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Prerequisites for cultivating frost-resistant peach varieties in the Right-Bank part of the Western Forest-Steppe of Ukraine

Abstract. The necessity of cultivating frost-resistant peach varieties in the Forest-Steppe zone of Ukraine arises due to frequent sharp fluctuations in air temperature during the winter-spring period. Their cultivation can mitigate the impact of weather conditions, ensuring stable fruit production of this crop. The study aimed to analyse the prospects for growing peaches (*Prunus persica* Mill.) using intensive technologies under changing climate conditions. An analysis of the peach-growing situation revealed that it is a widely cultivated drupe in Ukraine and globally. The main countries leading in peach fruit production were identified: China, Italy, Turkey, Greece, and Spain. Despite a 24% increase in global peach production between 2013 and 2023, the demand for this crop has also risen, leading to a deficit and increased imports to Ukraine. Calculations of the scientifically justified annual consumption norms for peaches showed a shortfall of 187 thousand tonnes in production, with current production standing at 11.2 thousand tonnes. Several factors hindering the expansion of peach orchards were identified. The development of frost-resistant varieties by breeders, suitable for cultivation in the Forest-Steppe of Ukraine, alongside changing weather conditions, offers opportunities for the safe cultivation of peaches in the region. An analysis of the weather conditions in the Right-Bank part of the Western Forest-Steppe of Ukraine was conducted. It was found that between 2013 and 2023, there was a significant increase in the total active temperatures, with 2023 recording a maximum of 3,777°C. At the same time, precipitation decreased by 58%, amounting to only 325 mm. Considering the changing weather conditions and the development of new frost-resistant varieties, which have expanded the peach cultivation zone to northern regions of Ukraine, it is essential to prepare and implement specific measures to adapt the horticultural industry to peach cultivation in these new regions to meet domestic

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market demands. It is recommended to initiate trials in irrigated horticulture and develop new methodological guidelines to provide scientific support for establishing perennial peach orchards in the Right-Bank part of the Western Forest-Steppe of Ukraine

Keywords: *Prunus persica* Mill.; productivity; fruit market; climate change; intensive technologies; drought resistance

INTRODUCTION

In the context of climate change and unstable temperature regimes, studying the preconditions for growing frost-resistant peach varieties is crucial for ensuring the effective adaptation of this crop to various climatic conditions, especially in regions with cold winters. Researching these preconditions will help develop agronomic approaches to optimise the growing process. Frost-resistant peach varieties have the potential to expand cultivation areas in new regions, such as the Forest-Steppe of Ukraine, where peaches were previously less suitable for cultivation. In addition, studying the preconditions for cultivation will help reduce the risk of crop losses from adverse weather conditions and stabilise the production of this crop, which is important for meeting the growing needs of the domestic market.

According to J. Mohammed *et al.* (2021) and W. Liu *et al.* (2022), the value of peaches as a fruit crop lies in their nutrient-rich and biologically active components. They also contain vitamin P (anthocyanins, catechins, flavones), vitamin C (ascorbic acid), provitamin A (carotene), malic and citric acids, and pectin substances (Geçer, 2020; Aubert & Chalot, 2020).

Peach fruits are primarily consumed fresh or used in the confectionery or canning industry. Recently, new methods of storing and using the fruit have been developed. In studies by P. Wang *et al.* (2018), Y. Zhong *et al.* (2021), and K. Zhu *et al.* (2023), it was shown that quick freezing fully preserves the dietary, nutritional, and taste qualities of the fruit. The diverse composition of peach fruits indicates not only their nutritional value but also their medicinal properties, which is especially important in the complex ecological situation in the world.

The peach, traditionally recognised as a southern crop, is gradually expanding into other regions of Ukraine due to the introduction of new varieties and the adaptation of cultivation technologies. V. Blinova (2019) emphasises that climate changes and improvements in agrotechnical practices have enabled the successful cultivation of peaches in more northern regions. Research by D. Hromov (2023) highlights the importance of selecting adapted varieties for the western and northern parts of the country, where climatic conditions differ from those in the southern regions. These areas experience cooler temperatures and higher humidity, which affect the growth and development of peach trees. According to I.V. Liadska & O.Yu. Holovko (2023), most of Ukraine offers favourable conditions for stable fruit production, including peach cultivation using intensive technologies. However, the combination of intensification factors and their role in yield formation vary significantly depending on the region, soil fertility, utilisation of the variety's biological potential, and the availability of material resources for the technology used.

