to the 2015-2022 reform of Ukraine's administrative and territorial structure, the environmental characteristics were averaged across administrative districts. This is due to the fact that the area of "traditional" rayons is smaller and more ecologically homogeneous than that of the new administrative units. Furthermore, data on crop yields have been collected over an extended period within the "old" administrative districts, which is crucial for elucidating the relationship between productive potential and climatic conditions.

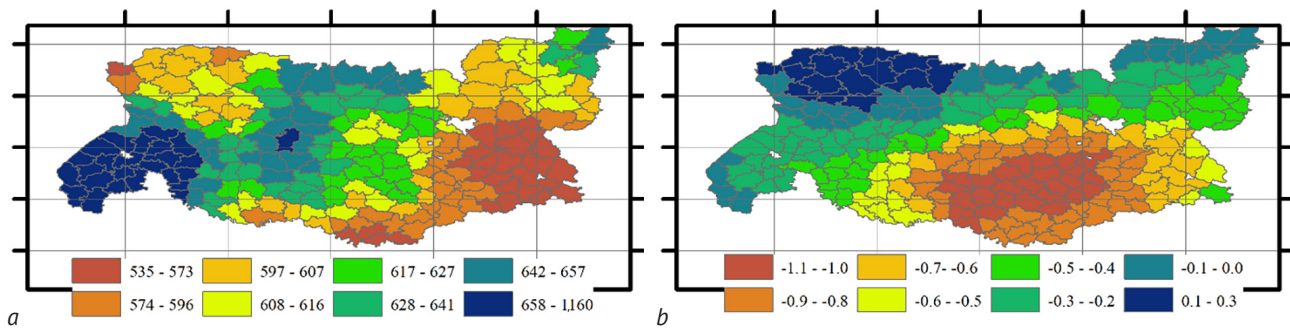
The historical data on the spatial variability of precipitation were obtained from the WorldClim (n.d.) website. A principal component analysis, Bartlett's test of sphericity, and the Monte Carlo test were conducted using the library stats (The R Project..., n.d.). The suitability of the precipitation data for the principal component analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) test (Kaiser, 1974), with the assistance of the KMOS function from the REdaS library (Maier, 2022) within the R computing environment. J.L. Horn's (1965)

technique for evaluating the components in a principal component analysis was implemented through the paran function from the Paran library (Dinno, 2024). The spatial database was created in ArcGIS 10.0. Descriptive statistics, as well as cluster and cluster analysis, were performed in StatSoft 12.0.

**RESULTS**

*Spatial and temporal dynamics of precipitation.* The average precipitation level within the study area from 1960 to 2023 was  $625 \pm 68$  mm, ranging from 535 to 1,160 mm. The lowest amount of precipitation was observed in 2005, amounting to  $488 \pm 59$  mm, while the highest was recorded in 1980, with  $803 \pm 85$  mm. The lowest precipitation level was recorded for the Chyhyryn District ( $535 \pm 79$  mm), and the highest in the Skole District ( $1,160 \pm 151$  mm).

A zone of local maximum precipitation is observed within the study region, extending diagonally from the northeast to the southwest (Fig. 2). Consequently, areas of local minima are located in the southeast and northwest of the region. The zone of highest precipitation levels is situated in the southwest and corresponds to the Precarpathian Upland. Precipitation levels in this zone range from 658 to 1,160 mm per year. Additionally, the central region exhibits elevated precipitation levels. The lowest precipitation levels are observed in the southeast, within the Forest-Steppe zone, where an average of 535-573 mm of precipitation falls per year. During the study period, a discernible trend of both increasing and decreasing precipitation was noted. The southeastern region exhibited a declining trend, whereas the northwestern and northern regions demonstrated an increasing trend.



**Figure 2.** Spatial variation of mean annual precipitation (mm, 1960-2023) (a) and temporal trend of precipitation variability (b)

**Source:** authors' development

*Global principal component analysis.* Linear regression can explain some of the variance in precipitation over time. Further analysis uses the residuals of the regression model of precipitation versus time. The variability of these residuals is also likely to be complex in nature. The variation in the residuals of a linear regression model contains random noise associated with inherent errors in the original data. Additionally, a

component associated with regular factors that may have environmental effects can be expected in the regression residuals. Bartlett's test of sphericity ( $P < 0.05$ ) indicates that principal component analysis can be applied to such data. Global principal component analysis identified six statistically significant principal components, which together explained 84.8% of the variation in the detrended precipitation data (Table 1).

**Table 1.** Results of the global principal component analysis

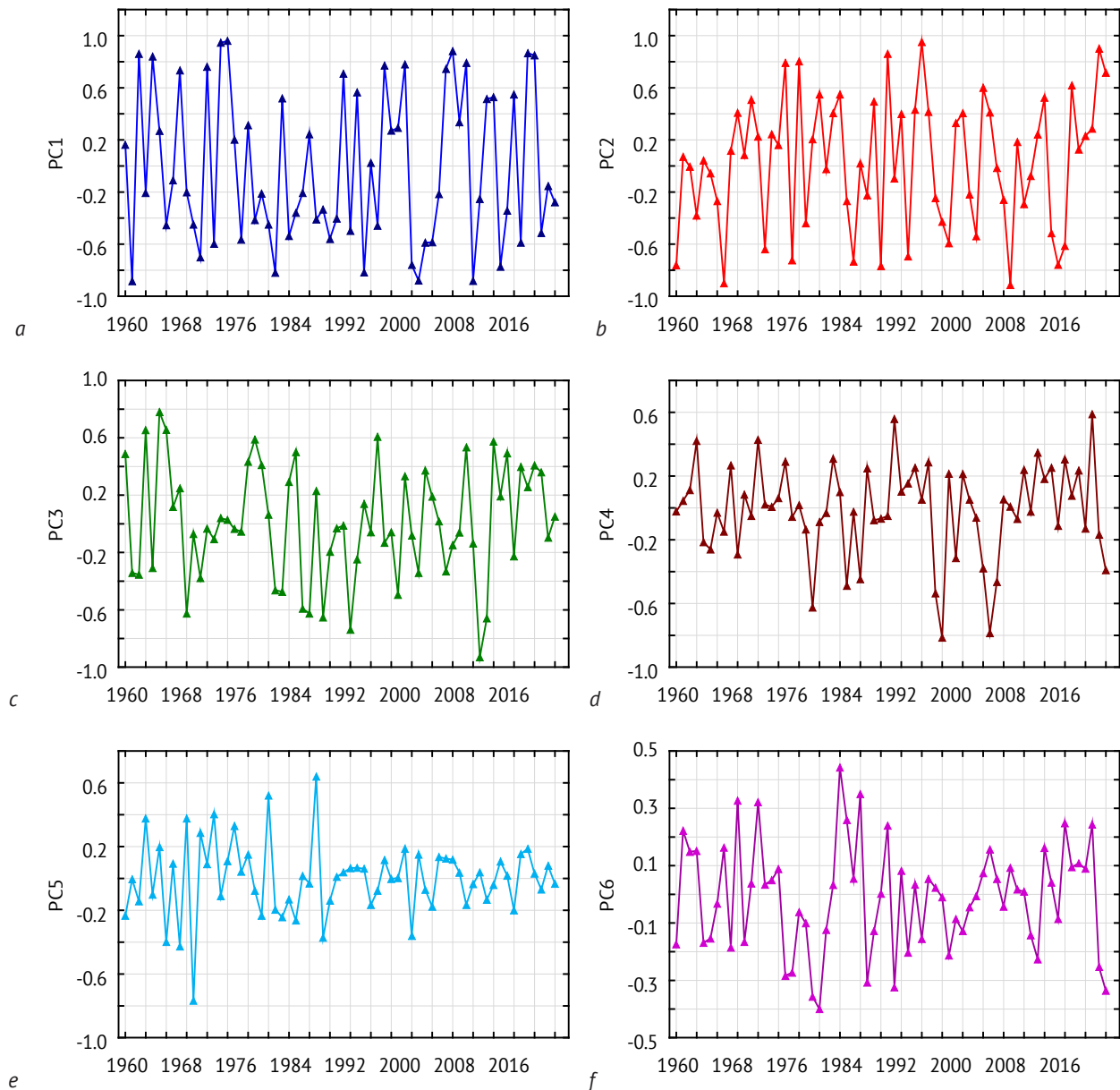
Principal component	Adjusted eigenvalue*	Eigenvalue	Shift	Explained variation	Standard deviation
1	20.35	21.66	1.31	33.84	4.64
2	14.54	15.73	1.19	24.57	3.96
3	9.06	10.16	1.10	15.87	3.18
4	4.47	5.49	1.02	8.58	2.34
5	2.40	3.35	0.95	5.24	1.83
6	1.37	2.26	0.89	3.53	1.50

**Notes:** \* – according to J.L. Horn (1965)

**Source:** authors' development

Years of research into the principal component space have revealed certain patterns. The properties of the principal components can be better understood by presenting their variability in both time (Fig. 3) and space (Fig. 4). Each principal component contrasts a particular sequence of years with another sequence in terms of precipitation, which has a

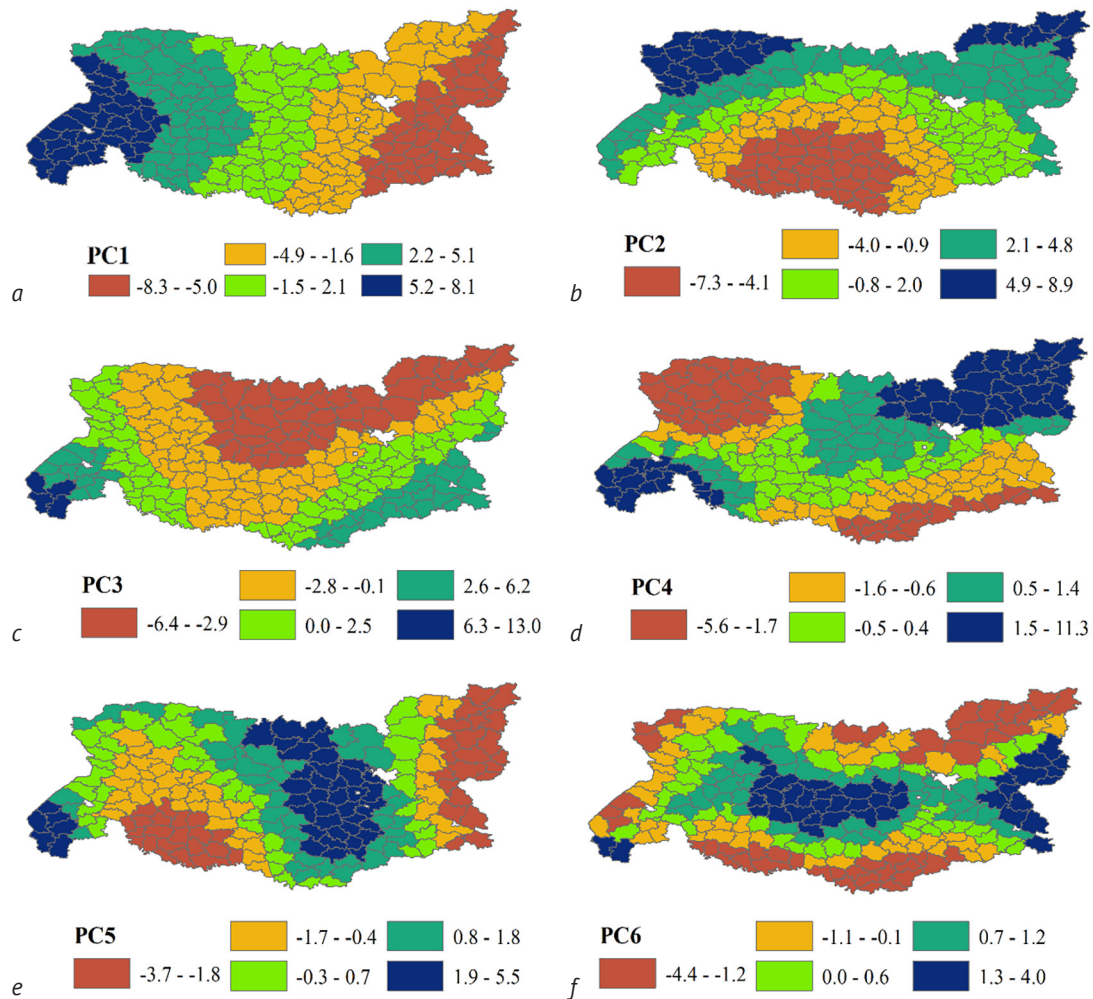
distinct spatial structure. Principal Component 1 accounts for 33.8% of the variation in precipitation and is the most sensitive to fluctuations in precipitation, with autocorrelation lags of 5 and 9 years. Spatially, this principal component contrasts the precipitation rhythm in the eastern part of the region with that of the western part.



**Figure 3.** Time variation of the loadings of principal components 1-6

**Notes:** a – Principal Component 1 (autocorrelation:  $-0.13 \pm 0.11$  for lag 5,  $0.13 \pm 0.11$  for lag 9, and  $0.90 \pm 0.08$  for lag 12); b – Principal Component 2 (autocorrelation:  $-0.22 \pm 0.12$  for lag 3,  $0.12 \pm 0.09$  for lag 4, and  $-0.15 \pm 0.12$  for lag 11); c – Principal Component 3 (autocorrelation:  $-0.26 \pm 0.12$  for lag 8,  $0.19 \pm 0.09$  for lag 13); d – Principal Component 4 (autocorrelation:  $-0.18 \pm 0.09$  for lag 12,  $-0.26 \pm 0.09$  for lag 15); e – Principal Component 5 (autocorrelation:  $-0.39 \pm 0.12$  for lag 1,  $0.22 \pm 0.12$  for lag 2, and  $-0.26 \pm 0.12$  for lag 3); f – Principal Component 6 (autocorrelation:  $-0.25 \pm 0.12$  for lag 5,  $-0.20 \pm 0.12$  for lag 7, and  $0.21 \pm 0.12$  for lag 12)

**Source:** authors' development



**Figure 4.** Spatial variability of the principal component scores 1-6

**Notes:** a – Principal Component 1 ( $\lambda = 20.35$ , 33.84% of the explained variation); b – Principal Component 2 ( $\lambda = 14.54$ , 24.57% of the explained variation); c – Principal Component 3 ( $\lambda = 9.06$ , 15.87% of the explained variation); d – Principal Component 4 ( $\lambda = 4.47$ , 8.58% of the explained variation); e – Principal Component 5 ( $\lambda = 2.40$ , 5.24% of the explained variation); f – Principal Component 6 ( $\lambda = 1.37$ , 3.53% of the explained variation)

**Source:** authors' development

Principal Component 1 is not statistically significantly correlated with soil properties (Table 2). The values of this principal component are higher in landscapes where the proportion of broadleaf and mixed forests and meadows is greater, and the proportion of agricultural areas is smaller. Principal Component 2 accounted for 25.6% of the variability in precipitation and is sensitive to the variability components with autocorrelation lags of 3, 4, and

11 years. This principal component differentiates the southwestern part of the region from other areas. Principal Component 2 is positively correlated with soil organic matter and sand but negatively correlated with clay and silt. Higher values of this principal component are found in landscapes with a greater proportion of coniferous, broadleaved, or mixed forests, and a smaller proportion of agricultural areas or sparse vegetation.

**Table 2.** Correlation between principal components and ecological properties of the territories (correlation coefficients are statistically significant for  $P < 0.05$ )

Variables	Principal components					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Soil properties						
Organic matter (OM)	–	0.41	0.19	–0.24	–0.23	–
Clay	–	–0.74	0.51	–	–	–

Table 2, Continued

Variables	Principal components					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Sand	-	0.71	-0.41	-	0.18	-0.15
Silt	-	-0.60	0.28	0.20	-0.25	0.24
Types of landscape cover (GlobCover)						
Rainfed croplands	-0.15	-0.64	0.23	-0.27	-0.14	-
Mosaic croplands (50-70%) / Vegetation (grassland/shrubland/forest) (20-50%)	-0.38	-0.25	-0.18	-	-0.35	-
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / Cropland (20-50%)	-0.23	-0.27	0.53	0.33	-	-
Closed (>40%) broadleaved deciduous forest (>5m)	0.44	0.49	-	-	-	-
Closed (>40%) needle-leaved evergreen forest (>5m)	-	0.30	-0.35	0.15	0.28	-
Open (15-40%) needle-leaved deciduous or evergreen forest (>5m)	-	0.49	-0.33	0.23	-	-0.28
Closed to open (>15%) mixed broadleaved and needle-leaved forest (>5m)	0.14	0.50	-0.38	-	0.29	-
Mosaic grassland (50-70%) / Forest or shrubland (20-50%)	0.47	-	0.44	0.30	-	-
Closed to open (>15%) herbaceous vegetation (grassland, savannas, or lichens/mosses)	0.28	-	0.35	0.24	0.21	-
Sparse (<15%) vegetation	-0.29	-0.48	0.17	-0.21	-	-0.29
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – fresh, brackish or saline water	-	-	-0.19	-	-	-
Artificial surfaces and associated areas (urban areas >50%)	-	-	-	-	-	-

**Source:** authors' development

Principal Component 3 accounted for 15.9% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 8 and 13 years. It contrasts the dynamics of oscillatory processes in the northern region with those in the central part of the area. Principal Component 3 is positively correlated with soil organic carbon, clay, and silt content, and negatively correlated with sand content. Higher values of this principal component are found in landscapes with a greater proportion of meadow and shrub vegetation and a smaller proportion of agricultural land, coniferous, or mixed forests.

Principal Component 4 accounted for 8.6% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 12 and 15 years. It contrasts the dynamics of oscillatory processes along a diagonal from the northeast to the southwest, compared with those in the northwest and southeast. Principal Component 4 is positively correlated with silt content and negatively correlated with organic carbon content. It is negatively correlated with the proportion of rainfed land or sparse vegetation cover and positively correlated with the proportion of meadows, coniferous, or mixed forests.

Principal Component 5 accounted for 5.4% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 1, 2, and 3 years. It contrasts the dynamics of oscillatory processes in the centre of the region with those in other areas. Principal Component 5 is negatively correlated with organic carbon and silt content but positively correlated with sand content. This component is negatively correlated with the proportion of agricultural land but

positively correlated with the proportion of coniferous forests, mixed forests, and herbaceous vegetation.

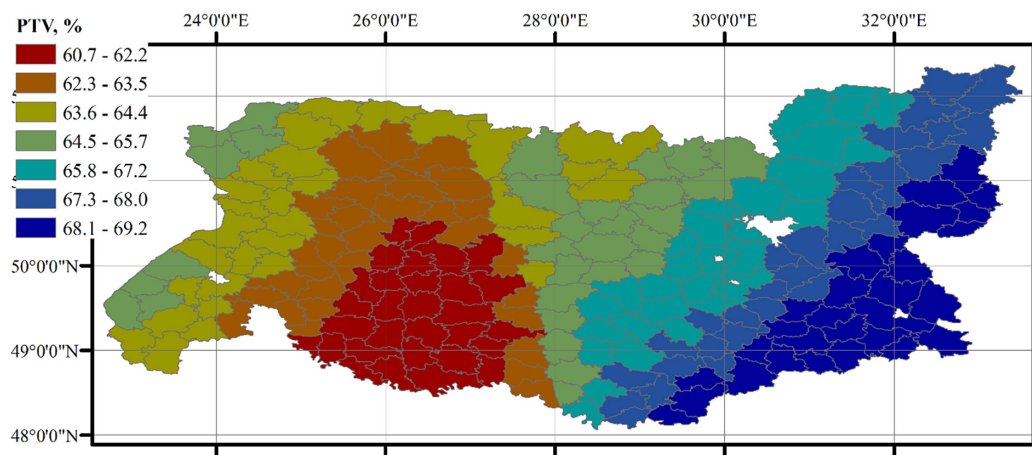
Principal Component 6 accounted for 3.5% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 5 and 7 years. It contrasts the dynamics of oscillatory processes in the centre of the region with the rhythm of processes in the north and south. Principal Component 6 is negatively correlated with sand content and positively correlated with silt content in the soil. This component is negatively correlated with the proportion of mixed forests and sparse vegetation.

*Geographically weighted principal component analysis (GWPCA).* The Monte Carlo test was conducted to determine whether the eigenvalues of the data matrix are characterised by a spatial component of variation. The *P*-value for testing the standard deviation of the local eigenvalues based on the GWPCA results is 0.01. This value indicates that the hypothesis of spatial invariance of local eigenvalues can be statistically significantly rejected; in other words, there is a high level of spatial non-stationarity represented in the data on the precipitation erosion factor. Before determining the optimal pass-through window, it is necessary to decide how many principal components to retain (Harris *et al.*, 2011; Gollini *et al.*, 2015). The results of the preliminary global principal components analysis indicate that the first two components together account for 58.4% of the variation in the data structure. Accordingly, it is reasonable to retain these two components for the subsequent GWPCA procedure. In the process of adaptive window selection, an optimal window of 220 nearest neighbours was established for performing the GWPCA

procedure. To obtain the corresponding results of the global principal component analysis, only the first two principal components, GWPC 1 and GWPC 2 were interpreted for comparison purposes.

The results of the GWPCA procedure can be visualised and interpreted by focusing on two key aspects: firstly, how the dimensionality of the data varies spatially, and secondly, how the original variables influence the principal components. The proportion of spatial variation in the total variation exhibits a notable degree of variability, with spatially homogeneous clusters emerging in the meridional direction (Fig. 5). In comparison to global principal component analysis,

GWPCA has been demonstrated to be an effective and efficient method for analysing spatial patterns of regional precipitation variability, through the mapping of the spatial variability of principal components. The first two principal components extracted from the global principal component analysis were found to be capable of explaining 58.4% of the variability in precipitation. The GWPCA explained between 60.7 and 69.2% of the precipitation variability. The nearest neighbours were selected for the GWPCA procedure. To facilitate comparison with the results of the global principal component analysis, only the first two principal components, GWPC 1 and GWPC 2, were interpreted.



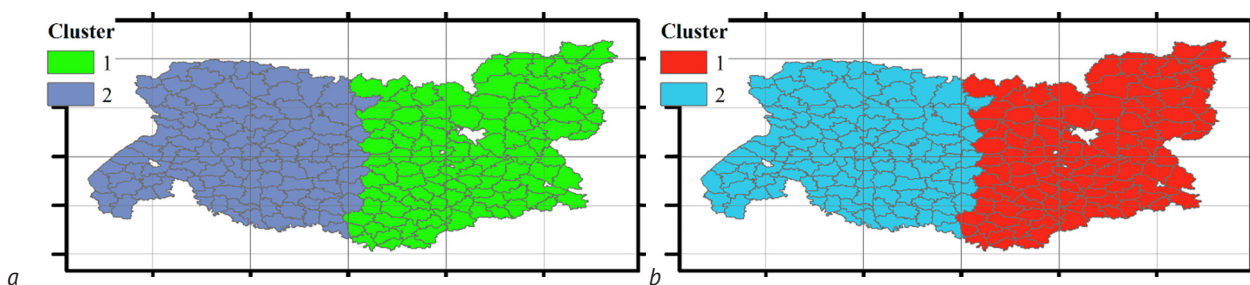
**Figure 5.** Spatial variation of the percentage of total variation of the first two principal components

**Notes:** PTV – percentage of total variation

**Source:** authors' development

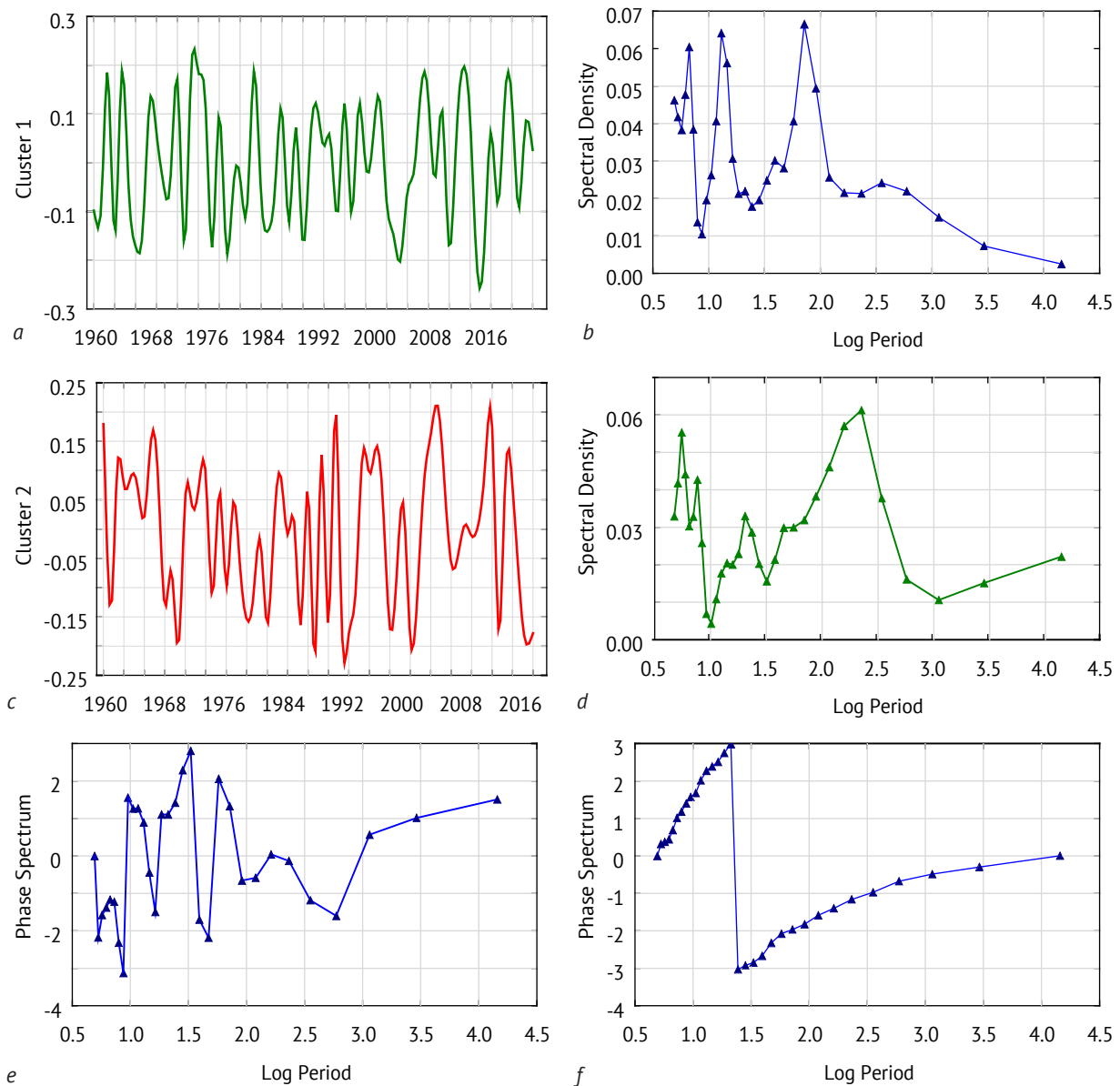
The application of cluster analysis to the administrative districts based on the GWPC 1 factor loadings enabled the identification of two distinct clusters (Fig. 6). The aforementioned clusters bisect the study area along the median meridian, delineating the eastern and western regions. The oscillatory process of precipitation variability within Cluster 1 exhibits autocorrelation lags of 1 and 6, whereas precipitation variability within Cluster 2 follows an oscillatory process

with autocorrelation lags of 3 and 10 (Fig. 7). The primary distinction between the oscillatory processes observed in the two clusters is the presence of three dominant oscillation periods in the density spectrum of the oscillatory process within Cluster 1, in contrast to the two most prominent periods observed in the spectrum of the oscillatory process in Cluster 2. Furthermore, the oscillatory processes of precipitation variability in Clusters 1 and 2 occur with a phase shift.



**Figure 6.** The spatial location of clusters obtained based on factor loadings GWPC 1 (a) and GWPC 2 (b)

**Source:** authors' development



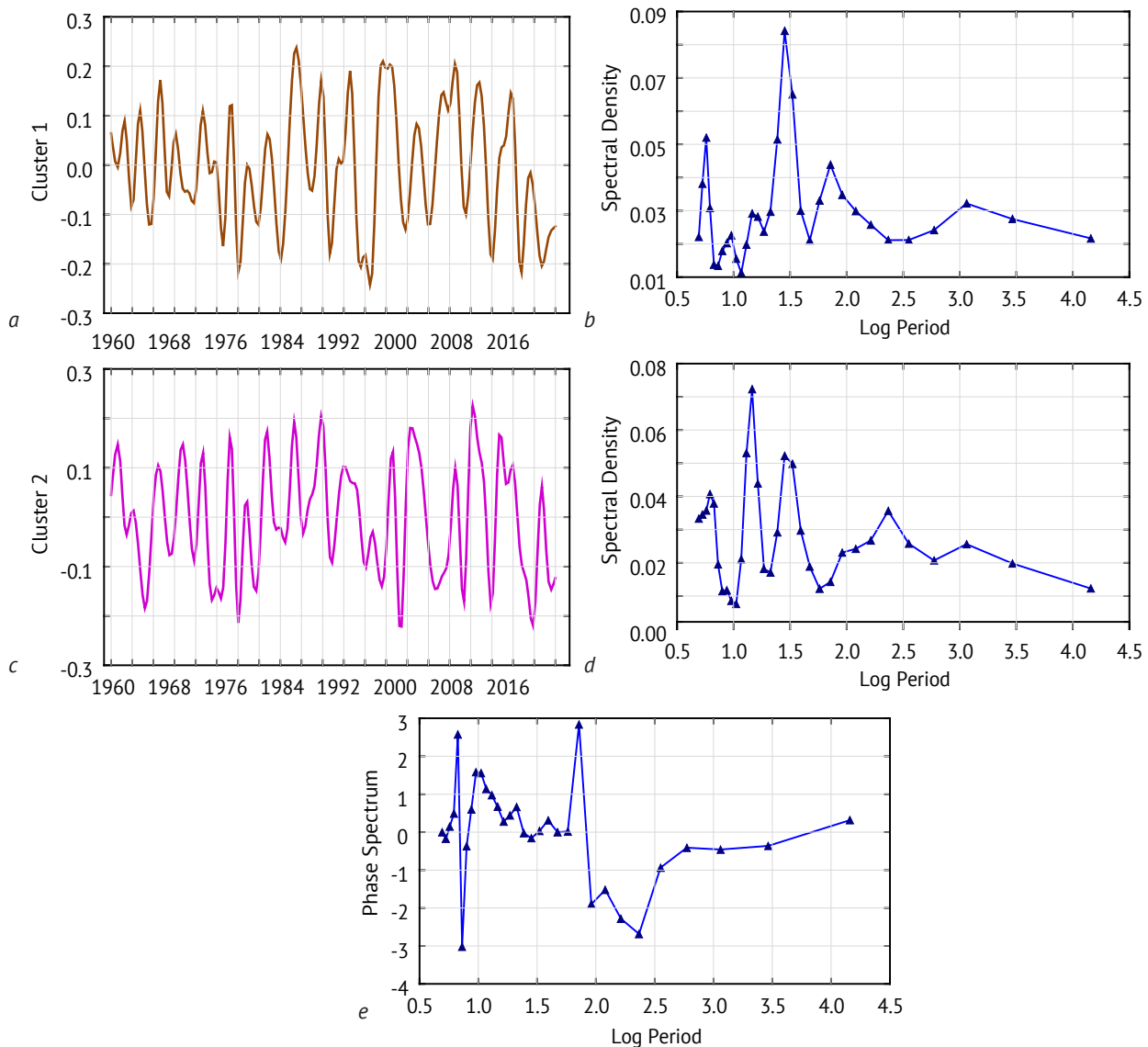
**Figure 7.** Time variation of the loadings of the principal component GWPC 1 for Clusters 1 and 2

**Notes:** a – Cluster 1 (autocorrelation:  $-0.14 \pm 0.09$  for lag 1,  $0.12 \pm 0.08$  for lag 6, and  $-0.19 \pm 0.11$  for lag 8); b – Spectral Density of the oscillatory process for Cluster 1; c – Cluster 2 (autocorrelation:  $-0.22 \pm 0.11$  for lag 3,  $0.10 \pm 0.07$  for lag 10, and  $-0.21 \pm 0.11$  for lag 14); d – Spectral Density of the oscillatory process for Cluster 2; e – Phase Spectrum of oscillatory processes within Cluster 1 and 2; f – Phase Spectrum of oscillatory processes with a shift of 3 lags between them

**Source:** authors' development

The application of cluster analysis to the administrative districts, based on the values of the GWPC 2 factor loadings, enabled the identification of two distinct clusters. The aforementioned clusters delineate the study area along the median meridian, resulting in the division of the area

into eastern and western sections. The oscillatory process of precipitation variability within Cluster 1 exhibits autocorrelation lags of 4 and 11, whereas precipitation variability within Cluster 2 follows an oscillatory process with autocorrelation lags of 4, 5, and 9 (Fig. 8).



**Figure 8.** Time variation of the GWPC 2 principal component loadings for Clusters 1 and 2

**Notes:** a – Cluster 1 (autocorrelation:  $0.17 \pm 0.09$  for lag 4,  $-0.21 \pm 0.08$  for lag 11 and  $0.27 \pm 0.11$  for lag 13); b – Spectral Density of the oscillatory process for Cluster 1; c – Cluster 2 (autocorrelation:  $0.11 \pm 0.07$  for lag 4,  $-0.16 \pm 0.07$  for lag 5, and  $0.18 \pm 0.11$  for lag 9); d – Spectral Density of the oscillatory process for Cluster 2; e – Phase Spectrum of oscillatory processes within Clusters 1 and 2

**Source:** authors' development

The primary distinction between the oscillatory processes observed in the two clusters is that the density spectrum of the oscillatory process within Cluster 1 encompasses the three most prominent oscillation periods, whereas the lags of these oscillatory processes are shifted to the left in the spectrum of the oscillatory process observed in Cluster 2. Furthermore, the oscillatory processes of precipitation variability in Clusters 1 and 2 occur with a phase shift.

## DISCUSSION

The distribution of total precipitation in the area under study is the result of a combination of processes that reflect the patterns of geographical and altitudinal zonation, as well as geographical sectorality (meridional zonation). The Forest-Steppe zone is characterised by a naturally lower level of precipitation compared to Polissia. The Carpathian region exhibits considerably higher precipitation levels than other areas within the

territory. Polissia displays a contrast in moisture conditions, ranging from regionally high to regionally low levels. In the central part of the region, from the north to the centre and southwest, a zone of increased precipitation is formed, exhibiting signs of sectoral variability. The Forest-Steppe fraction of the study area is included in the sub-zone of sufficient moisture, with an average annual precipitation of 570 to 600 mm.

The phenomenon of climate change is impacting the global water cycle, with implications for both the total amount of precipitation and extreme precipitation events. It is expected that total precipitation will increase by approximately 2-3% for each degree Celsius of global warming. Additionally, estimates indicate that extreme precipitation may become more intense by approximately 7% for each degree Celsius of warming (Allen & Ingram, 2002). It is anticipated that the projected changes in daily temperature, precipitation, wind, relative humidity, and global radiation will result in a decline in maize yields in Europe, with an estimated reduction of between 1 and 22% by 2050. Furthermore, wheat yields in Southern Europe are anticipated to decline by 49%. Nevertheless, in Northern Europe, some of the adverse effects of climate change on yields may be mitigated by elevated CO<sub>2</sub> concentrations in the atmosphere and alterations in precipitation patterns (Hristov *et al.*, 2020). A decline in total annual precipitation has been observed in the Forest-Steppe zone of Ukraine, with a reduction from 616 to 584 mm from 1990 to 2010. An evaluation of water losses due to evaporation demonstrates that even with annual precipitation exceeding 500 mm, a moisture deficit can occur. This phenomenon is observed in the Forest-Steppe zone with a frequency of approximately 60% of the cases studied (Petrychenko *et al.*, 2018). These findings align with the temporal precipitation trends previously identified in the Forest-Steppe segment of the study area. It should be noted, however, that this trend does not extend across the entire territory. In contrast, the Polissia segment of the region exhibits a reversal in the trend of precipitation variability over time. In particular, the northwest region exhibits a pronounced trend of increasing precipitation. It is also noteworthy that the diagonal zone within the study area represents the boundary between the opposing trends in precipitation over time. Consequently, this zone can be considered to exhibit a relatively constant temporal trend.

The findings highlight an additional dimension of precipitation variability that extends beyond a mere directional trend over time. Precipitation dynamics over time exhibit several distinct spatial patterns, which are identified by principal components that are statistically independent of one another. This indicates that disparate spatial and temporal patterns of precipitation arise

as a consequence of the influence of different factors. It is also important to note that the contribution of the respective patterns to the overall precipitation rhythm decreases in the corresponding principal component series. Consequently, their direct impact on ecological processes and agricultural production conditions also diminishes. If the "first" principal components are the result of geographical factors that are regular in space and time, then the subsequent factors in their genesis can be considered to be generated by factors of local environmental and landscape character.

Principal Component 1 reflects the meridional sectoral variability of precipitation rhythms. An increase in precipitation in the eastern region is accompanied by a decrease in precipitation in the western region, and vice versa. Therefore, the remote sensing data reveal a distinct meridional zonation of the marine ecosystem structure, with a markedly higher density of phytoplankton in coastal and Atlantic waters. This structure correlates well with the complex hydrographic circulation observed in the region (Mitchell *et al.*, 1991). The meridional zonation of phytoplankton productivity characteristics was identified through an analysis of the spatial distribution of primary production in the world ocean. The latitudinal zonation of vegetation is complemented by a meridional zonation, which should be taken into account when identifying biogeographic regions. The results demonstrate a distinct form of zonation, characterised by rhythmic patterns. Zonation can be defined as a sequence of geographically ordered areas of the Earth's surface that are quantitatively distinct in terms of specific properties. In this instance, the focus is on the cyclical variability of properties over time, which is characterised by a sectoral spatial organisation. Principal Components 2 and 3 show a spatial organisation that closely resembles geographic zonation, albeit with a cyclical rather than modal spatial pattern.

Principal Components 4-6 account for a decreasing proportion of the variability in precipitation; yet, they reflect more spatially detailed patterns of variability that do not align with the patterns of geographic zonation. These components are significantly correlated with both soil properties and vegetation cover. To gain a deeper understanding of the correlation between vegetation cover and precipitation variability, it is essential to distinguish between areas covered by crops and those covered by natural or distinct vegetation types. It can be posited that the natural variability of precipitation is related to the organisation of landscape cover, which, in turn, determines the distribution of suitable and unsuitable areas for agricultural production. Furthermore, it can be postulated that anthropogenic alterations to the landscape may influence precipitation

patterns and contribute to the emergence of significant spatial and temporal patterns.

A more comprehensive examination of the hypothesis that anthropogenic transformation influences the trajectory of climate processes could potentially yield insights that inform strategies for climate change adaptation. W. Lahmer *et al.* (2001) emphasise that the impact of global changes on the regional water cycle, caused by either climate change or land-use changes, represents a significant scientific issue. C. Stephens & A. Ngari (2024) note that the most important sources and drivers of global climate change are known to be at the regional level. N.W. Arnell *et al.* (2019) highlight that temperature and precipitation show significant regional variability in the context of global climate change. According to P.S. Roy *et al.* (2022), transformations in land use or land cover represent a human-induced systemic disturbance that exerts an influence, either direct or indirect, on a multitude of hydrological processes. P.A. Dirmeyer *et al.* (2010) also point out that the climatic features of the region exert a pivotal influence on the consequences of land-use modification. Thus, the results allow for a reasonable assumption that a significant oscillatory component of precipitation variability in the studied region can be induced by both natural landscape heterogeneity and anthropogenic landscape transformation, primarily through agricultural activities.

The oscillatory regularity observed in precipitation rhythms allows for two practical considerations to be made. This enables the forecasting of future precipitation dynamics based on data from previous years, as well as the consideration of fluctuating precipitation dynamics to recommend optimal crop rotations and select the most suitable range of crop varieties for cultivation. The established regularities provide a basis for formulating empirical rules for the selection of crops in crop rotation. It is well documented that the cultivation of soybeans as a predecessor to winter wheat in the sub-zone of sufficient moisture in Forest-Steppe is an inherently risky venture. The crop is highly susceptible to fluctuations in temperature and moisture levels throughout the growing season. However, the awareness of crop characteristics is of limited practical value in the absence of a forecast of the probable amount of precipitation in the subsequent year. Spatial and temporal patterns with different time lags have been established, which can serve as a foundation

for climate forecasts and the development of optimal crop rotations. The cultivation of sugar beet is adversely affected by the overlap of crops in the crop rotation, which can also be attributed to a discrepancy between the rhythm of climatic processes and the requirements of the crop.

## CONCLUSIONS

The distribution of total precipitation in the study area results from a superposition of processes that reflect the patterns of geographical and altitudinal zonation, as well as geographical sectorality (meridional zonation). The mean precipitation level within the study area for the period between 1960 and 2023 was  $625 \pm 68$  mm, with a range spanning from 535 to 1,160 mm. During the study period, there was a discernible trend towards both increasing and decreasing precipitation. The southeastern region exhibited a declining precipitation trend, whereas the northwest and north demonstrated an increasing precipitation trend over time. A global principal component analysis identified six statistically significant principal components, which collectively explained 84.8% of the variation in the detrended precipitation data. The principal components exhibited particular spatial patterns of variability and spectral features of time variation. The established spatial and temporal patterns of precipitation are formed as a result of the influence of various factors. Principal Components 1-3 result from geographical factors that are regular in both space and time. Principal Component 1 is indicative of the meridional sectoral variability of precipitation rhythms. Principal Components 2 and 3 exhibit a spatial organisation that closely corresponds to geographic zonation, albeit with a cyclical rather than modal spatial pattern. Principal Components 4-6 are the result of local ecological and landscape factors. The anthropogenic transformation of the landscape can also impact precipitation rhythms and contribute to the formation of relevant spatial and temporal patterns. For future research, it is essential to determine the impact of spatial and temporal dynamics of precipitation on the yield of key agricultural crops in the region.

## ACKNOWLEDGEMENTS

None.

## CONFLICT OF INTEREST

None.

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## Коливальна просторово-часова мінливість опадів в Поліссі та Лісостепу та вплив аграрного перетворення ландшафтів

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**Анотація.** Території Полісся та Лісостепу мають велике значення для України, пропонуючи значний потенціал для розвитку сільського та лісового господарства. У світлі нагальної проблеми глобальної зміни клімату вкрай важливо, щоб активне господарське використання цих територій відбувалося з урахуванням зобов'язань щодо збереження екологічних систем та підтримання екосистемних функцій. Метою цієї статті було з'ясувати закономірності просторової та часової мінливості опадів і встановити вплив антропогенної трансформації земель внаслідок сільськогосподарського виробництва. На досліджуваній території середній рівень опадів становив  $625 \pm 68$  мм і коливався від 535 до 1160 мм. Протягом досліджуваного періоду (1960-2023 рр.) спостерігалася тенденція як до збільшення, так і до зменшення кількості опадів. Південний схід регіону характеризувався тенденцією до зменшення кількості опадів, тоді як на північному заході та півночі часовий тренд показував збільшення кількості опадів. Кількість опадів у Карпатському регіоні значно вища, ніж в інших частинах території. Наявність коливальної закономірності в ритмі опадів дозволяє розглядати два практичні аспекти: можливість прогнозування майбутньої динаміки опадів на основі наявної інформації за попередні роки та врахування коливальної динаміки опадів при рекомендаціях оптимальних сівозмін і підборі найбільш придатного асортименту сортів сільськогосподарських культур для вирощування

**Ключові слова:** клімат; просторова структура; часова динаміка; ландшафтне різноманіття; рослинний покрив

## Characteristics of soft winter wheat varieties by crop structure and grain quality indicators

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**Abstract.** The purpose of the study was to investigate the collection of soft winter wheat varieties selected by four research institutions of Ukraine, covering Steppe and Forest-Steppe soil and climatic zones. As a result of the study, indicators of the yield structure and grain quality of 53 varieties of soft winter wheat were analysed. The obtained data allowed assessing the stability of productivity elements and identifying varieties with high indicators for further use in breeding. Based on the results obtained, tables and graphs were compiled that reflect the difference in structural indicators between varieties over the years of research, and an estimate of the frequency of distribution of such parameters as: the length of the ear rod, the weight of the ear, the number of spikelets per ear, the number of grains in the ear, the weight of grains from the ear, and the weight of 1,000 grains. Statistical analysis using ANOVA and construction of confidence intervals (significance level of 0.05) confirmed significant differences between varieties in terms of the indicators under study, which helped to identify varieties with high stability of grain yield and quality. When using correlation analysis, relationships between structural indicators were established. Special attention was paid to homeostatic varieties that showed high indicators during 2021/2022-2023/2024 studies, namely: the length of the ear rod, the number of spikelets per ear, and the weight of 1,000 grains, which are key breeding indicators to increase yields. Such indicators were determined by the specificity of genotypes, environmental conditions, and their interaction. After calculating the regression coefficient, varieties with a high level of adaptability were determined. The best varieties in terms of the parameters under study were recommended for further use in breeding programmes aimed at increasing productivity and improving the quality of soft winter wheat grain in the context of climate change

**Keywords:** weight of 1,000 grains; grain quality; protein; gluten; correlation; adaptability; homeostatic

### INTRODUCTION

Wheat is one of the main food crops in Ukraine and the world. Increasing the productivity and adaptability of varieties directly affects food security, especially in

the face of population growth, increased demand for grain, and climate change. Yield is one of the main indicators of productivity of a variety, which depends on

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various structural components, such as the number of ears per plant, the number of grains in the ear, and the weight of 1,000 grains. Evaluation of these parameters determines the most productive varieties adapted to specific growing conditions, considering climatic, soil, and agrotechnical factors. High-yielding varieties help to increase production efficiency, as they to get a stable yield with optimal use of resources. Grain quality is an equally important indicator, as it affects the nutritional and processing value of products. The main indicators of grain quality are the protein content, raw gluten, grain nature, and other parameters that affect its suitability for the bakery, confectionery, and other industries. The quality of grain also affects the possibility of its long-term storage and transportation, which is important for agro-industrial enterprises. The creation of modern wheat varieties requires a combination of inversely dependent characteristics in one genotype, such as productivity and quality, and the effectiveness of breeding will depend on the availability of genetic sources (Kyrylchuk & Kovalchuk, 2021). Therefore, it is the analysis of the crop structure and grain quality that allows breeders to identify varieties with optimal characteristics that increase the efficiency of agricultural production and meet modern market requirements (Lotysh & Kardash, 2021).