Special attention is paid to the choice of variety in the research of O.M. Aleksieieva & I.V. Yudytska (2023), as varieties created in Ukraine are the most adapted to its conditions and contribute to increasing the efficiency of fruit production. Each zone has its own characteristics. In the Forest-Steppe zone of Ukraine, new frost-resistant varieties of this valuable crop are being introduced, which is due to their high adaptability to temperature fluctuations in the winter-spring period. D.G. Bielenberg & K. Gasic (2022) have proven that this is facilitated by the duration of dormancy, the rate of morphogenesis, and the winter hardiness of the generative buds.

At the same time, the Forest-Steppe of Ukraine experiences unfavourable weather conditions during the growing season each year. D. Natalchuk & L. Pavliuk (2024) found that the spring and summer periods are marked not only by rising temperatures but also by frequent droughts. Although the average annual precipitation for 2013-2023 was 418 mm, its distribution was highly uneven. High air temperatures and low humidity levels lead to atmospheric drought, which eventually turns into soil drought. While peach is a drought-tolerant crop, a lack of rainfall can result in not only a decline in the commercial quality of fruit in a drought year but also affect the formation of generative buds for the following year. D. Natalchuk & L. Pavliuk (2024) found that although peach is noted for its drought tolerance, there are differences among varieties in terms of leaf tissue water content and water deficit indicators. These varieties are classified into three drought-resistance groups: highly drought-resistant, drought-resistant, and moderately drought-resistant. The water loss dynamics observed, depending on the drought-resistance group, indicate that highly drought-resistant combinations possess the highest water retention capacity. Therefore, in the context of climate change, it becomes increasingly important to develop varieties that are well-adapted to adverse abiotic environmental factors, particularly frost and drought resistance.

The aim was to analyse the prospects for peach cultivation using intensive technology under the conditions of climate change.

The study is based on a detailed analysis and identification of frost-resistant peach varieties listed in the State Register of Plant Varieties Suitable for Propagation in Ukraine (2024), as well as the most promising and introduced varieties. For these varieties, key factors that enable the expansion of peach cultivation to more northern regions of Ukraine have been identified based on a review of literature sources. The analysis of FAO data (n.d.) on global peach production is limited to 2022, as this was the most recent data available at the time of publication.

Peach Cultivation in Ukraine and Worldwide

Between 2012 and 2022, the global area under peach cultivation saw a slight increase. According to the FAO (2024), the area dedicated to peach orchards globally expanded by 1.8 thousand hectares, reaching 1,542,648 hectares by 2022. During this period, gross peach production grew by 24%, reaching 26.3 million tonnes. China remains the world's leading peach producer, with an average annual output of 15.4 million tonnes, which increased to 16.8 million tonnes in 2022 (Fig. 1). In contrast, Ukraine produces only 21 thousand tonnes of peaches. Other major peach-producing countries include Italy (1.2 million tonnes), Turkey (1 million tonnes), Greece (895 thousand tonnes), Spain (871 thousand tonnes), the USA (666 thousand tonnes), Iran (577 thousand tonnes), Chile (312 thousand tonnes), and Egypt (272 thousand tonnes).

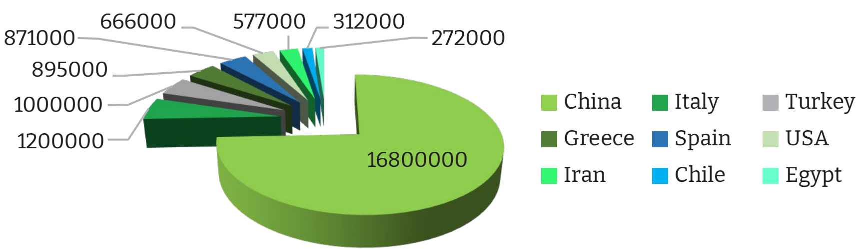

Figure 1. Global peach production, tonnes, 2022

Source: compiled by the authors based on FAO (n.d.)

In Ukraine, the largest area dedicated to peach orchards was recorded in 1998, totalling 20.5 thousand hectares. However, this area gradually declined to 3.3 thousand hectares by 2018 and further decreased to 1.5 thousand hectares by 2023 (Fig. 2), primarily due to the annexation of Crimea and the occupation of southern regions of Ukraine. Currently, the majority of peach orchards are concentrated in the Odesa Region (1 thousand hectares), Dnipropetrovsk

Region (0.2 thousand hectares), Mykolaiv Region (0.2 thousand hectares), and Zakarpattia Region (0.1 thousand hectares) (State Statistics Service of Ukraine, n.d.).

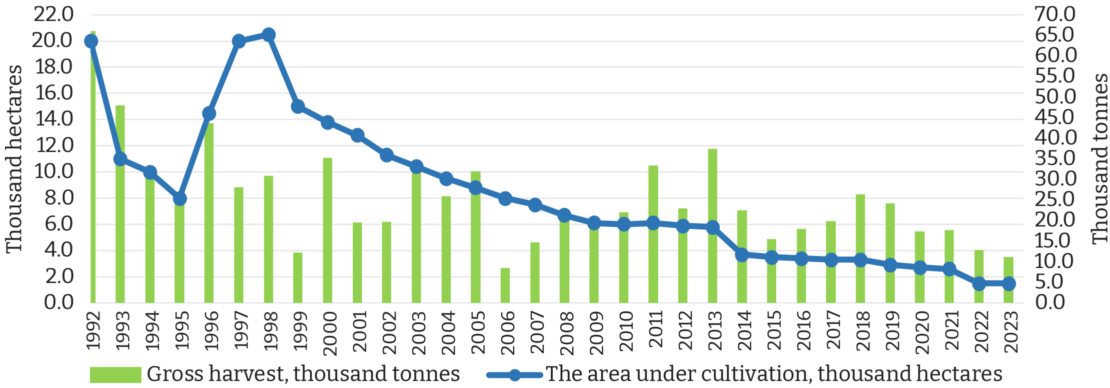

Figure 2. Peach orchard areas and gross harvest in Ukraine, 1992-2023
Source: compiled by the authors based on the State Statistics Service of Ukraine (n.d.)

Overall, as illustrated in the diagram, the area dedicated to peach orchards has decreased by a factor of 13.6, or nearly 93%. However, this decline has been accompanied by an increase in yield per unit area. In 1998, the gross harvest for an area of 20.5 thousand hectares was 30.9 thousand tonnes, resulting in a yield of only 1.5 tonnes per hectare. In contrast, by 2008, the figures were 6.7 thousand hectares, 22.7 thousand tonnes, and 3.4 tonnes per hectare, while in 2018, they stood at 3.3 thousand hectares, 26.4 thousand tonnes, and 8 tonnes per hectare, respectively. Consequently, the yield has increased by a factor of 5.3, primarily due to the intensification of production, which involves the use of new frost-resistant, high-yield varieties and rootstocks that promote precocity and enable orchard densification.

It is worth noting that, given the current level of production, the domestic market for peaches remains deficit. To meet the scientifically justified annual consumption norm of up to 6 kg per person, production must be increased to 198 thousand tonnes; however, in Ukraine, only 11.2 thousand tonnes were produced in 2023 (State Statistics Service of Ukraine, n.d.). This represents a niche that requires development and improvement, both in cultivation technologies and in the research of new promising variety-rootstock combinations, which would enable an increase in peach production in the more northern regions.

Analysis of Peach Varieties in Ukraine

Under certain socio-economic conditions, peach cultivation in Ukraine began to develop in the late 1940s. The main growing regions included Crimea, the western, central, and southern Steppe, as well as Transcarpathia. Here, varieties of Western European origin were predominantly cultivated, known for their excellent taste quality. However, these trees were susceptible to diseases and damage from low temperatures (Barabash *et al.*, 2000).