I. Shpakovych & H. Kovalyshyna (2023) investigated that the introduction of new varieties and species, in particular, the genus *Aegilops* as sources of valuable agricultural traits such as adaptability, and their inclusion in the scheme of the breeding process is an important condition for breeding. However, an important place in breeding for productivity remains for local varieties, especially in the context of climate change, soil degradation, and ecosystem destruction, including due to the consequences of military operations that do not avoid agricultural land. A. Ficiciyan *et al.* (2018) found that local varieties show high resistance to regional climatic conditions (droughts, high temperatures, frosts, etc.), which makes them stable in unstable and extreme weather conditions. In addition, such varieties are more adapted to local agroecosystems, and their study is the key to increasing the productivity of soft winter wheat varieties in modern conditions. The need to create new varieties adapted to changing climatic conditions with high yield and quality indicators determines the relevance of this study.

Numerous researchers have conducted studies to evaluate soft winter wheat varieties for yield and quality, and the results of their work have been used in the selection of modern wheat varieties. Z. Guo *et al.* (2018)

investigated the impact on yield of various manipulations regarding the structure of the ear, namely, indicators of the structure of the wheat crop and how they can predict the yield and change the architectonics of the crop to increase the yield. S. Ebrahimnejad & V. Rameeh (2016) found a high coefficient of variation between the characteristics of ear weight and plant biological yield. Accordingly, the effectiveness of using such dependence in breeding for productivity will be high. In their studies, M. Lozinskiy *et al.* (2021) established the features of the development of the length of the main ear under various environmental conditions. They investigated the influence of the length of the main ear on the development of the number of spikelets per ear, the number of grains in the ear, and the weight of grain from the main ear, and based on the results obtained, they established the adaptability of soft winter wheat varieties under study.

Adaptability should be understood as the ability of a variety to combine a sufficiently high yield with stability in the face of climate change, while genotypes with hyperreaction to growth conditions should be considered sensitive (Lytvynenko *et al.*, 2013). According to M. Helguera *et al.* (2020), wheat grain quality indicators are a determining factor in its further use and the quality of products obtained on its basis. Therefore, in addition to yield indicators, grain quality indicators occupy an important place in the selection of soft winter wheat. Thus, one of the indicators used for selection in hybrid nurseries is the content of protein and raw gluten (Khan, 2019).

The purpose of the study was to analyse the structure of the crop and grain quality indicators of soft winter wheat varieties selected by various breeding and research institutions of Ukraine.

Objectives of the study:

- to establish the interdependence between crop structure indicators and grain quality;
- to identify sources of valuable traits in the varieties under study.

## MATERIALS AND METHODS

The study analysed 53 varieties of soft winter wheat developed by 4 research institutes in Ukraine (Table 1). The study was conducted in accordance with the ethical standards provided for by the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). The provisions of these documents aimed at protecting Biological Diversity and preventing threats to the species under study were observed.

**Table 1.** List of soft winter wheat varieties created in research institutions

No.	Names of varieties	Number of varieties	Originators of varieties
1	Spivanka Poliska, Kesaria Poliska, Namysto, Pyriatynka, Myroliubna, Pamyati Hirka, Krayevyd, Efektna, Merezhka, Poliska 90, Liubito, Polisiianka, Vodohrai, Fortetsia Poliska, Shchedrivka Kyivska	15	Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine
2	MIP Yuvileyna, Svitanok Myronivskiy, Hratsia Myronivska, MIP Assol, Berehynia Myronivska, Hospodynina Myronivska, MIP Lada, Estafeta Myronivska, Oberih Myronivskiy, MIP Kniazhna, MIP Vyshyvanka, MIP Dniprianka, MIP Valencia	13	Myronivsky Institute of Wheat named after V.M. Remeslo
3	Legenda Bilotserkivska, Tsarivna, Perlyna Lisostepu, Hratsia Bilotserkivska, Ros, Romantyka, Kvitka Poliv, Lisova Pisia, Rozumnytsia, Vodohrai Bilotserkivskiy, Vidrada, Hadzynka, Lybid, Charodiyka Bilotserkivska	14	Bila Tserkva Experimental and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences
4	Aksioma Odeska, Nota Odeska, Duma Odeska, Fortetsia, Versia Odeska, Mudrist Odeska, Sich, Oktava Odeska, Doskonalist Odeska, Optyma Odeska, Palitra	11	Plant Breeding and Genetics Institute – National Centre of Seed and Cultivar Investigation of the National Academy of Sciences of Ukraine

**Source:** compiled by the authors

The research was conducted during 2021/2022-2023/2024 in the fields of a separate division of the National University of Life and Environmental Sciences of Ukraine "Agronomic Experimental Station", located in the Forest-Steppe soil and climate zone of Ukraine. The main indicators for evaluating soft winter wheat varieties were: the length of the ear rod, the weight of the ear, the number of spikelets per ear, the number of grains in the ear, the weight of grain from the ear, the weight of 1,000 grains, the content of protein and gluten. The assessment was carried out in accordance with generally accepted methods, which allowed comparing varieties in terms of the main structural indicators and grain quality indicators and identifying the most promising ones for use in the selection of soft winter wheat. Grain quality indicators of soft winter wheat varieties were determined on the FOSS "Infratec 1241 Grain Analyzer" express whole grain analyser (Denmark) using the method of Z. Kyienko *et al.* (2017).

The quality class of wheat grain was determined according to DSTU 3768:2019 (2019). Statistical analysis of the data was performed using Microsoft Excel software and the online ANOVA Calculator. Basic calculations were performed using Excel, in particular, summation, calculation of average values, standard deviations, coefficients of variation, and the least significant difference (LSD) between indicators. ANOVA Calculator was used to analyse variance (ANOVA) to compare groups. Differences in the confidence level  $p < 0.05$  were considered statistically significant.

Overall adaptive capacity was determined based on the calculation of the regression coefficient. If:

→  $b_i = 1$  – it was considered that the variety was medium-adaptive;

→  $b_i > 1$  – variety was high-yielding only under optimal growing conditions;

→  $b_i < 1$  – variety was resistant to stressful environmental conditions.

Field experiments were conducted on plots of 6 m<sup>2</sup> each, with silage maize as the predecessor in all years of the study. Pre-sowing tillage included the introduction of a compensatory rate of fertilisers in the amount of N<sub>90</sub>P<sub>60</sub>K<sub>90</sub>. The plots were not fertilised during the study period.

## RESULTS AND DISCUSSION

As a result of three-year studies of 53 varieties of soft winter wheat, the main indicators of the crop structure and grain quality were analysed (Fig. 1). The length of the spike rod of plants in the experimental sample varied from 4.10 to 10.25 cm. The highest indicators were recorded in the varieties Legenda Bilotserkivska (the average length over the years of research was 9.08 cm) and Spivanka Poliska (the average indicator was 8.47 cm), which suggests their potential to form a larger number of spikelets per ear, and accordingly, a larger number of grains from the ear.

The number of spikelets per ear of the crop varieties under study ranged from 11.00 to 26.80 units. The number of spikelets per ear can be a limiting factor in the yield of a variety. This indicator was highest in the varieties Legenda Bilotserkivska (21.30 units), Fortetsia Poliska (19.90 units) and Kesaria Poliska (20.30 units). The number of grains in one spikelet is an indicator of seed development in a particular year under certain weather conditions and cultivation technology and directly affects the yield of the crop, and is a varietal feature of soft winter wheat. The number of grains in the ear over the years of research in varieties varied from 17.80 to 56.50 units. This indicator was highest in the following wheat varieties: Legenda Bilotserkivska (46.43 units), Spivanka Poliska (45.79 units)

and Shchedrist Odeska (44.70 units). It is worth noting that in the 2023/2024 growing year, there was no

significant difference between varieties, relative to the average number of grains by variety.

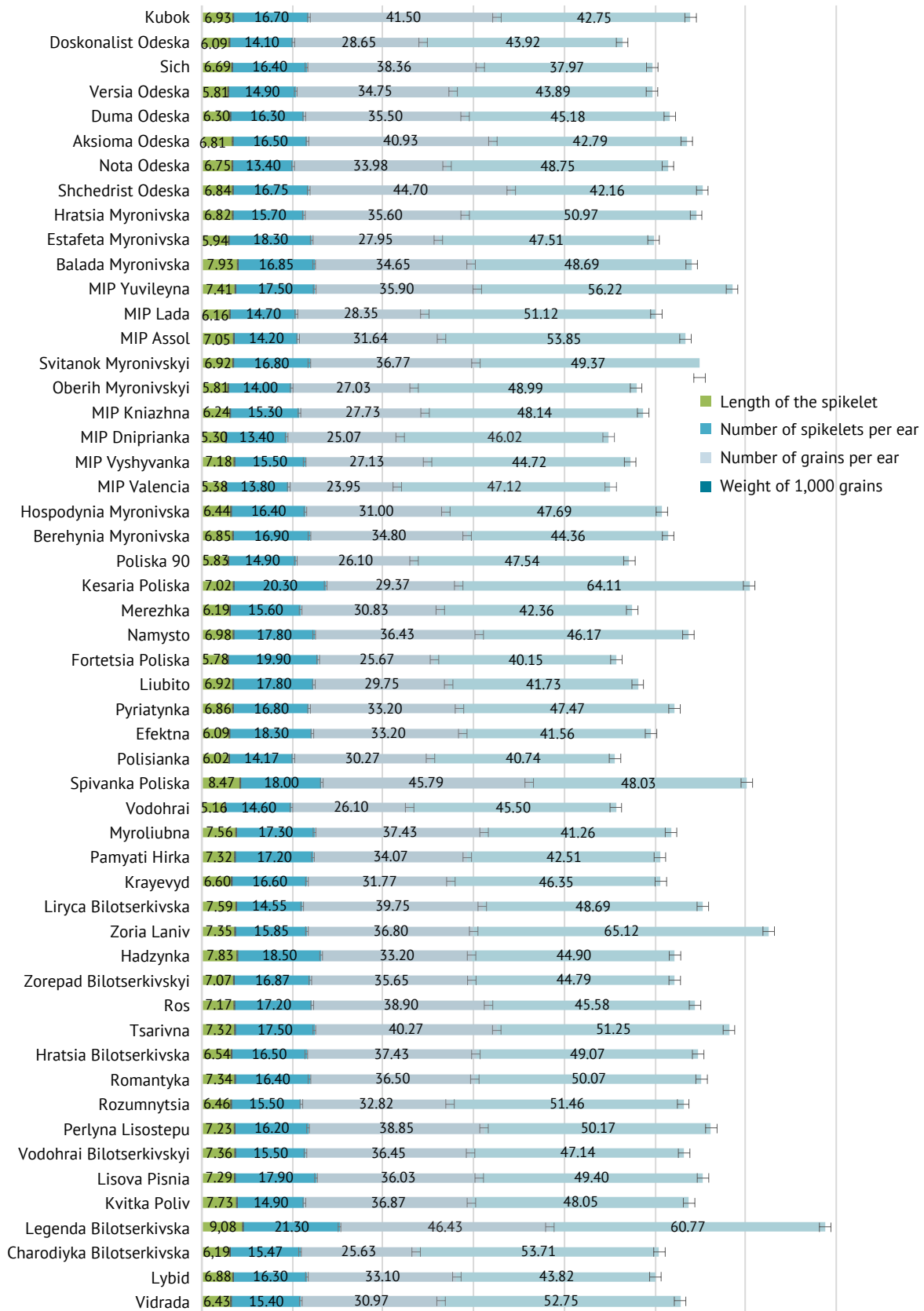


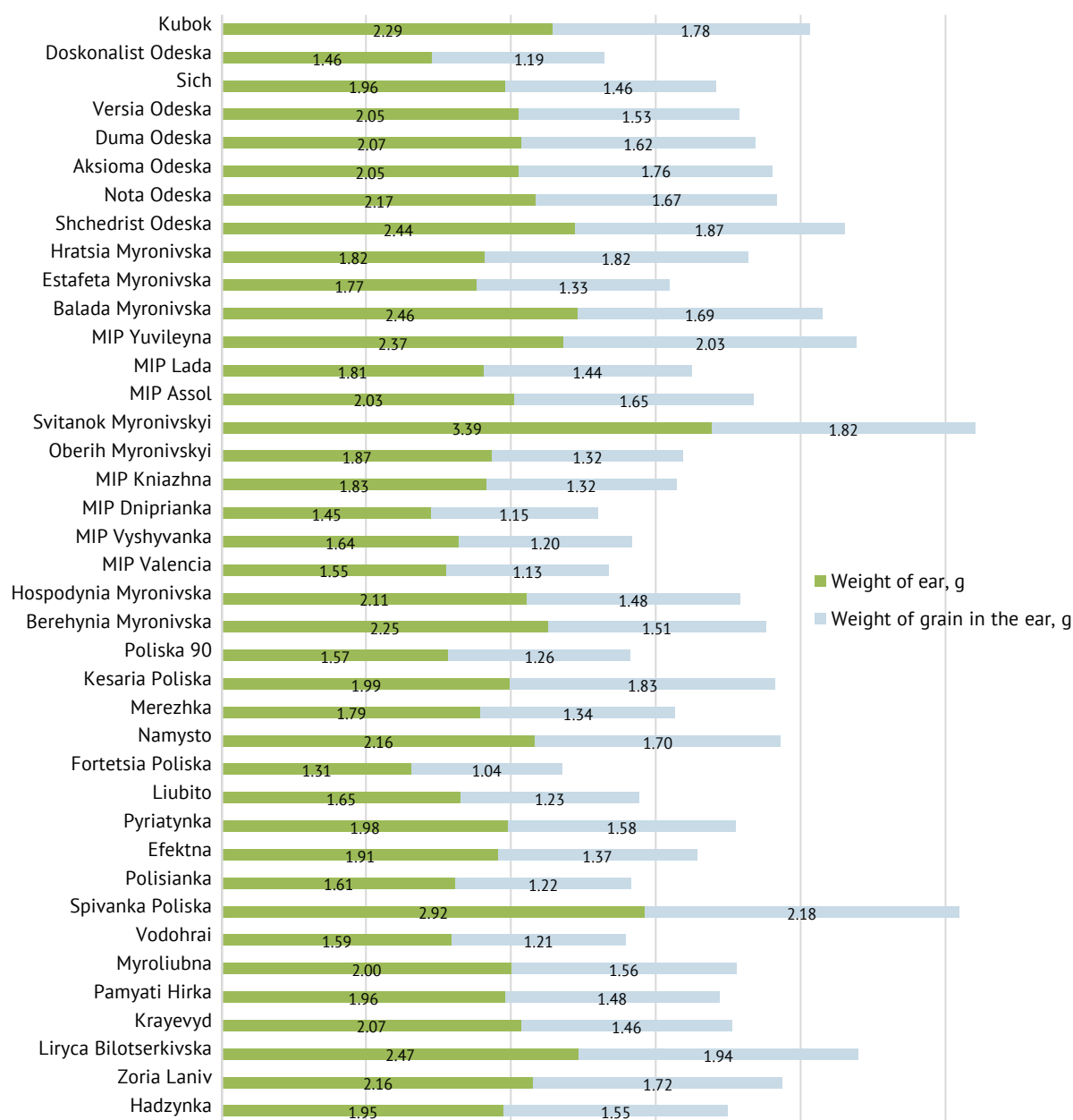
Figure 1. Indicators of the yield structure of soft winter wheat varieties

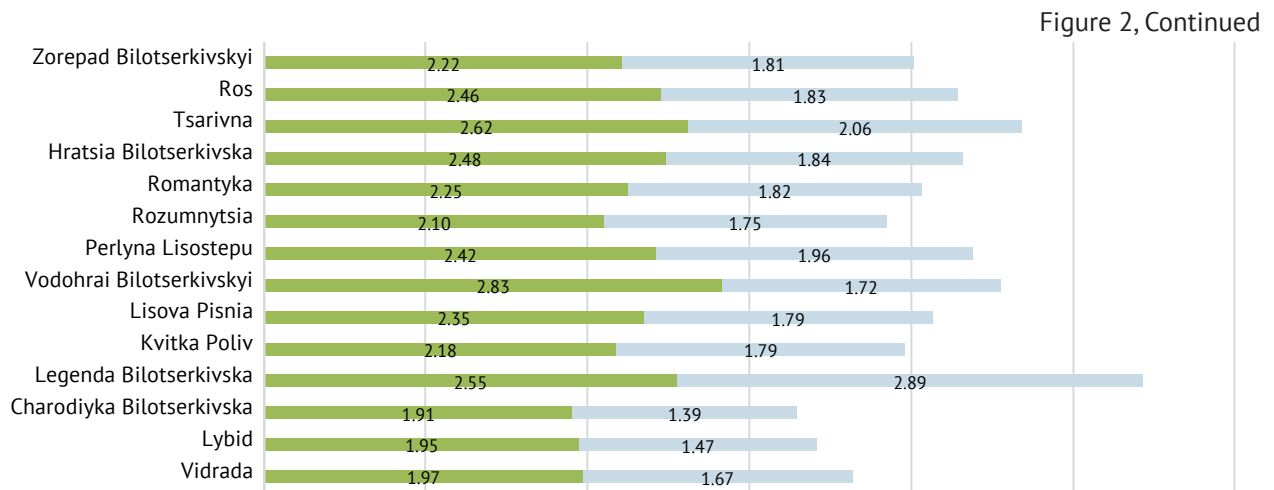
Source: compiled by the authors

Compared to previous indicators, the weight of 1,000 grains best reflects the quality and size of seeds. During the years of experiments, it ranged in varieties from 38.89 to 92.53 g. Thus, despite not significant previous indicators, high seed fullness and potentially high quality, due to the weight of 1,000 grains, were noted for a number of varieties: Vidrada (52.7 g), Charodiyka Bilotserkivska (53.7 g), Legenda Bilotserkivska (60.77 g), Perlyna Lisostepu (50.17 g), Rozumnytsia (51.46 g), Romantyka (50.07 g), Tsarivna (51.25 g), Zoria Laniv (65.10 g), Kesaria Poliska (64.11 g), MIP Assol (53.85 g), MIP Lada (51.12 g), MIP Yuvileyna (56.22 g), and Hratsia Myronivska (50.97 g). There was no significant difference between the varieties in this indicator in 2021/2022 and 2023/2024, which may indicate

favourable growing conditions in these years in contrast to the 2022/2023 growing year.

Ear weight (Fig. 2) of soft winter wheat varieties under study were in the range of 0.85-3.85 g. For varieties with a high ear weight, both a high number of grains and the weight of grain from the ear were noted. These varieties include Spivanka Poliska (average weight 2.92 g) and Svitanok Myronivskyi (3.39 g). The weight of grain from the ear varied according to the varieties of soft winter wheat from 0.70 to 4.71 g. In the 2023/2024 growing year, soft winter wheat varieties did not have a significant difference in grain weight per ear relative to the average value for the year. The largest grain weight significantly different from the average value was observed for Legenda Bilotserkivska variety – 2.89 g.





**Figure 2.** Yield of soft winter wheat varieties

**Source:** compiled by the authors

The variability of crop structure indicators depending on the year of research demonstrates that the 2023/2024 growing year was the most favourable for the development of soft winter wheat – all indicators are at a high level, while 2022/2023 was the least favourable. Homeostatic of the indicators under study (Table 2) indicates that the varieties of this sample have relatively stable indicators in the years of research in terms of the length of the ear rod, the number of spikelets per ear, and the weight of 1,000 seeds. Such structural indicators as the weight of the ear, the number of grains in the ear, and the weight

of grain from the ear for most varieties have a high variation (>30%), respectively, it can be assumed that they depend on the environmental conditions of a particular year and cultivation technology. Several varieties of soft winter wheat were identified that strongly respond to changes in growing conditions in many respects: Legenda Bilotserkivska, Perlyna Lisostepu, Zorepad Bilotserkivskiyi, Krayevyd, Pamyati Hirka, Posilianka, Liubito, Fortetsia Poliska, Merezhka, and Kesaria Poliska. These varieties have low homeostasis, so it is better to grow such varieties in regions with optimal growing conditions.

**Table 2.** Homeostatic indicators of the yield structure of soft winter wheat varieties

No.	Variety	Coefficient of variation by indicators, %					
		spike rod length	ear weight	number of spikelets per ear	number of grains per ear	grain weight per ear	weight 1,000 grains
1	Vidrada	9.37	23.79	8.70	18.23	<b>36.31</b>	21.31
2	Lybid	12.32	20.65	5.62	20.00	28.13	10.66
3	Charodiyka Bilotserkivska	19.04	29.64	71.87	14.86	21.84	8.89
4	Legenda Bilotserkivska	6.58	12.86	<b>49.37</b>	10.95	<b>54.71</b>	<b>45.49</b>
5	Kvitka Poliv	19.63	<b>36.91</b>	17.60	<b>34.46</b>	<b>37.03</b>	4.74
6	Lisova Pisia	15.15	21.80	3.11	10.97	17.45	9.06
7	Vodohrai Bilotserkivskiyi	15.13	26.83	4.92	19.15	27.52	16.45
8	Perlyna Lisostepu	26.50	<b>33.18</b>	11.43	<b>32.89</b>	<b>35.19</b>	10.75
9	Rozumnytsia	18.53	<b>42.30</b>	9.37	28.57	<b>43.10</b>	19.70
10	Romantyka	6.31	5.72	5.49	7.46	6.34	10.11
11	Hratsia Bilotserkivska	14.44	21.52	2.78	10.71	14.26	5.40
12	Tsarivna	7.42	20.48	10.37	21.68	20.72	4.76
13	Ros	21.45	23.82	8.18	29.70	<b>43.64</b>	17.16
14	Zorepad Bilotserkivskiyi	19.32	<b>62.25</b>	17.68	<b>44.63</b>	<b>60.72</b>	20.56
15	Hadzynka	19.15	<b>41.28</b>	6.23	27.43	<b>48.01</b>	22.69

Table 2, Continued

No.	Variety	Coefficient of variation by indicators, %					
		spike rod length	ear weight	number of spikelets per ear	number of grains per ear	grain weight per ear	weight 1,000 grains
16	Zoria Laniv	13.38	20.67	17.40	22.29	20.56	<b>41.00</b>
17	Liryca Bilotserkivska	7.27	1.43	0.49	1.60	1.10	2.70
18	Krayevyd	17.66	<b>45.41</b>	29.45	<b>43.93</b>	<b>40.84</b>	10.55
19	Pamyati Hirka	<b>30.33</b>	<b>50.61</b>	29.75	<b>41.16</b>	<b>51.77</b>	11.54
20	Myroliubna	3.62	21.57	11.88	18.05	24.93	8.04
21	Vodohrai	16.87	29.63	10.51	27.18	<b>36.38</b>	10.26
22	Spivanka Poliska	18.31	27.71	4.40	24.41	24.88	15.68
23	Polisianka	9.38	<b>55.38</b>	18.11	<b>52.72</b>	<b>48.38</b>	4.22
24	Efektna	17.55	18.14	14.56	18.82	15.72	7.20
25	Pyriatynka	12.35	8.23	12.32	7.33	8.42	1.24
26	Liubito	18.59	<b>39.18</b>	12.45	<b>37.83</b>	<b>34.94</b>	6.02
27	Fortetsia Poliska	27.23	<b>40.48</b>	<b>32.45</b>	<b>36.57</b>	<b>40.81</b>	4.22
28	Namysto	14.82	18.66	8.28	21.43	27.82	8.59
29	Merezhka	21.83	<b>45.00</b>	16.06	<b>42.26</b>	<b>50.77</b>	11.46
30	Kesaria Poliska	12.71	<b>59.03</b>	28.98	<b>41.75</b>	<b>39.29</b>	<b>30.84</b>
31	Poliska 90	12.60	<b>35.68</b>	18.86	29.15	<b>37.53</b>	9.11
32	Berehynia Myronivska	5.70	12.03	6.51	17.47	14.16	22.07
33	Hospodynia Myronivska	16.33	<b>35.38</b>	3.00	27.42	27.50	11.25
34	MIP Valencia	19.19	27.37	12.30	3.25	15.71	18.91
35	MIP Vyshyvanka	9.40	13.82	5.95	10.68	11.28	1.16
36	MIP Dniprianka	9.49	17.20	15.37	12.45	14.78	13.33
37	MIP Kniazhna	7.24	6.15	7.03	24.55	16.24	8.65
38	Oberih Myronivskiyi	8.56	19.82	3.12	6.52	8.95	7.66
39	Svitanok Myronivskiyi	6.25	<b>56.06</b>	3.43	8.61	16.69	7.86
40	MIP Assol	19.06	10.82	3.50	14.94	24.60	<b>38.60</b>
41	MIP Lada	3.33	3.45	1.45	10.73	5.24	5.36
42	MIP Yuvileyna	13.27	11.06	0.81	3.55	22.70	19.23
43	Balada Myronivska	2.77	8.05	11.33	13.26	15.90	2.66
44	Estafeta Myronivska	26.67	18.83	11.24	4.30	11.70	7.41
45	Hratsia Myronivska	<b>32.48</b>	<b>61.67</b>	2.70	12.31	17.09	4.83
46	Shchedrist Odeska	2.79	8.85	10.55	13.29	1.51	11.79
47	Nota Odeska	11.43	<b>33.89</b>	1.06	22.17	26.76	4.73
48	Aksioma Odeska	2.54	10.35	3.87	3.71	14.91	11.22
49	Duma Odeska	4.49	22.55	23.93	17.93	28.81	11.17
50	Versia Odeska	1.46	6.90	10.44	7.12	15.71	8.64
51	Sich	1.28	24.77	0.92	24.49	23.57	0.71
52	Doskonalist Odeska	5.57	5.35	11.03	23.94	22.58	<b>45.30</b>
53	Kubok	1.63	2.17	1.27	1.75	1.99	0.24

**Notes:** varieties with a high level of variability are highlighted in bold

**Source:** compiled by the authors

Soft winter wheat varieties with high homeostaticity are important for breeding programmes, especially for regions with unstable climates. Homeostatic varieties in the years of research turned out to be: Lybid, Charodiyka

Bilotserkivska, Lisova Pisnia, Vodohrai Bilotserkivskiyi, Romantyka, Hratsia Bilotserkivska, Tsarivna, Zoria Laniv, Liryca Bilotserkivska, Myroliubna, Vodohrai, Spivanka Poliska, Efektna, Pyriatynka, Namysto, Berehynia

Myronivska, MIP Valencia, MIP Vyshyvanka, MIP Dni-prianka, MIP Kniashna, Oberih Myronivskiyi, MIP Lada, MIP Yuvileyna, Balada Myronivska, Estafeta Myronivska, Shchedrist Odeska, Aksioma Odeska, Duma Odeska, Versia Odeska, Sich, and Kubok. The most variable indicators of the structure of the yield of soft winter wheat were the number of grains in the ear and the weight of grains from the ear. The most stable indicators were the length of the ear rod and the number of spikelets per ear.

Since the influence of year conditions on the structural indicators under study is established, it is advisable to determine statistically significant differences over the years of research using the Tukey HSD test. Based on the data of the analysis of soft winter wheat

varieties by the length of the ear rod, the weight of the ear, the number of spikelets per ear, the weight of grain from the ear, and the weight of 1,000 grains (Table 3), the following conclusions can be drawn: over the course of three years, a significant increase in the studied indicators was observed, especially between the second and third years. This may indicate an improvement in growing conditions or an improvement in agrotechnical measures, which contributed to an improvement in these indicators of soft winter wheat in the last year of research. However, between the 2021/2022 and 2022/2023 growing years, the differences in indicators are not significant, which may indicate stable or similar conditions during these periods.

**Table 3.** Comparison of indicators of the structure of the yield of soft winter wheat by years of observation (ANOVA)

Pair of years	Average difference between the compared groups	Standard error, SE	Tukey's range test, Q	Confidence interval limits		Critical average	p-value
<b>by the length of the spike rod</b>							
xI-xII	0.2611	0.1813	1.4405	-0.3462	0.8684	0.6073	0.5664
xI-xIII	0.6787	0.1704	3.9832	0.1078	1.2497	0.5709	0.01527
xII-xIII	0.9398	0.1747	5.3789	0.3544	1.5253	0.5854	0.0006207
<b>by ear weight</b>							
xI-xII	0.1037	0.09391	1.1041	-0.211	0.4183	0.3146	0.7155
xI-xIII	0.4271	0.08866	4.8169	0.13	0.7242	0.2971	0.002474
xII-xIII	0.5308	0.0909	5.8393	0.2262	0.8353	0.3046	0.0001846
<b>by the number of spikelets per ear</b>							
xI-xII	0.2644	0.1581	1.6718	-0.2655	0.7942	0.5298	0.4658
xI-xIII	0.812	0.1493	5.4388	0.3118	1.3123	0.5003	0.0005335
xII-xIII	1.0764	0.1531	7.0323	0.5635	1.5893	0.5129	0.000005748
<b>by weight of 1,000 grains</b>							
xI-xII	4.2114	1.2653	3.3283	-0.02833	8.4511	4.2397	0.05197
xI-xIII	4.7673	1.1947	3.9903	0.7642	8.7705	4.0031	0.01506
xII-xIII	0.5559	1.2248	0.4539	-3.548	4.6599	4.1039	0.9448
<b>by the number of grains in the ear</b>							
xI-xII	6.8646	1.2181	5.6355	2.7831	10.946	4.0814	0.000319
xI-xIII	2.8242	1.1501	2.4556	-1.0295	6.6779	3.8537	0.1954
xII-xIII	9.6888	1.1791	8.2172	5.7381	13.6395	3.9507	1.232e-7
<b>by grain weight per ear</b>							
xI-xII	0.1648	0.07508	2.1952	-0.08675	0.4164	0.2516	0.27
xI-xIII	0.2764	0.07089	3.8989	0.03887	0.5139	0.2375	0.01808
xII-xIII	0.4412	0.07268	6.071	0.1977	0.6848	0.2435	0.00009746

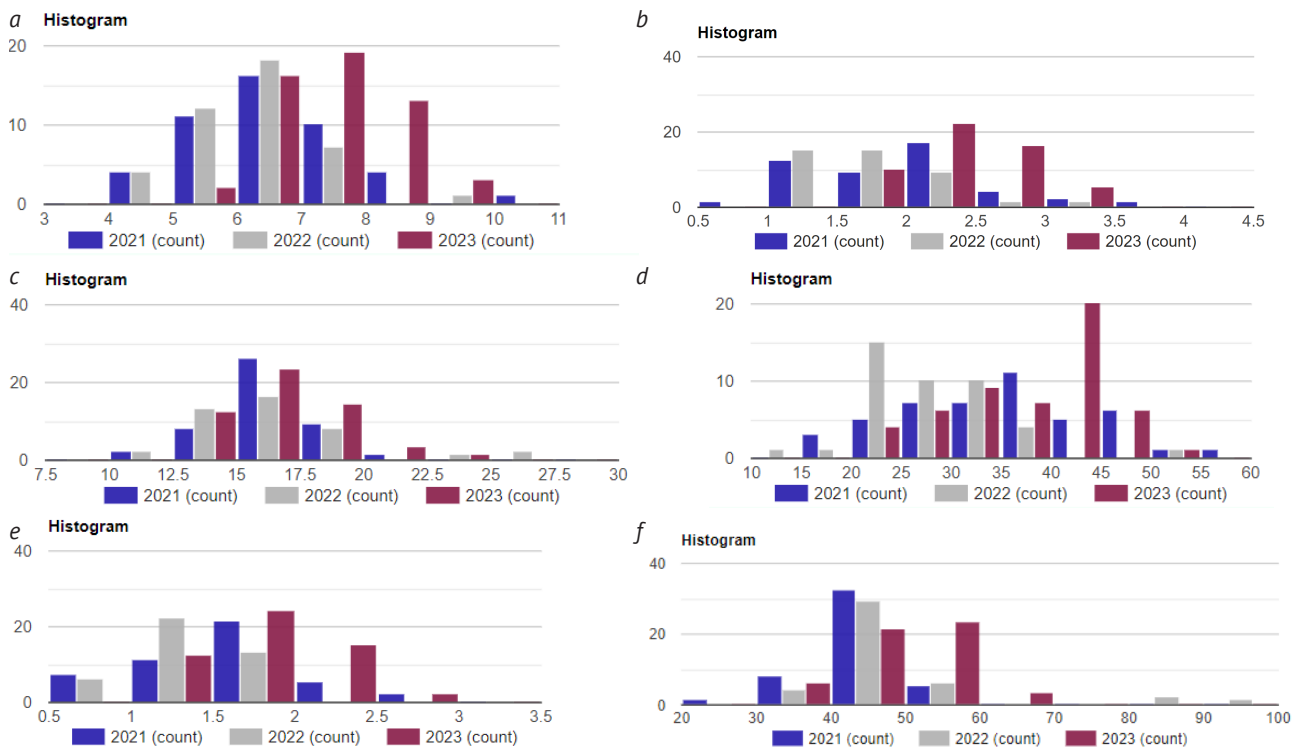
**Source:** compiled by the authors

The previous trend is changing for the number of grains in an ear, because the indicators did not have a significant difference in 2021/2022 and 2023/2024, while in the 2022/2023 growing year such a difference was observed. This indicates the similarity of weather and climatic conditions during the flowering period of soft winter wheat in the first and last year of research. A large proportion of soft winter wheat varieties in 2021/2022 and 2022/2023 g.y. had a spike rod length of 6-7 cm, while in the 2023/2024 growing

year this indicator increased to 7-8 cm (Fig. 3a). A significant proportion of varieties had a grain weight in 2021/2022 g.y. (growing year) in the range of 1-2.5 g, in 2022/2023 – 2-2.5 g, in 2023/2024 – 2-3 g (Fig. 3b). The number of spikelets per ear of a significant proportion of varieties during three years of research was in the range of 15-17.5 units (Fig. 3c). Figure 3d shows a significant variation between varieties in terms of the number of grains in the ear. A significant proportion of varieties had 35-40 grains per

ear in 2021/2022 g.y., in 2022/2023 this number decreased to 20-25 grains, and in 2023/2024 it increased to 40-45 grains. Given that the number of spikelets per ear has not changed significantly over the years of research, it can be assumed that the decrease in seed setting in 2022/2023 g.y. was caused by unfavourable weather conditions, and a significant increase in the number of seeds in the ear in 2023/2024 g.y. was caused by favourable conditions. The weight of grains

in the ear of most varieties in 2021/2022 g.y. was 1.5-2.0 g, in 2022/2023 it decreased to 1.0-1.5 g, and in 2023/2024 g.y. it increased again to the limits of 1.5-2.0 g (Fig. 3e), which also indicates the impact of adverse weather conditions on the indicator. The weight frequencies of 1,000 grains of soft winter wheat are quite dense over the years of research – this indicates that most varieties have similar values, namely in the range of 40-50 g (Fig. 3f).



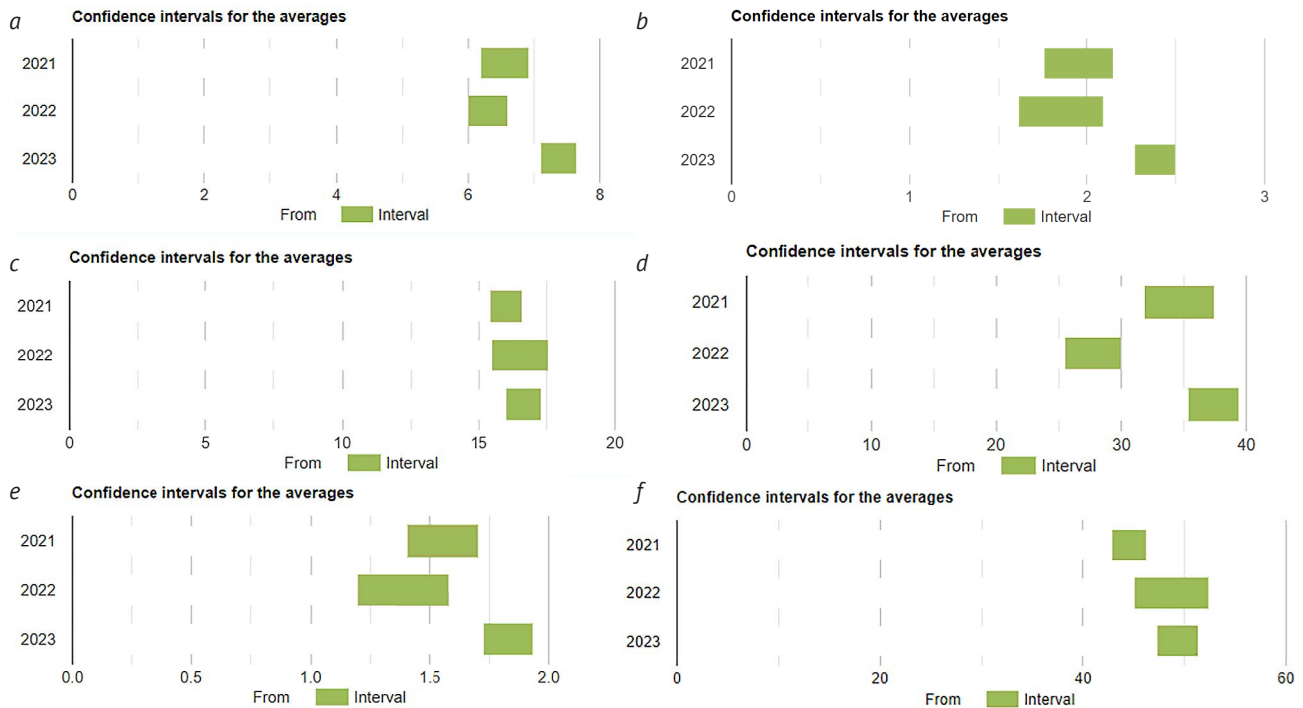
**Figure 3.** Distribution of frequencies of indicators of the yield structure of soft winter wheat varieties for 2021/2022-2023/2024

**Notes:** a) by the length of the ear rod; b) by the weight of the ear; c) by the number of spikelets per ear; d) by the number of grains in the ear; e) by the weight of grains from the ear; f) by the weight of 1,000 grains. ANOVA Calculator was used to build diagrams

**Source:** compiled by the authors

Analysis of confidence intervals for 95% of the significance level indicates fluctuations in the values of indicators of the structure of the crop of soft winter wheat by year (Fig. 3). It follows that the most stable indicator by year for all the crop varieties under study is the number of spikelets per ear (Fig. 4c), because only for this indicator can the average value be within acceptable limits for all years of research. By the length of the spike rod (Fig. 4a), the weight of the ear (Fig. 4b), and the weight of grains from the ear (Fig. 4e) in 2023/2024 g.y., the values of indicators went beyond the confidence intervals of previous years, which may indicate a positive impact of this year's weather conditions on these

indicators. However, the development of the number of grains in the ear was negatively affected by the weather indicators of 2022/2023 g.y. (Fig. 4d), since the confidence intervals in the studied years do not coincide. Confidence intervals for the weight of 1,000 grains also fluctuated over the years (Fig. 4f). The largest range of indicator values was found in 2022/2023 g.y., while in 2021/2022 the weight of 1,000 grains was the lowest, and in 2023/2024 the values were within the range of the previous year. Hence, it can be assumed that the weather conditions of 2023/2024 g.y. were favourable for the gradation of wheat varieties according to the best seed fullness.



**Figure 4.** Confidence intervals (0.05 significance level) for average structural yield indicators of soft winter wheat varieties for 2021/2022-2023/2024

**Notes:** a) by the length of the ear rod; b) by the weight of the ear; c) by the number of spikelets per ear; d) by the number of grains in the ear; e) by the weight of grains from the ear; f) by the weight of 1,000 grains. ANOVA Calculator was used to build diagrams

**Source:** compiled by the authors

The protein content in the grain of soft winter wheat varieties in 2021/2022-2023/2024 ranged from 8.5 to 13.3% (Table 4), with an average value of 10.07%. According to DSTU 3768:2019 (2019), the first class of wheat includes a grain that has a protein content of at least 14%, and a raw gluten content of at least 28%. Over the years of research on the quality indicators of seeds of soft winter wheat varieties, not a single variety was identified that would belong to class 1, which is conditioned by the specificity of the soil and climatic conditions of the zone. The highest quality indicators of

crop varieties were observed in the 2021/2022 growing year. Most varieties of soft winter wheat this year had seed quality corresponding to class 3, and Poliska 90 – class 2 (protein content of 13.3% and gluten content of 24.2%. In 2022/2023 g.y., the seed quality indicator for all varieties was quite low, so the grain was classified as feed. However, MIP Kniazhna (protein content 11.0%, gluten content 19.6%), MIP Lada (11.2 and 19.6%, respectively) and Hratsia Myronivska (11.0 and 18.8%) varieties had higher grain quality indicators, which corresponded to class 3.

**Table 4.** Grain quality indicators of soft winter wheat varieties over the years of research

No.	Variety	Protein content, %					Gluten content, %				
		2021-2022	2022-2023	2023-2024	$\bar{x}$	$V, \%$	2021-2022	2022-2023	2023-2024	$\bar{x}$	$V, \%$
1	Vidrada	12.30	9.10	9.60	10.30	16.71	22.00	16.40	17.10	18.50	16.49
2	Lybid	12.10	9.40	9.30	10.30	15.42	21.30	16.70	16.90	18.30	14.21
3	Charodiyka Bilotserkivska	12.30	8.30	9.10	9.90	21.38	21.70	15.90	16.50	18.03	17.69
4	Legenda Bilotserkivska	12.50	10.50	9.40	10.80	14.55	22.30	18.10	15.90	18.77	17.33
5	Kvitka Poliv	12.90	7.80	8.30	9.70	28.98	22.40	15.90	11.90	16.73	31.67
6	Lisova Pisia	12.30	9.00	10.70	10.70	15.42	22.70	17.40	20.20	20.10	13.19

Table 4, Continued

No.	Variety	Protein content, %					Gluten content, %				
		2021-2022	2022-2023	2023-2024	$\bar{x}$	V, %	2021-2022	2022-2023	2023-2024	$\bar{x}$	V, %
7	Vodohrai Bilotserkivskiyi	11.50	8.40	11.00	10.30	16.16	20.00	16.10	18.70	18.27	10.87
8	Perlyna Lisostepu	12.60	8.00	11.50	10.70	22.45	22.10	16.00	19.70	19.27	15.95
9	Rozumnytsia	12.70	8.30	12.00	<b>11.00</b>	21.49	21.70	16.00	20.20	<b>19.30</b>	15.31
10	Romantyka	10.50	9.00	11.20	10.20	11.02	19.20	17.20	21.10	19.17	10.18
11	Hratsia Bilotserkivska	11.50	9.20	12.00	10.90	13.70	20.10	16.20	22.40	19.57	16.02
12	Tsarivna	11.30	8.60	10.80	10.20	14.08	20.10	16.40	20.40	19.00	11.73
13	Ros	13.20	8.80	10.50	10.80	20.54	22.50	16.30	18.40	19.07	16.54
14	Zorepad Bilotserkivskiyi	11.40	8.90	10.00	10.10	12.41	19.80	16.20	17.40	17.80	10.30
15	Hadzynka	10.80	9.50	8.70	9.70	10.93	18.10	16.60	15.80	16.83	6.94
16	Zoria Laniv	10.70	9.20	8.70	9.50	10.96	18.30	16.60	16.30	17.07	6.32
17	Liryca Bilotserkivska	10.80	10.20	8.90	10.00	9.71	17.90	17.00	16.20	17.03	4.99
18	Krayevyd	8.80	8.70	8.10	8.50	4.45	15.70	16.10	15.70	15.83	1.46
19	Pamyati Hirka	9.90	8.90	9.20	9.30	5.52	15.20	15.60	15.70	15.50	1.71
20	Myroliubna	9.40	8.30	8.50	8.70	6.74	16.10	16.00	16.10	16.07	0.36
21	Vodohrai	10.20	8.70	10.70	9.90	10.51	16.60	15.80	19.10	17.17	10.03
22	Spivanka Poliska	11.00	9.50	8.70	9.70	12.04	19.10	16.50	16.00	17.20	9.68
23	Polisianka	11.40	10.20		10.80	7.86	19.50	17.30		18.40	8.45
24	Efektna	9.60	10.70	8.40	9.60	11.98	16.50	18.00	16.00	16.83	6.18
25	Pyriatynka	9.60	9.70	9.00	9.40	4.03	17.10	17.10	16.60	16.93	1.70
26	Liubito	9.60	9.40	8.50	9.20	6.37	16.40	16.60	15.90	16.30	2.21
27	Fortetsia Poliska	10.30	9.20	8.90	9.50	7.76	19.10	16.90	16.50	17.50	8.00
28	Namysto	10.90	10.00	9.40	10.10	7.48	19.10	17.30	16.90	17.77	6.60
29	Merezhka	11.30	10.20	9.70	10.40	7.87	19.60	17.50	17.20	18.10	7.22
30	Kesaria poliska	9.50	8.30		8.90	9.53	16.40	15.70		16.05	3.08
31	Poliska 90	<b>13.30</b>	10.10	11.30	<b>11.60</b>	13.94	<b>24.20</b>	17.40	20.60	<b>20.73</b>	16.41
32	Berehynia Myronivska	12.10	10.30	8.90	10.40	15.42	21.50	17.80	16.40	18.57	14.19
33	Hospodynia Myronivska	12.00	9.90	9.10	10.30	14.54	20.80	17.80	16.50	18.37	12.01
34	MIP Valencia	11.80		9.30	10.60	16.68	19.80		16.40	18.10	13.28
35	MIP Vyshyvanka	10.60	10.30	8.80	9.90	9.74	18.10	17.80	16.20	17.37	5.88
36	MIP Dniprianka	11.80	9.80	8.90	10.20	14.55	20.60	17.30	16.10	18.00	12.95
37	MIP Kniazhna	12.70	11.00	9.50	<b>11.10</b>	14.42	22.90	19.60	17.30	<b>19.93</b>	14.12
38	Oberih Myronivskiyi	10.80	10.20	10.00	10.30	4.04	18.80	17.40	17.50	17.90	4.36
39	Svitanok Myronivskiyi	9.90	10.40	10.00	10.10	2.62	17.70	18.20	18.20	18.03	1.60
40	MIP Assol	10.00		9.70	9.90	2.14	17.30		17.40	17.35	0.41
41	MIP Lada	11.10	11.20	10.10	10.80	5.63	19.30	19.60	17.60	18.83	5.73

Table 4, Continued

No.	Variety	Protein content, %					Gluten content, %				
		2021-2022	2022-2023	2023-2024	$\bar{x}$	V, %	2021-2022	2022-2023	2023-2024	$\bar{x}$	V, %
42	MIP Yuvileyna	10.00	9.80	10.50	10.10	3.57	17.90	17.60	11.20	15.57	24.31
43	Balada Myronivska		10.60	9.50	10.10	7.70		18.10	16.70	17.40	5.69
44	Estafeta Myronivska	9.70	10.70	9.70	10.00	5.77	17.00	18.70	17.40	17.70	5.02
45	Hratsia Myronivska	10.90	11.00	9.60	10.50	7.44	18.10	18.80	16.90	17.93	5.36
46	Shchedrist Odeska	9.50	10.30	9.30	9.70	5.46	16.50	18.00	16.80	17.10	4.64
47	Nota Odeska	10.20	9.40	9.50	9.70	4.49	16.80	16.80	19.00	17.50	7.2
48	Aksioma Odeska	9.80	9.60	8.00	9.10	10.84	16.10	17.20	15.30	16.20	5.89
49	Duma Odeska	10.60	10.20	8.50	9.80	11.38	19.50	18.10	15.90	17.83	10.18
50	Versia Odeska	10.80	10.30	8.80	10.00	10.41	19.40	18.20	16.10	17.90	9.33
51	Sich	9.90	10.90	8.60	9.80	11.77	17.40	19.00	15.90	17.43	8.89
52	Doskonalist Odeska	11.50	10.30	8.60	10.10	14.43	19.80	17.70	16.10	17.87	10.39
53	Kubok	10.60		10.70	10.70	0.66	18.70		18.60	18.65	0.38
	$\bar{x}$	11.01	9.63	9.54	10.07	11.05	19.17	17.20	16.89	17.76	9.91

Source: compiled by the authors

Based on the above data (Table 2; Figs. 3, 4) it is possible to distinguish varieties that can maintain stable productivity and quality under various environmental conditions (Table 5). High adaptive ability according

to the indicators under study was established for the following varieties: Romantyka, Liryca Bilotserkivska, Pyriatynka, MIP Vyshyvanka, MIP Lada, Estafeta Myronivska, and Kubok.

Table 5. Adaptability of soft winter wheat varieties by grain weight of the main ear and grain quality

No.	Varieties	General adaptive capacity, $b_1$		
		ear weight	protein content	gluten content
1	Vidrada	1.39	2.06	2.58
2	Lybid	0.53*	1.93	2.22
3	Charodiyka Bilotserkivska	0.74*	2.51	2.71
4	Legenda Bilotserkivska	-1.04	1.81	2.64
5	Kvitka Poliv	1.36	3.39	4.23
6	Lisova Pisia	1.66	1.69	1.90
7	Vodohrai Bilotserkivskiyi	0.03*	1.22	1.26
8	Perlyna Lisostepu	2.08	1.94	2.06
9	Rozumnytsia	2.44	1.73	1.73
10	Romantyka	0.22*	0.25*	-0.01*
11	Hratsia Bilotserkivska	1.89	0.59*	0.33*
12	Tsarivna	0.87*	1.09	0.80*
13	Ros	0.33*	2.46	2.52
14	Zorepad Bilotserkivskiyi	2.97	1.35	1.47
15	Hadzynka	2.19	1.20	0.95*
16	Zoria Laniv	1.19	1.23	0.92*
17	Liryca Bilotserkivska	-0.09*	0.90*	0.65*
18	Krayevyd	2.13	0.29*	-0.09*
19	Pamyati Hirka	3.47	0.59*	-0.22*
20	Myroliubna	1.08	0.70*	0.02*
21	Vodohrai	1.50	0.32*	-0.45*

Table 5, Continued

No.	Varieties	General adaptive capacity, $b_i$		
		ear weight	protein content	gluten content
22	Spivanka Poliska	-0.63*	1.34	1.41
23	Polisianka	3.04	0.85*	1.10
24	Efektna	1.20	0.07*	-0.23*
25	Pyriatynka	0.53*	0.19*	0.13*
26	Liubito	2.12	0.47*	0.08*
27	Fortetsia Poliska	1.64	0.88*	1.19
28	Namysto	1.05	0.85*	0.99*
29	Merezhka	2.23	0.95*	1.11
30	Kesaria poliska	4.06	0.85*	0.35*
31	Poliska 90	1.98	1.80	2.53
32	Berehynia Myronivska	0.21*	1.78	2.18
33	Hospodynia Myronivska	2.15	1.77	1.81
34	MIP Valencia	2.41	1.73	1.66
35	MIP Vyshyvanka	0.85*	0.76*	0.56*
36	MIP Dniprianka	0.38*	1.73	1.94
37	MIP Kniazhna	-0.24*	1.74	2.22
38	Oberih Myronivskiyi	1.01	0.49*	0.66*
39	Svitanok Myronivskiyi	-3.68	-0.20*	-0.25*
40	MIP Assol	1.24	0.21*	-0.05*
41	MIP Lada	0.17*	0.33*	0.37*
42	MIP Yuvileyna	0.70*	-0.12*	1.79
43	Balada Myronivska	0.53*	25.43	25.78
44	Estafeta Myronivska	0.89*	-0.33*	-0.50*
45	Hratsia Myronivska	6.34	0.44*	0.14*
46	Shchedrist Odeska	1.20	-0.19*	-0.43*
47	Nota Odeska	4.18	0.52*	-0.56*
48	Aksioma Odeska	1.20	0.73*	-0.06*
49	Duma Odeska	-2.65	0.90*	1.25
50	Versia Odeska	-0.80*	0.90*	1.13
51	Sich	-2.77	0.14*	0.01*
52	Doskonalist Odeska	0.44*	1.46	1.45
53	Kubok	0.20*	-0.07*	0.05*

**Notes:** \* – no influence of adverse environmental factors on this indicator, that is, a high indicator of adaptability of the variety for this feature

**Source:** compiled by the authors

For successful breeding of soft winter wheat for yield and quality, it is advisable to establish a relationship between the indicators under study. Using the correlation analysis of grain quality indicators and the structure of the yield of soft winter wheat varieties for 2021/2022-2023/2024, a strong direct relationship was established between the number of grains in the ear and the weight of grains from the ear (0.84), between the weight of grains from the ear and the length of the ear rod (0.78), between the weight of grains from the ear and the weight of the ear (0.77), between the

number of grains in the ear and the weight of the ear (0.76), and with the length of the ear rod (0.74) (Table 6). The average positive correlation should be noted between the indicators of the length of the ear rod and the number of spikelets per ear (0.50) and the weight of the ear (0.65). The weight of 1,000 grains is characterised by an average positive correlation with the length of the ear rod (0.32), the weight of the ear (0.32), and the weight of grains from the ear (0.59). For the number of grains in the ear, a positive average correlation was established with the number of spikelets per ear (0.38).

**Table 6.** Interdependence between the indicators under study

	Spike rod length	Ear weight	Number of spikelets per ear	Number of grains per ear	Grain weight per ear	Weight 1,000 grains	Protein content	Gluten content
Spike rod length	1.00							
Ear weight	0.65	1.00						
Number of spikelets per ear	0.50	0.27	1.00					
Number of grains per ear	<b>0.74</b>	<b>0.76</b>	0.38	1.00				
Grain weight per ear	<b>0.78</b>	<b>0.77</b>	0.44	<b>0.84</b>	1.00			
Weight 1,000 grains	0.32	0.32	0.21	0.07	0.59	1.00		
Protein content	-0.16	0.05	-0.27	-0.06	0.08	0.21	1.00	
Gluten content	-0.13	0.06	-0.06	-0.05	0.05	0.14	<b>0.83</b>	1.00

**Source:** compiled by the authors

The obtained results demonstrate the plasticity of the indicator of the number of spikelets per ear of soft winter wheat during the studied years, and its variability, depending on the genotype (variety). Yu. Chernobai (2023) noted that the number of spikelets per ear is the most plastic indicator. According to L. Khudolii (2019), there is a direct relationship between the number of spikelets and weather conditions, the fertiliser system, and plant protection elements. Therefore, observations of varieties in these studies, which indicate a low variability of this indicator, suggest that the weather conditions during ear differentiation were similar. The effect of the fertiliser system and plant protection elements on the number of spikelets was not recorded, since these factors remained constant. The study by M. Lytus & V. Starychenko (2018) also confirmed that the number of spikelets per ear largely depends on genetic factors, in particular, on the genotype.

V. Morgun *et al.* (2015), based on many years of experience, came to the conclusion that the number of spikelets per ear is the most stable indicator, and the number of grains from the ear is the most variable. The same conclusion was obtained in the current study. In addition, the length of the ear rod and the weight of 1,000 grains were attributed to stable indicators in the years of research, and the weight of the ear and the weight of grains from the ear were attributed to variable indicators. Z. Guo *et al.* (2018) found a significant association between yield and weight of 1,000 grains. Based on these data, it can be assumed that the varieties under study with a high value of this indicator also have a high yield potential.

V. Lykhochvor (1999) argued about the direct influence of grain weight from the main ear on wheat yield. S. Ebrahimnejad & V. Rameeh (2016) found a high coefficient of variation between the characteristics of ear weight and plant yield, which is also confirmed by the results of the current research, namely, a strong direct relationship between ear weight and grain weight from

the ear. A. Polyovyi *et al.* (2022) analysed the indicators of the moisture-temperature regime of the forest-steppe soil – climate zone in order to predict climate change in the coming years and concluded that there is a slight increase in temperature and a noticeable decrease in precipitation (as a result of drought), especially during the summer period – the growing season of most agricultural crops. According to M. Shtakal *et al.* (2022), climate change does not currently pose a critical threat to the high yields of modern varieties of soft winter wheat, but these varieties do not have sufficient adaptive potential to effectively counteract weather changes during the research period. However, according to the results of the research during 2021/2022-2023/2024, the influence of weather conditions on elements of wheat productivity was revealed.

A positive average correlation (0.38) was found between the number of ears and the number of grains per ear. The same conclusions were obtained by L. Burdeniuk-Tarasevych & M. Lozinsky (2013), based on which a positive correlation was established between the indicators of the length of the main ear, the number of spikelets in the ear, the number and weight of grains from the ear. This relationship of indicators is probably conditioned by the influence of weather conditions during flowering on the tying process. L. Prysiazniuk *et al.* (2022) in their studies established a significant effect on the protein and gluten content of soft winter wheat under the conditions of the growing year, which is confirmed in this study and is a consequence of the influence of moisture supply and air temperature during grain filling and maturation on the synthesis and accumulation of nutrients.

The average correlation between the length of the ear rod and the number of spikelets in the ear (0.50) and the weight of the ear (0.65) can be explained by the fact that as the length of the ear rod increases, the number of spikelets also increases. This, in turn, contributes to the setting of more grains in the ear of wheat and the development of more ear weight.

## CONCLUSIONS

As a result of a three-year study of soft winter wheat varieties in the Forest-Steppe of Ukraine, according to the indicators of the yield structure, the following donors of traits that will potentially increase the yield of new varieties were identified: by the length of the ear rod – Legenda Bilotserkivska and Spivanka Poliska varieties; by the weight of the ear – Spivanka Poliska and Svitanok Myronivskiy; by the number of spikelets in the ear – Legenda Bilotserkivska, Fortetsia Poliska, and Kesaria Poliska; by the number of grains in the ear – Legenda Bilotserkivska, Spivanka Poliska, and Shchedrist Odeska; by the weight of grain from the main ear – Legenda Bilotserkivska; by weight of 1,000 grains – Vidrada, Charodiya Bilotserkivska, Legenda Bilotserkivska, Perlyna Lisostepu, Rozumnytsia, Romantyka, Tsarivna, Zoria Laniv, Kesaria Poliska, MIP Assol, MIP Lada, MIP Yuvileyna, and Hratsia Myronivska; by grain quality indicators – Rozumnytsia, Poliska 90, and MIP Kniazhna.

Both a strong and weak direct correlation between the indicators of the crop structure was established, which indicates a positive effect of increasing these indicators on the yield of modern varieties of soft winter

wheat. Therefore, these varieties can be recommended for use in breeding programmes aimed at increasing the yield of this crop. Based on correlation analysis, it was found that there is no strong influence of crop structure parameters on grain quality indicators in specific conditions. High adaptive capacity in the years of research was established for the following varieties: Romantyka, Liryca Bilotserkivska, Pyriatynka, MIP Vyshyvanka, MIP Lada, Estafeta Myronivska, and Kubok. These varieties have maintained the stability of grain yields and quality indicators under stressful conditions, so they can be donors of resistance to adverse environmental conditions. The prospect of further research may be to identify the interdependence of specific weather conditions on the development of crop structure indicators. It is also advisable to study the nature of inheritance of the traits under study for use in the selection of soft winter wheat for productivity and quality.

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## CONFLICT OF INTEREST

None.

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## Характеристика сортів пшениці м'якої озимої за показниками структури врожаю та якості зерна

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**Анотація.** Метою дослідження було вивчення колекції сортів пшениці м'якої озимої селекції чотирьох науково-дослідних установ України, що охоплюють Степову та Лісостепову ґрунтово-кліматичні зони. У результаті дослідження було проаналізовано показники структури врожаю та якості зерна 53 сортів пшениці м'якої озимої. Отримані дані дозволили оцінити стабільність елементів продуктивності та виділити сорти з високими показниками для подальшого використання у селекції. На основі одержаних результатів було сформовано таблиці та графіки, що відображають різницю у структурних показниках між сортами за роками досліджень, а також проведено оцінку частоти розподілу таких параметрів, як: довжина колосового стрижня, маса колоса, кількість колосків у колосі, кількість зерен у колосі, маса зерен із колоса та маса 1000 зерен. Статистичний аналіз із застосуванням ANOVA та побудова довірчих інтервалів (рівень значущості 0,05) підтвердили суттєві відмінності між сортами за досліджуваними показниками, що дозволило виявити сорти з високою стабільністю врожайності та якості зерна. За використання кореляційного аналізу встановлено взаємозв'язки між структурними показниками. Особливу увагу було приділено гомеостатичним сортам, які демонстрували високі показники упродовж 2021/2022-2023/2024 рр. досліджень, а саме: довжину колосового стрижня, кількістю колосків у колосі та масу 1000 зерен, що є ключовими ознаками для селекції на підвищення врожайності. Такі показники зумовлені особливістю генотипів, умов навколишнім середовищем та їх взаємодією. Розрахувавши коефіцієнт регресії, визначили сорти з високим рівнем адаптивності. Кращі за досліджуваними параметрами сорти рекомендовано для подальшого використання у селекційних програмах, спрямованих на підвищення продуктивності та покращення якості зерна пшениці м'якої озимої в умовах змін клімату

**Ключові слова:** маса 1000 зерен; якість зерна; білок; клейковина; кореляція; адаптивність; гомеостатичність

## Improving the process of plant protection mechanisation in grape growing

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**Abstract.** The study aimed to investigate the impact of modern vineyard cultivation technologies on reducing pesticide consumption and increasing yields. The study evaluated the effectiveness of using AgriSpray 5000 sprayers and DJI Agras T30 drones in agronomy, particularly in viticulture. The research methodology included an analysis of pesticide consumption and grape yields before and after the introduction of these technologies. For this purpose, a comparative analysis was carried out with traditional methods of processing, in particular by hand. The use of AgriSpray 5000 sprayers and DJI Agras T30 drones has reduced pesticide consumption by 30 and 25%, respectively, thanks to the precise distribution of solutions and the automation of field processing. The main results of the study showed that AgriSpray 5000 sprayers reduced the number of diseased grape plants by 40%, which led to a 15% increase in yield. At the same time, DJI Agras T30 drones reduced the number of diseased plants by 35% and increased yields by 12%. The integration of new technologies has reduced the overall cost of vineyard cultivation by 20%, in particular, due to lower pesticide and labour costs. The study findings show that the introduction of modern sprayers and drones significantly optimises vineyard processing, reduces costs and increases yields. The AgriSpray 5000 and DJI Agras T30 technologies provide a high level of precision in the application of agrochemicals, which has a positive impact on the environment

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and economic results. The results confirm the effectiveness of the latest technologies as an important tool for increasing the competitiveness of Ukrainian vineyards and improving product quality

**Keywords:** pesticides; sustainable development; irrigation; crop production; agriculture; diseases

## INTRODUCTION

In modern viticulture, the mechanisation of plant protection processes is an important aspect of increasing the efficiency of agronomic practices and ensuring the sustainable development of the industry. Traditional methods of vineyard cultivation often require significant human resources and can be inefficient due to irregularity and incomplete coverage of cultivated areas. In this regard, there is a need to introduce new mechanised technologies that can ensure more accurate and cost-effective application of pesticides and other agrochemicals.

The research relevance is determined by the need to adapt modern technologies to improve the efficiency of vineyard protection. Due to global climate change and growing demands for environmentally friendly agronomic practices, traditional cultivation methods are becoming less effective and often do not meet modern standards. Mechanisation, including the latest spraying and monitoring systems, can ensure precision and efficiency in pesticide application while reducing environmental impact.

The problem of the study is the gap between traditional methods of plant protection and modern technological advances. While the latest systems show great potential, there are gaps in their integration and practical application. It is necessary to assess their impact on plant resistance to diseases, economic efficiency and the overall condition of vineyards, which will allow agronomists to better implement these technologies to achieve maximum results.

There are several important aspects of improving the process of plant protection mechanisation in grape growing that have already been studied by various authors. The issue of increasing the resistance of grapes to diseases such as black rot was addressed by Q. Kong *et al.* (2024), who found that UV irradiation could improve grape resistance by regulating the synthesis of phenolic compounds. At the same time, M. Karim *et al.* (2024) focused on improving the classification of grape leaf diseases using a lightweight convolutional neural network architecture, which showed potential for real-time disease diagnosis. P. Wang *et al.* (2021) proposed an improved grape leaf disease recognition methodology based on enhanced attention, which achieved high accuracy in disease detection.

A study conducted by K. Pandey & A. Chandak (2024) addressed deep-learning techniques used to detect

grape diseases. This study not only confirms the relevance of the latest approaches in the mechanisation of plant protection but also emphasises the importance of introducing modern technologies into agronomic practice. Detecting diseases at early stages is critical to ensuring vineyard health and increasing yields, making these technologies extremely valuable to farmers. In addition, R. Patil & A. More (2023) conducted a detailed technical review of grape disease prediction methods using machine learning. Their study pointed out a wide range of technologies that can be integrated into the process of mechanising protection, including algorithms for data analysis and modelling, which allows for more accurate prediction of disease epidemics. This opens up new opportunities for agronomists to plan protection measures and optimise processing costs.

P. Sindhu & G. Indirani (2022) also demonstrated the effectiveness of using optimisers and deep neural networks to classify grape diseases. This shows the great potential for integrating the latest technologies into agronomic practices, which can significantly improve the accuracy and speed of disease detection. The use of such innovative solutions can not only increase the effectiveness of plant protection but also reduce the environmental impact of the agricultural sector, ensuring the sustainable development of viticulture.

Despite these achievements, there are gaps in the development of integrated systems for mechanised protection, in particular combinations of bio-control agents and chemical fungicides, as reported by L. Ons *et al.* (2020). Z.S. Asgarian *et al.* (2024) investigated the effect of calcium and zinc spraying on berry quality during storage, which highlights the importance of integrating new protection methods into the growing process. The study by X. Zhou *et al.* (2024) showed that new quantitative indices of grape quality can improve the assessment of quality parameters. Thus, the main gaps in research relate to the integration of new technologies and mechanisation methods to improve the sustainability and quality of grapes.

This study focused on improving the process of mechanisation of plant protection in grape growing by introducing new models of sprayers, drones for agronomy and monitoring systems. Study goals include:

1. Evaluate the effectiveness of new mechanised systems for vineyard cultivation.

2. Determine the impact of new technologies on plant health and protection against diseases and pests.

3. Develop recommendations for optimising plant protection processes based on the results obtained.

## MATERIALS AND METHODS

The study was conducted from May 2024 to September 2024 in the vineyards of the Vinogradnaya Gora farm, which is located in the southern region of Ukraine. A vineyard area of 10 hectares was selected for the experiments, which was used to obtain representative data on the impact of new mechanical systems on various aspects of cultivation. The sample included a variety of grape varieties (Arcadia 1995, Bianca 2007, Perseus 2020, Kishmish 2007, Kobzar 2009, Iskoroka 2015, Isabella 2017, Aromatic 2009) that were subject to treatment with new mechanical protection systems, which was used to assess their effectiveness in different conditions. The study also included an analysis of the impact of mechanisation on crop quality and plant resistance to diseases. Robotic sprayers (AgriSpray 5000 – the United States of America); drones for agronomy (DJI Agras T30 – China); innovative sensors for plant monitoring (AquaSpy 9000 – Germany); precision farming systems for data monitoring and analysis (Trimble Ag Leader 360 – the United States) were used in the study.

An experimental methodology was used to assess the effectiveness of new sprayers and drones by comparing their performance with traditional methods of cultivation. The analytical methodology was used for the analysis of the collected data to determine the level of pesticide consumption reduction and improvement of the grapes' condition. Technical specifications of sprayewrs: AgriSpray 5000 (USA) – tank volume: 500 litres; processing range: up to 12 metres; weight: 1,200 kg; Global Positioning System (GPS) for precise application. DJI Agras T30 drones (China) – tank capacity: 30 litres; maximum treatment area per charge: 40 hectares; automatic control and programming of routes; a camera for monitoring the condition of plants.

All experiments and data collection were carried out under the supervision of the agronomic service of the Vinogradna Gora farm, using the farm's developed methods and processing protocols. The study complies with ethical standards and adheres to the Convention "On Biological Diversity" (1992). Regulation

of the European Parliament and of the Council No. 1107/2009 (2009), which regulates the conditions and procedures for the registration and use of pesticides in the European Union, was taken into account. Chemicals for plant protection: Systemic fungicide "Kuproksat" (Active ingredient: Kuproksat; intended for control of fungal diseases on grapes (Israel)); Insecticide "Keltis" (Active ingredient: Lambda-cyhalothrin; intended for control of insect pests in vineyards (France)).

## RESULTS

The AgriSpray 5000 sprayer and the DJI Agras T30 drone are innovative solutions for modern agriculture that focus on increasing the efficiency of crop processing and reducing the negative impact on the environment. The AgriSpray 5000 is a sprayer equipped with a GPS navigation and mapping system that ensures precise positioning and uniform coverage of the field, avoiding re-treatment and skipping parts of the field, which reduces pesticide consumption. The system automatically adjusts the spraying height and solution flow to ensure optimum plant coverage. It also includes pressure regulators and nozzles with variable droplet sizes for even applications. The precise distribution of pesticides reduces the total amount of pesticide used and minimises water and soil contamination. The intuitive automatic control system and mobile monitoring apps ensure ease of use.

The DJI Agras T30 is a drone equipped with an advanced automated control system that can be used to plan routes and spray with high accuracy. Sensors and mapping technologies ensure precise positioning and control of the spraying process. The DJI Agras T30 can cover up to 40 hectares on a single battery charge, which significantly reduces the need for manual labour. It can also be used to operate in hard-to-reach areas, increasing overall efficiency. By precisely managing pesticide and fertiliser consumption, the drone helps to avoid excessive amounts of solutions and reduces the likelihood of soil and water pollution. Both solutions provide significant benefits in crop production, particularly through high precision and automation, which reduces costs and minimises negative environmental impact. Table 1 illustrates a comparison of the costs of cultivating fields using the latest methods, showing that the use of drones can achieve significant cost savings due to their high productivity and accuracy.

**Table 1.** Impact of new technologies on pesticide consumption

Technology	Pesticide consumption before implementation	Pesticide consumption after implementation	Reduction (%)
AgriSpray 5000	100 litres/ha	70 litres/ha	30
DJI Agras T30	100 litres/ha	75 litres/ha	25

**Source:** compiled by the authors

The use of AgriSpray 5000 sprayers significantly reduced the number of diseased grape plants – by 40% (Table 2). This is the result of precise pesticide application

using advanced solution distribution systems, which ensures uniform coverage of each plant and eliminates problems associated with uneven protection.

**Table 2.** The number of diseased plants before and after applying the latest technologies

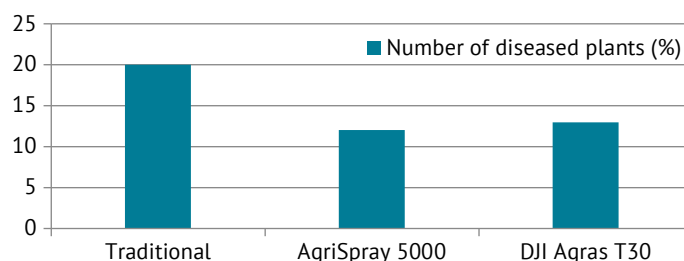
Technology	Number of diseased plants before treatment (per 10 ha)	Number of diseased plants after treatment (per 10 ha)	Reducing the number of diseased plants
AgriSpray 5000	2,000	1,200	-40%
DJI Agras T30	2,000	1,300	-35%

**Source:** compiled by the authors

Among fungal diseases such as powdery mildew and grey rot, a significant reduction in their manifestations was observed due to precision spraying, which reduces the number of affected berries, which is important for maintaining crop quality. The reduction in the number of diseased plants has had a positive impact on the overall condition of the vineyards. The plants had healthier leaves, and less yellowing and stunting, which contributed to their normal growth and development. After the introduction of AgriSpray 5000, an increase in grape yields of 15% was noted. This is due to the increased health of grape plants and a reduction in the number of dead berries due to diseases, which leads to an increase in the number of productive shoots.

DJI Agras T30 drones demonstrated a significant reduction in the number of diseased plants by 35% due to the introduction of automated control and precise

programming of processing routes. This state-of-the-art technology solution effectively covered even hard-to-reach areas of vineyards that are traditionally difficult to cultivate. Due to the high speed and accuracy of spraying, drones have been able to significantly reduce the occurrence of dangerous diseases such as oidium and mildew. This, in turn, led to a reduction in overall yield losses and improved berry quality, which is an important factor for growers. The introduction of drones for vineyard treatment not only had a positive impact on the overall condition of the plants, but also provided better and more even coverage of the pesticide, which significantly reduced the risk of disease, increasing plant viability and, consequently, their productivity. Thus, drone technology is becoming an integral part of modern agricultural production, contributing to the efficiency and quality of grape growing (Fig. 1).



**Figure 1.** Reducing the number of diseased plants using new systems

**Source:** compiled by the authors

The cost analysis carried out as part of the study showed that the introduction of the latest vineyard cultivation technologies does indeed lead to a significant reduction in overall costs. In particular, the integration

of the AgriSpray 5000 sprayer system in combination with DJI Agras T30 drones has reduced vineyard processing costs by an impressive 20% compared to traditional methods (Table 3).

**Table 3.** Comparison of costs before and after implementing new methods

Processing method	Total costs (thousand UAH/ha)	Difference (%)
Traditional	8	-
AgriSpray 5000	6.4	-20
DJI Agras T30	6.5	-18.75

**Source:** compiled by the authors

This positive result not only illustrates the reduction in pesticide costs but also indicates a reduction in labour costs, as process automation reduces the need for manual labour. The use of drones and modern sprayers has significantly reduced the time required to process vineyards, which has increased overall production efficiency. Thus, the introduction of these technologies is not only cost-effective but also helps to optimise agonomic processes in viticulture.

Traditional vineyard management methods used for many years often involved manual labour to apply pesticides and fertilisers. This process was not only labour-intensive but also required significant effort on the part of the workers, leading to fatigue and reduced efficiency. Manual application of pesticides was time-consuming, which increased the overall cost of vineyard management. The high labour costs in this situation were a serious challenge for growers, as they had to spend significant financial resources on hiring labour.

Manual application of pesticides did not always guarantee the accuracy and uniformity of the solution distribution. The conventional sprayers used in such cases were less accurate, resulting in uneven coverage of the plants. This caused pesticide overspending, as some areas were overtreated while others were left insufficiently protected. Such shortcomings required additional treatments, which further increased the costs and time required to care for the vineyards. As a result, traditional treatments were not only economically unprofitable but also less effective in ensuring vineyard health and productivity.

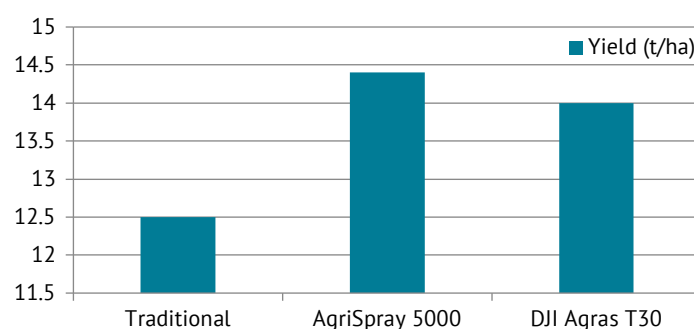
The AgriSpray 5000 sprayer has become an important tool for farmers as it ensures accurate and efficient application of pesticides. This has not only improved

the quality of crop treatment but also reduced the cost of using chemical plant protection products. The high accuracy and uniform distribution of the solution led to a 30% reduction in pesticide costs. As a result, farmers were able to significantly optimise their costs while maintaining the effectiveness of their crops.

DJI Agras T30 drones, in turn, provided automated control and precise programming of processing routes, which significantly optimised field processing. This has reduced labour costs, as drones can perform tasks with high productivity without the need for many employees. Pesticide costs have also been reduced by 25% due to the high accuracy of processing and the ability to access hard-to-reach areas that previously required significant effort and resources to process.

The introduction of modern technologies, such as AgriSpray 5000 and DJI Agras T30, has allowed farmers to significantly reduce the cost of vineyard cultivation. This has a direct impact on reducing overall production costs, which, in turn, increases the competitiveness of products on the market. Thus, the use of these innovative solutions contributes not only to cost savings but also to the overall efficiency of agricultural production. This included savings on pesticides, reduced labour requirements and reduced processing time.

Experimental data obtained as a result of the research shows that the latest technologies introduced in viticulture have a significant positive impact on grape yields. In particular, the use of the innovative AgriSpray 5000 equipment has led to an impressive 15% increase in yields (Fig. 2). This demonstrates the effectiveness of this device in optimising crop processing, which in turn helps to improve the quality and quantity of the harvest.



**Figure 2.** Changes in grape yields by different cultivation methods

**Source:** compiled by the authors

In addition, the use of drones for monitoring and processing vineyards also proved to be effective, as yields increased by 12%. The use of drones allows for high accuracy in the distribution of fertilisers and plant protection products, which significantly reduces losses

and increases the overall productivity of vineyards. These results confirm that the integration of modern technologies into agriculture is an important step towards achieving sustainable development and increasing the efficiency of the agricultural sector (Table 4).

**Table 4.** Influence of the latest technologies on the yield of different grape varieties

Grape variety	Processing method	Yield before treatment	Yield after treatment	Difference (%)
Arcadia	AgriSpray 5000	80 t/ha	94 t/ha	+18%
	DJI Agras T30	80 t/ha	90 t/ha	+13%
Bianca	AgriSpray 5000	75 t/ha	85 t/ha	+14%
	DJI Agras T30	75 t/ha	82 t/ha	+10%
Perseus	AgriSpray 5000	70 t/ha	81 t/ha	+16%
	DJI Agras T30	70 t/ha	78 t/ha	+11%
Kishmish	AgriSpray 5000	85 t/ha	95 t/ha	+12%
	DJI Agras T30	85 t/ha	93 t/ha	+9%
Kobzar	AgriSpray 5000	90 t/ha	103 t/ha	+15%
	DJI Agras T30	90 t/ha	101 t/ha	+12%
Iskorka	AgriSpray 5000	78 t/ha	89 t/ha	+14%
	DJI Agras T30	78 t/ha	86 t/ha	+10%
Isabella	AgriSpray 5000	82 t/ha	95 t/ha	+16%
	DJI Agras T30	82 t/ha	91 t/ha	+11%
Aromatic	AgriSpray 5000	77 t/ha	87 t/ha	+13%
	DJI Agras T30	77 t/ha	84 t/ha	+9%

**Source:** compiled by the authors

The introduction of modern mechanised systems in the field of crop protection is an important step towards optimising agronomic processes, as it will significantly reduce the cost of crop processing. This, in turn, will increase the overall effectiveness of crop protection, which has been confirmed by numerous studies and practical trials. All the results obtained in the course of research show that new technologies not only reduce the cost of pesticide use but also significantly improve the condition of plants, which has a positive impact on their health and development. In addition, the introduction of such systems helps to increase yields, which is an important factor in ensuring food security. This confirms the validity of the hypothesis and demonstrates the high efficiency of the implemented mechanised systems, which can become the basis for further development of the agricultural sector. Based on the results obtained, which indicate the significant potential of new technologies, it is recommended to implement innovative solutions to reduce costs and increase the efficiency of vineyard processing. Among such technologies, it is worth highlighting the use of robotic sprayers and drones that can ensure the accuracy and speed of agronomic tasks, including spraying plants and monitoring the condition of the crop.

Farmers should account for the long-term economic benefits of investing in new technologies that not only reduce processing costs but also significantly increase labour productivity. Investing in automation and digitalisation of processes can lead to a significant reduction in labour costs, which is an important aspect in the current market environment. This helps to reduce the cost of crop protection products, as new technologies allow for more precise and efficient application of

agrochemicals, which not only reduces costs but also has a positive impact on the environment. In addition, the introduction of modern technologies can significantly improve the quality of products, which undoubtedly opens new opportunities for sales and increased competitiveness in the market. Strategic investment in innovation can be a key success factor for farms in the future.

These results can serve as a basis for further research and practical application in the field of viticulture, contributing to the development of innovative approaches and increasing the competitiveness of Ukrainian winemakers in the international market. The introduction of new technologies will allow Ukrainian producers not only to maintain but also to increase their market share, responding to the growing demands of consumers for quality and environmental friendliness of products.

## DISCUSSION

A detailed study of the resilience of European wine regions to climate change was conducted by S. Tscholl *et al.* (2024), who focused on the importance of adapting technologies to new, changing conditions. In their work, they emphasised that climate change can have a significant impact on wine production, so winemakers should take steps to adapt their technologies. The results of the current study support their conclusions, demonstrating that improved spraying technologies can be effectively adapted to increase the resilience of vineyards to the negative impacts of climate change, which in turn can contribute to the sustainability of wine production in the face of global warming.

S. Mehretie *et al.* (2024) developed an innovative ultrasonic sensor that allows predicting the quality

of grape bunches at different stages of maturity. This approach is revolutionary in the field of grape quality assessment, as it provides more accurate data on the condition of the product. These findings support the current study, confirming that new technologies can significantly improve grape quality through more accurate monitoring, which in turn can increase the competitiveness of wineries in the market. A study conducted by J.Y. Park *et al.* (2023) focused on the impact of plant growth regulators and bunch thinning on the quality of Shine Muscat grapes. This study found that the use of mechanisation in agronomy can significantly contribute to the optimisation of plant processing, which in turn leads to an increase in grape quality. This emphasises the importance of using modern technologies in viticulture to achieve high standards of product quality.

The significant effect of growth regulators and bunch thinning on the overall productivity of grapes was investigated by S. Choi *et al.* (2023). The findings confirm that these factors are crucial for achieving optimal yield quality and quantity. The conclusions of this study indicate that the introduction of improved mechanisation in the cultivation processes can significantly improve control over product quality, which in turn contributes to the competitiveness of viticulture farms in the market. M. Li *et al.* (2024) assessed the current state of plant protection mechanisation technologies in China and identified an urgent need to improve these technologies to increase the efficiency of crop treatment. These results confirm the importance of innovation, as they demonstrate the positive impact of new technologies on reducing pesticide consumption, which in turn contributes to improved vineyard protection.

The introduction of agrochemical technologies in viticulture was studied by D.G. Bhalekar *et al.* (2024a), who emphasise the importance of the safety and efficiency of the spraying process. The results of their work also confirm the conclusions about the need to improve technologies to ensure not only high efficiency but also safety for the environment and human health. Research by O. Nefti *et al.* (2024) focused on the possibility of partial pesticide phase-out in viticulture. They found that the latest technologies being introduced into the industry could provide such an alternative. The findings support their conclusions, demonstrating that advanced spraying can reduce pesticide use without negatively impacting grape quality, which is an important consideration for producers and consumers. Thus, these studies highlight the importance of integrating new technologies into viticulture practices to achieve sustainable development in the agricultural sector.

A. Bjørnåvold *et al.* (2022) conducted an in-depth study analysing the reasons why France is not achieving

its goals in reducing pesticide use. Scholars addressed the socio-economic bargaining power of farmers, which often becomes an obstacle to the implementation of new environmental practices. The findings indicate the positive impact of new technologies that can significantly reduce pesticide costs, which in turn can be useful in overcoming such problems in agriculture. This study emphasised the importance of integrating innovative technologies into the agricultural sector to achieve sustainable development.

The mechanical removal of leaves was studied by B. Hed & M. Centinari (2024), which is an important aspect of improving the control of bunch rot. This study confirms the basic idea that new technologies are effective in reducing pesticide use. The authors note that mechanical technologies not only increase the efficiency of plant processing but also significantly reduce the need for chemical plant protection products. This discovery is important for agronomists and farmers, as the introduction of such technologies can contribute to environmentally friendly agriculture and improve product quality. E. Fouillet *et al.* (2024) demonstrated that reducing the use of pesticides not only does not reduce yields but also does not affect labour intensity, which is an important aspect of the agricultural sector. The study also confirms that the introduction of improved technologies can significantly reduce pesticide costs without compromising overall crop productivity. This opens new opportunities for sustainable development of agricultural production, as reducing the chemical burden on the ecosystem is an important task.

The development of a combined effector for bunch removal was carried out by S. Sui *et al.* (2024), which also confirms the effectiveness of mechanical technologies in viticulture. This study demonstrates that the mechanisation of processes can significantly reduce the need for manual labour and increase the efficiency of vineyard processing. The introduction of such innovative solutions not only optimises work processes but also contributes to the economic efficiency of production, which is critical in today's competitive agricultural market. A. Le Roux (2024) addressed in detail the issue of improving equipment for spraying crops by recycling excess solution through modifying the airflow. The research provides strong evidence that the introduction of such innovations can significantly increase the efficiency of spraying processes, reducing the cost of crop protection products and improving their uniform distribution. This opens new opportunities for optimising agricultural production and increasing yields.

L.S. de Oliveira *et al.* (2024) focused on the use of aerial spraying for mildew control in vineyards using an unmanned aerial vehicle (UAV). The results of this

work confirm that UAV technology can be extremely effective in the vineyard treatment process, ensuring the accuracy and speed of application of protective agents. This can reduce the risks associated with traditional spraying methods and increase overall viticulture productivity. F. Ahmad *et al.* (2020) also studied the effectiveness of using UAVs for spraying rice fields, finding a positive impact of such systems on the uniform distribution of the spray. The results show that UAV technologies can not only be effective in vineyards but can also be successfully applied in other agricultural sectors. This highlights the potential of drone technology to transform traditional agriculture by providing more efficient solutions for crop protection and agricultural resource management.

The water consumption and drift of fungicides used for mildew control in grapes were studied by B. Bajagić *et al.* (2022). This work provided important data that support the conclusions about the need to optimise pesticide and water consumption. This study emphasises the importance of rational use of resources in viticulture, which can significantly reduce costs and increase the effectiveness of plant disease control. F.K. Carvalho *et al.* (2020) studied the problems associated with the use of aircraft and drones for crop spraying. Their study analysed the technical and practical challenges that arise when using these modern technologies. The results confirm their findings regarding the difficulties faced by agronomists and farmers seeking to incorporate UAVs into their field operations and highlight the need for further improvements in these methods. C. Michael *et al.* (2022) evaluated the effectiveness of low-volume spraying in vineyards, which is consistent with the results of this paper. Their study demonstrates that the use of low-volume spraying technologies can significantly reduce the cost of pesticides, as well as reduce the risk of their negative impact on the environment. These results confirm the importance of introducing innovative vineyard management practices to increase productivity and sustainability.

The use of UAVs for crop spraying was studied by J.O. Silva Neto *et al.* (2021), focusing on their ability to reduce pesticide use and improve accuracy. Their findings support their conclusions about the effectiveness of unmanned technologies, indicating that the use of UAVs can not only reduce processing costs but also reduce the negative impact on the environment through more precise application of chemicals. G. Wang *et al.* (2020) investigated the effectiveness of low-volume pesticide application in rice fields, focusing on reducing water consumption and increasing yields. The results of the study support these findings, demonstrating a similar positive effect in vineyards, where the use of

low-volume spraying leads to improved crop quality and reduced risk of plant diseases. D.G. Bhalekar *et al.* (2024b) optimised the configuration of spraying systems, focusing on improving fluid distribution mechanisms and reducing losses during treatment. These results support their findings that pneumatic spraying systems are more efficient than traditional methods, providing more uniform coverage of plants and increasing overall treatment efficiency. Overall, the results of the study confirm that the integration of new technologies into vineyard protection mechanisation can significantly increase efficiency and reduce pesticide consumption. They are also consistent with research showing the positive impact of new technologies on grape quality and processing efficiency.

## CONCLUSIONS

The study confirmed the effectiveness of the introduction of AgriSpray 5000 sprayers and DJI Agras T30 drones in vineyards, which led to a reduction in pesticide consumption and an increase in yields. Specifically, the use of sprayers reduced pesticide consumption by 30% and increased yields by 15%. Drones, in turn, reduced costs by 25% and increased yields by 12%. Qualitative indicators include a 40% reduction in plant disease with sprayers and 35% with drones, indicating improved plant health and reduced disease. The results of research confirm that the introduction of modern viticulture technologies can significantly improve the efficiency of vineyard cultivation. This is achieved through process optimisation, which reduces pesticide costs and significantly increases yields. The use of innovative methods, such as precision farming, automation and plant health monitoring, opens new opportunities for agronomists. In addition, these technologies have a significant potential to reduce the negative impact on the environment, as the reduced use of chemicals helps to preserve ecosystems and improve soil quality. Thus, the integration of modern technologies not only increases the economic efficiency of production but also contributes to the sustainable development of the agricultural sector.

To further improve agricultural outcomes, especially in the context of drones and sprayers, there is a need to focus on improving the technologies that ensure their effectiveness. This includes improving the precision of pesticide application, which is critical to reducing pesticide losses to the environment and minimising negative impacts on beneficial organisms. It is necessary to adapt these technologies to different types of vegetation and specific climatic conditions to ensure optimal treatment results. Longer and more detailed field trials are also recommended to assess the long-term impacts

of drone and sprayer use on soil quality and ecosystem integrity. This includes monitoring changes in biodiversity, vegetation and overall ecosystem health, which will help identify possible negative impacts and develop recommendations to avoid them. Thus, the integration of new technologies into agriculture should be accompanied by a comprehensive analysis and assessment of environmental aspects, which will ensure the sustainable development of the agricultural sector. Limitations

of the study include the limited number of surveyed sites and the potential impact of unforeseen weather conditions that could affect the accuracy of the results.

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None.

## CONFLICT OF INTEREST

None.

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## **Вдосконалення процесу механізації захисту рослин при вирощуванні винограду**

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**Анотація.** Метою роботи було дослідити вплив сучасних технологій обробки виноградників на зменшення витрат пестицидів та підвищення врожайності. Під час дослідження оцінено ефективність використання обприскувачів «AgriSpray 5000» та дронів «DJI Agras T30» в агрономії, зокрема у виноградарстві. Методологія дослідження включала аналіз витрат пестицидів і врожайності винограду до і після впровадження зазначених технологій. Для цього було проведено порівняльний аналіз з традиційними методами обробки, зокрема вручну. Застосування обприскувачів «AgriSpray 5000» та дронів «DJI Agras T30» дозволило зменшити витрати пестицидів на 30 % і 25 % відповідно, завдяки точному розподілу розчинів і автоматизації обробки полів. Основні результати дослідження показали, що обприскувачі «AgriSpray 5000» зменшили кількість хворих виноградних рослин на 40 %, що привело до збільшення врожайності на 15 %. Водночас, дрони «DJI Agras T30» забезпечили зменшення кількості хворих рослин на 35 % і підвищили врожайність на 12 %. Інтеграція нових технологій дозволила зменшити загальні витрати на обробку виноградників на 20 %, зокрема завдяки зниженню витрат на пестициди та робочу силу. Висновки дослідження свідчать про те, що впровадження сучасних обприскувачів і дронів суттєво оптимізує процеси обробки виноградників, знижує витрати та підвищує їхню врожайність. Технології «AgriSpray 5000» і «DJI Agras T30» забезпечують високий рівень точності у застосуванні агрохімікатів, що має позитивний вплив на екологічну ситуацію та економічні результати. Результати підтверджують ефективність новітніх технологій як важливого інструмента для підвищення конкурентоспроможності виноградних господарств в Україні та покращення якості продукції

**Ключові слова:** пестициди; сталий розвиток; зрошення; рослинництво; сільське господарство; хвороби

## Drivers of inclusive rural infrastructure development in Ukraine

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**Abstract.** The economic system of a society involves the constant movement of goods, services, money, securities, and labour. The coordinated interaction of market mechanism elements is achieved through their balanced development. It is impossible to increase the efficiency of the agricultural sector of the country's economy without improving rural infrastructure. The article is devoted to the study of theoretical and practical provisions for accelerating the development of rural infrastructure, ensuring access to it for all segments of the rural population and developing recommendations for improving the living standards of rural residents. The main research methods used were analysis of scientific literature, analysis of statistical data, comparative analysis, and expert assessments. The research paper examined the main indicators of improving the living standards of rural residents in terms of political, social and economic aspects. In order to adjust the goals of sustainable development, the article characterised the losses caused to infrastructure as a result of theft, destruction or damage to facilities. It is shown that the impact of economic growth on poverty alleviation increases with the growth of human capital, but weakens with significant income inequality. Particular attention was paid to indicators of improving the living standards of rural residents in terms of political, social and economic aspects. Conclusions were also drawn on the main tasks facing rural communities to ensure their sustainable development. The practical value of the study lies in the empirical results obtained, which can be used to develop and implement the state policy of rural development. The developed recommendations may be useful for local governments, public organisations and other entities involved in rural development. It is proposed to use the experience of Poland on the way to inclusive rural infrastructure development

**Keywords:** sustainable development; rural areas; rural communities; labour market; economic development; inclusive education

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## INTRODUCTION

The development of any country is impossible without improving the well-being of its citizens, especially in rural areas. This process is closely linked to the rapid growth of national income per capita and the improvement of overall living standards. A well-developed rural infrastructure plays an important role in this process, ensuring access to basic services for all segments of the population, stimulating economic activity in rural areas and making them more attractive for living. An inclusive approach to the development of rural infrastructure involves creating equal conditions for all rural residents, regardless of their social, age or gender characteristics. Such an approach is a prerequisite for social integration and the harmonious development of rural communities.

Infrastructure changes not only improve material living conditions, but also help create new jobs, attract investment and reduce social inequality between urban and rural areas. Infrastructure development has a multiplier effect, covering all sectors of the economy and territorial units of the country. This, in turn, stimulates the development of agricultural production and improves the quality of life in rural areas. Particularly important components of rural infrastructure are the transport network, water and wastewater systems, electricity supply, as well as educational, healthcare and cultural institutions. The development of these infrastructure elements not only improves the living standards of rural residents, but also creates the basis for economic growth and social development in the region. In addition, the development of digital infrastructure in rural areas is of particular importance in today's environment. Access to high-speed Internet and modern information and communication technologies opens up new opportunities for education, work and business in rural areas, facilitating their integration into the global economy and reducing the digital divide between urban and rural areas.

As noted by Yu. Kormyshkin & I. Moskal (2023), the insufficient level of development of social, communal, household, information and communication infrastructure leads to a low level of meeting modern human needs and the quality of life of rural residents, as evidenced by the scientific works and aspects revealed in the above study. In addition, there is a steady trend towards a significant deterioration in demographic indicators and the human development index in rural areas. There has been a significant decline in labour potential, rising unemployment and poverty among the population. The migration outflow of young people from rural areas to cities and abroad further exacerbates this negative phenomenon.

In their research, O. Dovgal *et al.* (2022) focused on increasing the competitiveness of staff, highlighting

such factors as motivation, management, and social aspects. The authors emphasised the importance of innovative development of Ukrainian enterprises through continuous professional development of employees and improvement of the education system. However, the issue of inclusive staff development, especially in rural communities, remained outside the scope of their study. A. Poltorak *et al.* (2021) demonstrated the effectiveness of modified approaches to managing the financial security of the state using a polynomial extrapolation algorithm. The correlation-regression model they developed allows considering such key indicators as the effectiveness of innovative development, the level of corruption, and debt dependence. However, the researchers did not assess the impact of rural infrastructure development on the financial security of the state.

O. Lazarieva (2019) considered the issue of rural infrastructure development in the context of ensuring sustainable development of the country. She emphasised the importance of not only economic factors, but also environmental and social aspects, in particular the development of infrastructure in the areas of water supply, sanitation and energy. O. Borodina & I. Prokopa (2019) studied the impact of information and communication technologies on rural development. The authors noted that access to modern technologies allows rural residents to be integrated into the national and global economy, creating new opportunities for development and improving the quality of life.

The purpose of the study was to develop both theoretical and practical provisions to accelerate the inclusive development of rural infrastructure and to develop recommendations for improving the living standards of the rural population.

## MATERIALS AND METHODS

A wide range of theoretical and empirical methods were used to conduct a comprehensive study of inclusive rural infrastructure development. The choice of methods was driven by the need to ensure a comprehensive analysis of the problem, taking into account its multidimensional nature. A detailed analysis of scientific publications, reports of international organisations, and national strategic documents was conducted to identify current trends, theoretical approaches, and empirical evidence on inclusive rural development. Particular attention was paid to research on the drivers of rural infrastructure development, the role of institutional factors, and the experience of other countries. A systemic approach was used to identify the interrelationships between different components of the rural system (economy, social sphere, infrastructure, natural environment) and to identify key factors

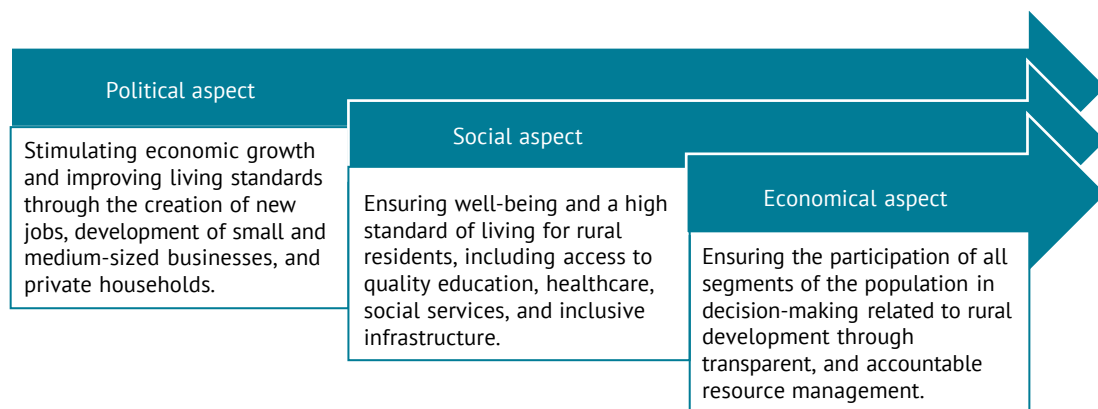
that influence inclusive development. A comparative analysis of the experience of different countries (in particular, the European Union) in rural development was carried out to identify best practices and potential directions for Ukraine.

To quantify the state of rural infrastructure and the dynamics of its development, statistical data from Minfin (n.d.), State Statistics Service of Ukraine (2023), National Institute for Strategic Studies (2024) and other official sources were analysed. The indicators studied include employment rates, incomes, investments in agriculture, and infrastructure development. Based on the empirical material, a list of tasks faced by communities is outlined, taking into account the programmes of inclusive sustainable development of rural infrastructure. The main indicators of rural development for the period from 2005-2022 are assessed. The introduction of martial law in Ukraine in February 2022 made it difficult to obtain complete operational statistical information, and additional uncertainty factors made it impossible to analyse some indicators for 2023-2024. With this in mind, the main challenges facing the socio-economic development of rural areas and the infrastructure sector were identified.

The choice of research methods was driven by the need to provide a comprehensive and in-depth analysis of the problem. Theoretical methods helped to form the theoretical basis of the study and define key concepts. Empirical methods provided quantitative and qualitative data on the state of rural infrastructure and the factors influencing its development.

## RESULTS AND DISCUSSION

A high level of economic development in countries does not always guarantee a corresponding standard of living in rural areas. Economic growth does not automatically lead to an improvement in the living standards of poor and low-income families. Research by M. Tymoshenko (2014) has shown that the impact of economic growth on poverty reduction increases with the growth of human capital, but weakens with significant income inequality. In Ukrainian practice, the focus has been on the growth of the agricultural sector and its export potential. As a result, the majority of vulnerable groups in rural areas are left out of the programmes developed by the government. Improving living standards is one of the conditions for sustainable rural development, based on the aspects shown in Figure 1.



**Figure 1.** Indicators of improving the living standards of rural residents

**Source:** compiled by the authors

These living standards indicators are the main criteria that determine the degree of development of rural areas. Inclusive development helps to create better living conditions in Ukraine, ensure equal opportunities, and build a fair and prosperous society. Ukraine is implementing a number of programmes to ensure inclusive development of rural infrastructure:

1) reconstruction and construction of social infrastructure facilities is carried out in accordance with the requirements of barrier-free access. For example, as part of the implementation of Decree of the President of Ukraine No. 533/2020 (2020), equal opportunities are created for all groups of the population in

education, medical care, self-realisation, employment and other areas of life;

2) adapted services for people with disabilities are being introduced. For example, according to the UN Convention on the Rights of Persons with Disabilities, access to all spheres of life, including the physical environment, transport, information, communication, education, employment, healthcare, and participation in political and public life, is ensured for people with disabilities (United Nations Convention, 2006);

3) information materials on rural development are being developed in various forms. For example, pursuant to a decision of the Government of Ukraine,

special sections for people with disabilities are being created on the websites of local governments and other institutions providing services in rural areas, where information can be presented in Braille, audio or video, etc. (Ministry of Education and Science of Ukraine, 2021).

The implementation of these programmes should contribute to the achievement of sustainable rural development and improvement of living standards. The

constant empowerment of local communities poses new challenges for them in terms of harmonisation and further development of territorial communities, as O. Pavlov (2009) wrote. This requires taking into account the interests and initiatives of every resident of rural areas, since only joint efforts can achieve high production efficiency, preserve the environment and improve the quality of life. Rural communities face a number of tactical challenges (Table 1).

**Table 1.** List of tasks for communities in terms of their sustainable development

Tactical tasks of territorial communities	Expected results from the implementation of tactical tasks
Development of agricultural production	Through decentralisation and the involvement of local communities in decision-making, rational use of resources will be achieved, innovations will be introduced, labour productivity will be increased, and new jobs will be created, making life in rural areas more comfortable and attractive.
Improving the quality of life	The development of infrastructure will improve the quality of housing, educational, medical, transport, information and communication services, as well as participation in political and social activities.
Environmental protection	Conscious attitude to nature and rational use of resources are the key to preserving the environment for future generations.

**Source:** compiled by the authors

A key element in the development of the country's agricultural sector is the comprehensive development of rural areas aimed at ensuring appropriate progress in agriculture, improving working conditions, living conditions and the environment. In the current economic, financial and social environment, the creation of a self-sufficient and self-regulating system of socio-economic development of rural areas remains problematic. Achieving the intermediate and ultimate goals of sus-

tainable rural development is complicated by many factors. This is especially true for the so-called frontline and adjacent areas. The impact of rural areas on socio-economic development requires the attention of state and local authorities. To achieve this goal, effective management technologies and tools are needed to preserve and expand the potential of rural areas. This will help to increase the competitiveness of the national economy and improve the welfare of rural residents (Table 2).

**Table 2.** Dynamics of indicators of agricultural sector development in Ukraine by components

Indicators	Average during		
	2005-2010	2010-2015	2015-2020
<b>Economic component</b>			
Share of the industry in GDP, %	11.9	9.3	6.7
Gross value added of the industry, USD billion	10.9	14.4	11.9
Share of the industry in value added, %	14.2	10.8	11.1
Public expenditures on the industry, UAH million	1,636.3	4,665.0	7,693.7
Trade openness (share of exports), %	31.8	38.3	44.8
Annual capital investments, million USD	1,380.7	1,879.8	2,378.9
including for the 1 <sup>st</sup> enterprise, thousand USD	30.4	39.5	48.6
<b>Social component</b>			
Salaries of employees in the industry per month, UAH	3,309	9,734	16,159
including in % to the average in the economy	74.8	84.0	93.2
Share of people employed in agricultural production, %	17.5	17.1	16.7
Relative level of rural poverty (by expenditures), %	27.9	43.8	59.7
<b>Environmental component</b>			
Ploughed agricultural land, %	78.4	79.5	80.6
Amount of mineral fertilisers applied per 1 ha, kg	98	152	206
Area treated with pesticides, %	42.6	91.4	95.4
Area under organic production, %	19.0	7.0	3.0
Carbon dioxide emissions, million tonnes	161.1	150.5	139.9
Share of water used for production needs in agricultural production, %	20.3	21.8	23.3

**Source:** compiled by the authors on the basis of data from I. Kryukova & S. Stepanenko (2022)

Not only are there no financial opportunities to restore infrastructure in the war-affected settlements, but existing infrastructure facilities are being further destroyed, leading to an increase in the problems of technogenic and environmental safety (contamination of territories with explosive devices, destroyed buildings). In Ukraine's agriculture, the war caused the greatest losses to agricultural machinery, warehouses and stocks of produce (Table 3).

The problem of socio-economic recovery of the territories affected by the war is gaining national proportions, which requires the implementation of a comprehensive social policy at the state level to effectively address it. As a result, the key element is the creation and practical implementation of strategic planning aimed at the socio-economic development of each specific rural settlement. Such strategic planning should meet the interests of every resident of rural areas (Dunayev *et al.*, 2024).

**Table 3.** Structure of losses caused to Ukrainian agriculture by the war

Category	Total cost, million USD
Agricultural machinery	2,885.4
Storage facilities	1,062.5
Animal husbandry	362.5
Perennial crops	348.7
Production factors (fuel, fertilisers, plant protection products)	95.4
Manufactured products	872.0
<b>Total</b>	<b>6,626.8</b>

**Notes:** data as of 15.09.2022

**Source:** compiled by the authors based on data from R. Neiter *et al.* (2022)

Rural areas continue to lose their attractiveness not only because of the low level of housing with basic amenities, but also because of the absence or inaccessibility of such services as social, medical, educational, information and communication services. A significant number of residents of rural areas are also deprived of access to such services due to the dilapidated state of the road transport infrastructure. This negatively affects the ability to provide timely services (Belei, 2021). Further development of rural areas in Ukraine is complicated by a number of negative factors. These include: lack of coordination and control over the implementation of rural development measures, low financial capacity of territorial communities, insufficient financial and credit services, formal attitude to the development of development strategies and programmes, low investment attractiveness and weak branding of rural areas, underdeveloped social infrastructure, unsatisfactory wages, high unemployment and lack of qualified specialists (Dovgal *et al.*, 2022). Eliminating these problems requires joint efforts of the government and society to implement development strategies and programmes, attract investment, improve social infrastructure and ensure the development of non-agricultural activities. It is also necessary to attract and provide adequate training for qualified professionals who can use the latest technologies and make effective management decisions to solve problems at the local level.

Rural areas are heavily dependent on transport services for the supply of inputs and logistics in the process of selling products or providing services, which is

essential for ensuring the proper efficiency of agricultural production and the quality of life in rural communities (Borko *et al.*, 2022). The low level of development of transport networks serving rural areas reduces their investment attractiveness and limits the possibility of introducing innovative development of promising activities, such as tourism, recreation, and others. Insufficient development of social, communal, household, information and communication infrastructure lead to a low level of meeting the modern needs and quality of life of rural residents.

Economic relations are the basis on which the development of all spheres of life – social, cultural, political and others – rests. This is especially evident in rural areas. The decline of the rural economy leads to the destruction of other important areas of life. There is a steady trend towards a significant deterioration in demographic indicators and living standards in rural areas. They are experiencing a significant decline in labour potential, rising unemployment and poverty among the population. The migration outflow of young people from rural areas to cities and abroad further exacerbates this negative phenomenon. Another problem for rural development is the low level of wages. The level of wages in agriculture is determined by national standards (minimum wage, taxation) and cannot be lower than the level established by law for a fully worked day. However, in order to minimise labour costs, employers use the practice of part-time employment and dismissal after the end of the employment contract, which makes full-time employment impossible (Yekimov *et al.*, 2024).

One of the factors affecting wages is the qualifications of employees. About 60% of people working in the agricultural sector perform the simplest jobs, so their wages are determined by the lowest tariff category. In 2021-2023, the cost of labour and social measures in the structure of agricultural production costs averaged 6.1%. In 2019-2024, this figure decreased by almost 40% (National Institute for Strategic Studies, 2024). Employers explain low wages in agriculture by insufficient labour productivity. However, labour productivity depends to a greater extent on the employer itself: its ability to organise production, introduce modern technologies, and provide advanced training for employees. By saving on modernisation, investment, and innovation, employers reduce profitability and, as a result, eliminate the possibility of raising wages for employees.

Research by S. Yekimov *et al.* (2023) shows that the low share of wages in production costs is associated with the raw material nature of agricultural production, low levels of added value, and the rise in the cost of logistics services. Farmers are business owners but formally belong to the corporate sector. However, due to the small share of production (8.7%) and additional goals (meeting the needs of their families and rural communities), their profitability is much lower than that

of owners of large agricultural enterprises. Farming can be seen as the most optimal model of management in the agricultural sector in terms of inclusiveness, as farmers independently determine the forms and methods of management, as well as the use of the results of their production activities. Hired workers are not involved in production management, profit distribution, and are not liable for losses. Their inclusion is limited. On the one hand, they are included in the production process, enjoy socio-economic protection and other legal guarantees of formal employment, but on the other hand, receiving a fixed salary, they are not entitled to share in the results of economic activity.

The war is having a severe impact on the country's economy and employment. Part of the rural population is forced to leave their homes and go abroad, and those who remain join the ranks of the unemployed. The current demographic situation in rural areas is characterised by depopulation of the rural population, decreased life expectancy and birth rates, increased mortality, and an increase in the migration outflow of rural residents, resulting in a shrinking settlement network. There are more than 200 million unemployed people in the world. Due to the full-scale war, Ukraine is among the countries with the highest unemployment rates (Table 4).

**Table 4.** Number of registered unemployed in Ukraine, 2010-2022

Years	Total population, thousand people	Number of registered unemployed, thousand people
2010	45,795.9	452.1
2015	42,774.6	461.1
2020	41,629.9	459.2
2021	41,208.1	295
2022	41,167.3	186.5

**Source:** compiled by the authors based on data from Minfin (n.d.)

It should be noted that in 2010-2022, Ukraine has been experiencing a steady downward trend in the country's population. The main reasons for this are, first and foremost, the negative impact of military aggression by the Russian Federation and, as a result, the

out-migration of citizens. Since the beginning of the full-scale invasion, as of September 2022, 6.98 million people have become internally displaced in Ukraine. The negative population growth rate also has a negative impact on the country's population (Table 5).

**Table 5.** Dynamics of natural population change in Ukraine, thousand people

Years	Number of births	Number of deaths	Natural increase, population decline
2010	497.7	698.2	-200.5
2015	411.8	594.8	-182.6
2020	293.5	616.8	-323.3
2021	273.8	714.3	-440.5
2022	207.0	541.7	-334.7

**Source:** compiled by the authors based on *How Ukraine's population...* (2024)

Employment rates in urban and rural areas differ significantly. According to the data for 2021-2024, the employment rate in cities is significantly higher and shows positive growth dynamics. In contrast, the opposite trend is observed in rural areas: the employment rate is lower and tends to decline. Employment and unemployment rates are important indicators of the country's socioeconomic development and the state of the labour market. Unemployment causes not only the economic decline of rural areas, but also the moral impoverishment of people, which ultimately suppresses the economic activity of the rural population (Minfin, n.d.).

The economically active population of rural areas is the part of the working-age population that offers its labour for production or service provision. The degree of participation in labour activity and employment opportunities reflects the level of economic activity of the rural population. The most active in registering as unemployed, as well as in looking for work, are people aged 35 to 40. Young people in Ukraine are more flexible and ready for social change. They also have greater potential for career growth and are willing to work longer hours. Therefore, it is important to have an active employment policy aimed at stimulating youth employment, especially during and after the military conflict. A significant proportion of rural residents are forced to engage in private farming in the face of a declining supply of paid work. Most of them are aged between 50 and 60 years (State Statistics Service of Ukraine, 2023).

Given the significant shrinkage of the production sector in rural areas, agriculture remains the main source of employment. Deeper specialisation of production, concentration of land use, and growth in the size of business entities in the corporate sector have not been accompanied by an increase in employment due to economies of scale. This is due to the focus on monoculture production and the decline of labour-intensive industries. The best employment option depends on the needs and circumstances of each individual. If flexible working hours are required, part-time employment is the most appropriate choice. If it is a stable job with a high salary and social guarantees, employment under an employment contract is the most suitable. Seasonal work is a viable option when employment is effectively secured for a short period.

Diversification of the rural economy is the way to its socio-economic sustainability, development, and overcoming depression and territorial disproportions. It involves the use of all available resources in rural areas to create jobs, enter new markets, support regional specialisation and realise local competitive advantages. Diversification includes sustainable and inclusive development of rural areas, implementation of effective

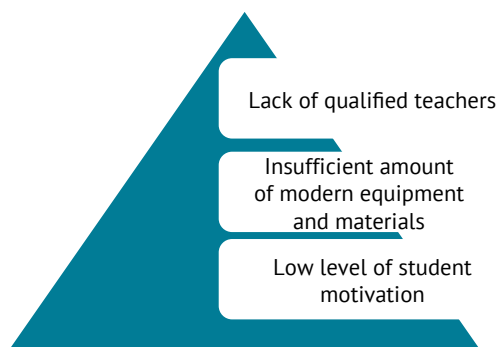
development tools, such as building infrastructure and ensuring access to relevant services; a new vision of the use of natural and climatic resources, and intensification of the development of the service sector. This will improve the living standards of rural residents, reduce their dependence on agriculture, create new jobs, stimulate the development of small and medium-sized businesses, and make villages more attractive places to live and work.

The issues of stimulating the diversification of the rural economy, creating a favourable investment climate, and developing public-private partnerships require appropriate regulatory changes and additions in terms of defining preferential conditions and modes of operation for business, especially in the context of the construction and operation of facilities related to the provision of social services to rural areas. Strategic and current planning is a powerful tool that can help accelerate the process of rural development, taking into account the principles of inclusiveness and content. However, it should be noted that not all communities have developed and approved development strategies, even after amalgamation. In addition, existing strategies are based on different methodological approaches and differ in structural changes and content. Therefore, it is necessary to develop unified methodological guidelines for professionals to use when determining priorities and current tasks for the development of territories. It is also necessary to establish a mechanism for analysing the effectiveness of the implementation of local development strategies and current plans, as well as a procedure for approving amendments to these documents.

Despite the fact that local authorities have their own powers and responsibilities for the socio-economic development of their territories, there may be problems with uneven distribution of resources and different levels of economic development of individual territories. Therefore, it is necessary to monitor the development of rural areas and make appropriate management decisions to reduce inequalities, which is discussed in detail in O. Dovgal *et al.* (2024). The effectiveness of planning as an important tool for managing inclusive rural development depends on financial resources and the willingness and ability of managers to attract additional resources. Financial decentralisation has provided local governments with opportunities to increase local budget revenues by boosting economic activity and increasing tax revenues. Local governments also have the opportunity to develop inter-municipal cooperation and receive additional funding through the State Fund for Regional Development. However, the main problem is the lack of strategic vision and the unpreparedness

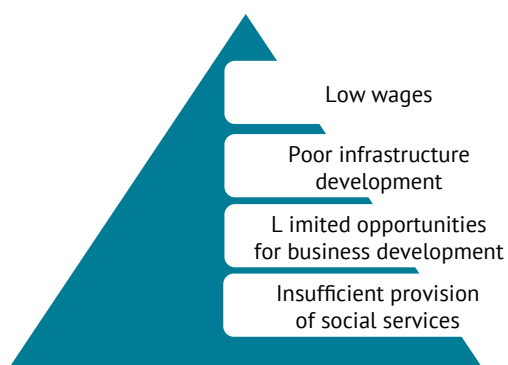
of managers to work in the new business environment, as well as the lack of qualified professionals who can justify management decisions and prepare project documents. Therefore, the issue of encouraging highly qualified specialists to work in rural areas is relevant.

The socio-economic changes that took place in Ukraine between 1991 and 2024 could not have spared rural areas. As a result of the reforms, rural residents became hostages not only to the modernisation of society and the bankruptcy of agricultural enterprises, but also to a sharp decline in income and reform of rural social infrastructure. The transformation processes place greater demands on the financing and organisation of rural infrastructure. Improving employment and reducing unemployment in rural areas depends on the quality of education and increasing its funding. The organisation of education in rural areas has its own specifics compared to urban areas. Due to the lack of students willing to study in grades 10-11, the period of study in schools is shortened as much as possible. This leads to the fact that young people do not acquire the necessary knowledge and skills for successful employment (Figs. 2, 3).



**Figure 2.** Reasons for the low quality of education in rural areas

Source: compiled by the authors



**Figure 3.** Impact of limited funding for rural areas

Source: compiled by the authors

Pre-school education in Ukraine is the first element in the structure of continuing education, forming the continuity of upbringing and education of a child in the kindergarten, family and school. This level requires physical and moral education, skills, training, care and health of a preschool child based on supporting his or her individuality, respecting his or her interests and needs, and developing his or her creative abilities. As of 2024, rural schools are part of the national education system. Its main goals, functional tasks and key indicators are not determined by the village. For schools in rural areas, there are no exclusively "rural" curricula, training programmes, textbooks and teaching methods. Social requirements for the professional and pedagogical activities of teachers in rural and urban schools are generally the same. At the same time, rural schools function under the influence of demographic, psychological, socio-cultural, environmental and legal factors.

The deterioration of the situation in rural education is evidenced by the fact that 153 schools were closed in rural areas between 2021 and 2023, half of which were primary schools (State Statistics Service of Ukraine, 2023). Schools with a small number of students are transformed into branches of a hub educational institution (usually primary or secondary schools). In this case, high school students are transported to neighbouring settlements by school bus, but it should be noted that not every school is provided with the necessary transport, which creates additional problems and is one of the reasons that prompts families to change their place of residence.

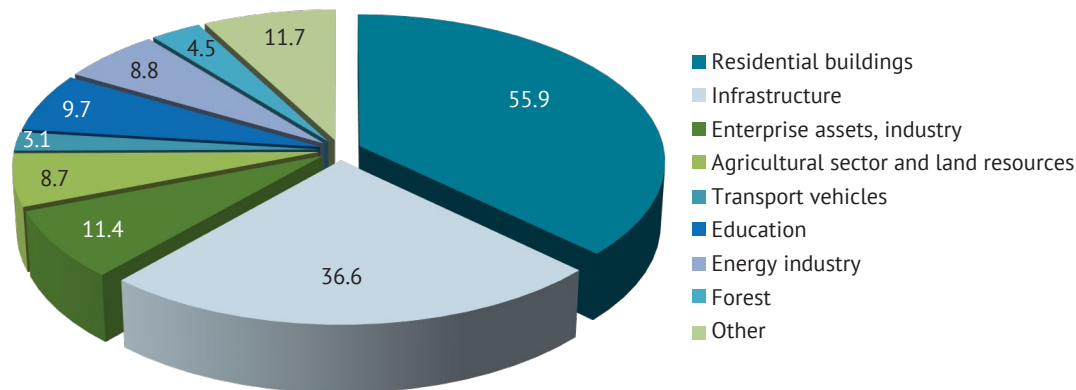
To improve the situation with employment and unemployment in rural areas, it is necessary to improve the quality of education, i.e. to provide educational institutions with qualified personnel, to update the material and technical base of schools, to motivate students to study, to increase the level of wages in rural areas and to develop infrastructure (Honcharenko & Honcharenko, 2023). The situation is similar in the healthcare sector. Rural areas employ 5.3% of doctors and 11.5% of junior and middle-level medical staff. However, more than 55% of the equipment in healthcare facilities is recognised as outdated. The healthcare sector in Ukraine is constantly undergoing ongoing reforms, closely linked to political and socio-economic transformations in the country. At the same time, the rural healthcare system is a relatively autonomous social entity that has the property of inertia in relation to the ongoing reforms. The inertia is determined by both resource factors (low living standards in rural areas, lack of education, insufficient funding, shortage of personnel, territorial remoteness, sparse information flows,

etc.) and traditions of the rural population's way of life, a certain conservatism of life attitudes.

The rural healthcare system has a number of peculiarities in contrast to urban healthcare. Medical support for rural residents is provided in various types of institutions. Hospital care is provided in inpatient facilities of central district hospitals, district hospitals and district hospitals. The outpatient stage includes polyclinics, rural medical outpatient clinics, general medical practices, and paramedic and obstetric stations. Small medical institutions that are significantly distant from each other prevail. The majority of rural residents served by such healthcare facilities are unemployed pensioners. The population of rural areas has virtually no choice of healthcare facilities, as in small settlements medical care is usually provided by a single doctor or paramedic. Specialised medical care, which is less accessible to the rural population, is provided mainly in district and regional hospitals.

Further reforms of the healthcare system should not lead to the destruction of the historically estab-

lished practices of providing medical care to the rural population. It is necessary to improve medical care in rural areas by expanding its infrastructure and changing the content of the work of a particular type of institution. Therefore, one of the most important tasks of healthcare in rural areas in the current development environment is to use the available financial resources of communities to achieve the best possible result. The modern Ukrainian village requires not only the expansion and strengthening of social infrastructure facilities, but also fundamentally new approaches to the problem of engineering arrangement, primarily from the standpoint of their comprehensive solution and urgency. A comprehensive approach is needed to address the issues of gasification, heating and water supply in rural areas. Providing rural residents with housing and relevant communal services is a priority task of the state policy on the revival of rural areas. The military aggression of the Russian Federation has caused the greatest direct losses and destruction to residential buildings and infrastructure (Fig. 4).



**Figure 4.** Direct losses from destruction and damage by sector, USD billion

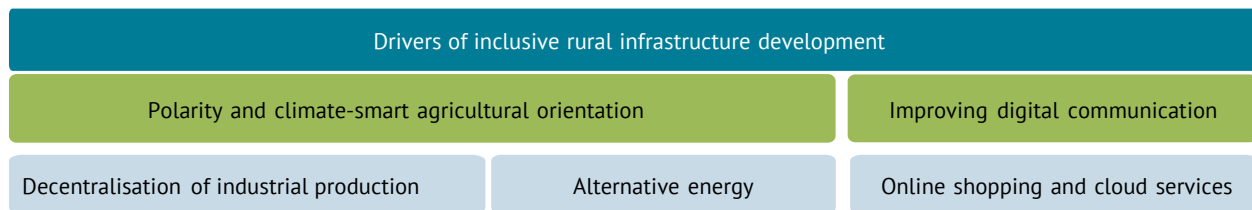
**Source:** compiled by the authors based on USAID (2023)

The main problems of housing construction in rural areas as of 2024 include: lack of budget funds for the construction of social housing; rising prices for construction materials; and low incomes of rural citizens. The poor development of rural infrastructure leads to the following negative consequences:

- vulnerability of rural areas and reduced efficiency of the existing resource potential;
- limited employment opportunities and dependence on the degree of infrastructure development in the settlement;
- increased risks of job losses for rural residents;
- pronounced seasonality in income generation and its low level;
- dependence of household income on weather conditions.

It is worth highlighting the drivers that contribute to the development of rural infrastructure (Fig. 5).

Market transformations have shown that the rural economy is inert to new challenges and opportunities. However, having become part of an open global economic space, rural areas cannot remain aloof from global processes, such as a reduction in the number of people employed in agricultural production, an increase in international trade, digitalisation of all spheres of human life, increased migration, and the spread of remote and other forms of employment. When looking for ways to solve the problem of inclusive rural infrastructure development, it is worth looking at the European experience. Rural development benchmarks that meet the principles of sustainable and inclusive development can be successfully applied in Ukraine.



**Figure 5.** Drivers of inclusive rural infrastructure development

**Source:** compiled by the authors

It seems unlikely that the indicators of countries with developed rural infrastructure (France and Germany) will be achieved in the near future. Therefore, the indicators of countries with similar development conditions, such as Poland, can serve as target benchmarks. Poland has succeeded due to several factors that should be taken into account: high labour productivity, an effective system of support for national agricultural producers, developed infrastructure, stimulation of research and development, active integration into European and global markets, and development of rural tourism. The challenges faced by Poland on the way to inclusive rural infrastructure development should also be taken into account. It is about the loss of labour force, which migrates to countries such as Germany and France in search of higher wages. However, through effective public policy, widespread implementation of scientific and technological progress, integration into the global market, and preservation of traditions, rural development can be achieved. As of 2024, Poland has become an active importer of labour from Ukraine. A large number of Ukrainians are employed in rural areas for seasonal work. This is due to limited employment opportunities in Ukraine (especially in rural areas) and higher wages in Poland.

It is important for Ukraine to study and adapt the experience of European countries to achieve inclusive development of rural infrastructure, promote farming, increase wages and improve working conditions in agriculture, and reduce dependence on raw material exports and increase exports of processed products. Improving the efficiency of agricultural production will be a source of increasing its competitiveness. The Global Donor Platform for Rural Development considers inclusive agribusiness as a key perspective for understanding and stimulating transformations in the agricultural and agro-industrial sectors. The source of finance plays an important role in the development of the private sector, from small local enterprises to large international corporations. Drawing on the experience of developed countries, it should be noted that an integral part of the modern infrastructure support of the rural market sector is agricultural logistics.

The study has shown that the current conditions of rural infrastructure development require its inclusive orientation, as well as the transformation of approaches to wartime conditions and possible post-war recovery. Given the needs of society in the current situation, the authors of this study support the opinion of A. Kliuchnyk & N. Halunets (2021) about the importance of using internal and additionally attracted external sources of development of territorial communities. The issues of stimulating the diversification of the rural economy, creating a favourable investment climate, and developing public-private partnerships require appropriate regulatory changes and additions in terms of defining preferential conditions and modes of operation for business, especially in the context of the construction and operation of facilities related to the provision of services to rural areas and social services to the population.

The importance of maintaining the gradual implementation of the European experience of higher education institutions is described in V. Shebanin *et al.* (2024). In this paper, the authors' conclusions were supplemented by the problems of preserving school education at the level of territorial communities. The situation in the field of medical care in rural areas was analysed. It is determined that the healthcare system has similar problems, which are manifested in the quantitative reduction of institutions, deterioration of their logistical support, optimisation of the system of institutions, and in the case of further reforms – to the destruction of the historically established practice of providing medical care to residents of rural areas.

The source of further economic development of rural areas is the overcoming of depressive disproportions by diversifying production based on sustainable development. The development of infrastructure support industries should take place in the context of the rational use of available budget funds of rural communities and additional attraction of investment resources. The development of strategic and current plans is an effective tool for accelerating the process of rural development based on inclusiveness. The directions of socio-economic development of rural areas are

described in S. Oneshko *et al.* (2022). Based on this source, this scientific study has supplemented the analysis of losses caused by the military aggression of the Russian Federation and pointed out the main aspects of further diversification of the agro-industrial complex to ensure food security. Thus, attention was paid to fundamentally new approaches to the engineering arrangement of villages, the introduction of integrated solutions to energy efficiency in gasification, heating and water supply, which should become the priority tasks of state policy. Attention is focused on the need to restore logistics links and high-quality transport links, develop economic activity of rural residents and provide jobs. The author analyses the dynamics of infrastructure indicators for the period from 2005-2020 by grouping them into five-year periods. In addition to the general information, an analysis of changes in the number of registered unemployed in the country is carried out. The dynamics of natural population movement under the influence of changes in the number of births and deaths on the total population of Ukraine is characterised. In turn, the study by M. Kovalenko & N. Onikiyenko (2018) focused on the issues of infrastructure provision of the social sphere of rural areas. The author emphasised that the availability of high-quality educational and medical institutions, cultural and sports facilities in rural areas stimulates population retention and growth, which, in turn, contributes to maintaining social stability and strengthening communities.

The peculiarity of the approach to any implementation of scientific work lies in the conceptual subdivision of drivers of inclusive directness according to the following criteria: political, social, economic. This made it possible to look at the current processes of development of territorial communities; The situation is that the rural territories are facing a position of infrastructural security, as well as the influx of destructive factors resulting from military aggression on the further economic development of the agro-industrial complex.

## CONCLUSIONS

Acceleration of the inclusive orientation of the development of rural infrastructure is not particularly relevant at the current stage. To achieve the specified goal, it is necessary to take comprehensive measures, such as diversification of the economy, modernisation of infrastructure and investment in research and development. It is also important to ensure the participation of local residents in decision-making and to study the experience of European countries. An inclusive agribusiness sector involves using resources from donors and development agencies as a catalyst for market-based solutions aimed at poverty alleviation. Government

investment and incentive policies play an important role in this, as the private sector cannot succeed on its own.

In rural areas, there is a certain variety of organisational forms of management, but there is a lack of labor force. Unemployment is an extremely negative social phenomenon. The highest level of unemployment is observed among persons aged 35 to 40 years. Young people are more flexible and ready for changes in social terms. They also have better potential for career growth and are ready to handle a greater workload. Therefore, it is important to implement an active employment policy aimed at stimulating the employment of young people, especially during and after a military conflict.

Increasing the efficiency of agricultural production is key to ensuring competitiveness. Creating a self-sufficient system of socio-economic progress and achieving the goals of sustainable development of rural areas are important tasks for improving living conditions and ensuring the prosperity of communities. To improve the situation with employment and unemployment in rural areas, it is necessary to increase the quality of education, providing educational institutions with qualified teaching staff, updating the material and technical base of schools, motivating students to study, increasing the level of wages in rural areas, and developing infrastructure.

It is necessary to improve medical care in rural areas by expanding its infrastructural support. One of the most important tasks of health care is the use of available financial resources of communities. The modern Ukrainian village needs not only the expansion and strengthening of infrastructure facilities of the social sphere, but also fundamentally new approaches to the problem of engineering arrangement, first of all, from the standpoint of their comprehensive solution and urgency. An optimal approach is needed in solving issues related to gasification, heating and water supply of rural areas.

It is important for Ukraine to study and adapt the experience of European countries to achieve inclusive development of rural infrastructure. Indicators of Poland's sustainable development can serve as target benchmarks. Inclusive agribusiness creates new jobs, increases incomes and improves access to food for the poor. In addition, it promotes economic growth, infrastructure development and social services in rural areas. The inclusive orientation of rural areas also contributes to the improvement of the quality of manufactured products. All this makes inclusion an indispensable tool for the sustainable development of rural areas and improving the quality of life of the population.

In the future, it is necessary to focus attention on several factors: the economic efficiency of inclusive models, social impact, environmental aspects, the role of institutional factors, innovations in agriculture.

Further research in the field of inclusive development of rural areas will allow to develop more effective strategies and policies aimed at ensuring the sustainable development of rural areas of Ukraine and improving the quality of life of the rural population.

None.

None.

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## CONFLICT OF INTEREST

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## Драйвери інклюзивної спрямованості розвитку сільської інфраструктури України

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**Анотація.** Економічна система суспільства передбачає постійний рух товарів, послуг, грошей, цінних паперів, робочої сили. Злагоджена взаємодія елементів ринкового механізму досягається їх збалансованим розвитком. Неможливо підвищити ефективність функціонування аграрного сектора економіки країни без вдосконалення сільської інфраструктури. Стаття присвячена вивченню теоретичних і практичних положень щодо прискорення розвитку інфраструктури сільських територій, забезпеченню доступу до неї усіх верств сільського населення та розробленню рекомендацій щодо підвищення рівня життя селян. Основними методами дослідження були аналіз наукової літератури, аналіз статистичних даних, порівняльний аналіз, експертні оцінки. У науковій роботі досліджено основні індикатори покращення рівня життя мешканців сільських територій у розрізі політичного, соціального та економічного аспектів. Для корегування цілей сталого розвитку було охарактеризовано втрати завдані інфраструктурному забезпеченню через викрадення, знищення або пошкодження об'єктів. Показано, що вплив економічного зростання на подолання бідності посилюється з ростом людського капіталу, але слабшає при значній нерівності доходів. Особливу увагу було приділено індикаторам покращення рівня життя мешканців сільських територій у розрізі політичного, соціального та економічного аспектів. Також було зроблено висновки щодо основних завдань, що стоять перед сільськими громадами для забезпечення їхнього сталого розвитку. Практична цінність дослідження полягає в одержаних емпіричних результатах, що можуть бути використані для розробки та реалізації державної політики розвитку сільських територій. Розроблені рекомендації можуть бути корисними для органів місцевого самоврядування, громадських організацій та інших суб'єктів, які займаються питаннями розвитку сільської місцевості. Запропоновано використання досвіду Польщі на шляху до інклюзивного розвитку сільської інфраструктури

**Ключові слова:** сталий розвиток; сільські території; сільські громади; ринок праці; економічний розвиток; інклюзивна освіта

# ВІСНИК АГРАРНОЇ НАУКИ ПРИЧОРНОМОР'Я

*Науковий журнал*

**Том 28, № 4. 2024**

Заснований у 1997 р.  
Виходить чотири рази на рік

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