However, the development and utilisation of frost-resistant peach varieties under favourable weather conditions enable the production of high and consistent yields (Shoferistov & Bunchuk, 2013; Liadska & Holovko, 2023). Many varieties begin to bear fruit within two to three years of being planted in a permanent location, and by the fifth or sixth year, they can produce exceptionally high yields, making this crop highly profitable in commercial orchards (Hulko, 2009). For this reason, peach fruits enjoy unrestricted demand among the population, creating the conditions for further comprehensive study of this crop in various fruit-growing zones.

As of 2024, the list of peach varieties suitable for propagation in Ukraine comprises 26 officially recommended varieties. Among these, 16 are recommended for the Forest-Steppe zone, with frost-resistant varieties including Kniazhehradskyi, Dniprovskyi, Druzhba, Kyivskyi rannii, Lesia, Liubymets II, Oksamytovyi, Pamiat Hryshko, Pecherskyi, and Slavutych. Most of these varieties were developed at the M.M. Hryshko Central Botanical Garden and the Institute of Horticulture of the National Academy of Agrarian Sciences (NAAS) in Kyiv (State Register..., 2024). Significant work has also been undertaken to create high-quality winter-hardy peach varieties that are resilient to the climatic conditions of Ukraine at the Nikita Botanical Garden (Yalta), the Institute of Irrigated Horticulture (Melitopol), Odesa State Agrarian University, and Uzhhorod State Agrarian University (Turovtseva & Turovtsevoi, 2002; Rikhter, 2013). Notable varieties developed at these institutions include Iiunskyi Rannii, Krymskyi Feierverk, Charivnyk, Skazka, Zlatodar, Posol Myru, Vireneia, and Zolotystyi. Furthermore, peach breeding is ongoing, with new varieties being created that have already been registered or are proposed for inclusion: Mostyskyi, Mostyskyi diamant, Kniazhe bahatstvo, Kniazhe Zoloto, Pontiiskyi, Osvizhaiuchyi and Karnavalnyi (Lytovchenko *et al.*, 2011).

The assortment of peaches in Ukraine is also being supplemented by varieties of foreign breeding. The primary criteria for selecting a variety for cultivation in commercial orchards are, first and foremost, frost resistance, marketability, and transportability (Klochko, 2014). The most commonly introduced varieties include Redhaven, Early Crest, Rich May, Ruby Prince, George Line, Harbinger, and Harness. Additionally, there is considerable popularity for varieties marketed under the general brand name Flemin Fury: PF 58, PF 11N, PF 19 007, PF 24C, PF 23, and PF 24 007. H.H. Klochko (2013), in studying the introduced peach varieties Gold Line, Harrow Beauty, Montar, and Harrow Diamond, noted their high adaptability to cultivation conditions and indicated that they could serve as parent varieties exhibiting high fruit quality for future breeding efforts.

Frost and Winter Hardiness of Peaches in the Context of Climate Change

Cultivating peaches in the majority of Ukraine is a risky endeavour. A crucial factor influencing both productivity and the regularity of fruiting is the tree's winter hardiness. According to I.M. Holubkova (2016), I.V. Liadska & O.Yu. Holovko (2022), peaches are the most thermophilic deciduous fruit crop in temperate climate zones. Temperature regime is one of the primary factors that determines the cultivation of peaches in a particular area. When there is insufficient warmth during the growing season, peach trees may grow, but their fruits do not ripen. For instance, in Denmark and southern Sweden, peach plants can withstand winter temperatures; however, due to a lack of the necessary warmth in the summer months, their fruits fail to mature (Aleksieieva & Yudytska, 2023).

In her research, O. Bezkrovna (2014) established that an optimal sum of effective temperatures of up to 2,500 °C is required for the normal growth and ripening of peach fruits. However, prior to 2013, the sum of active temperatures in the Kyiv Region did not support the cultivation of peaches. Between 2013 and 2023, however, a significant increase in the sum of active temperatures was recorded in Kyiv. According to data from the meteorological station located in the experimental orchards of the Institute of Horticulture of the NAAS, the sum of active temperatures was 3,192 °C in 2013 and remained at that level until 2017. From 2018 onwards, it increased to 3,681 °C and continues to rise with periodic fluctuations (Fig. 3).

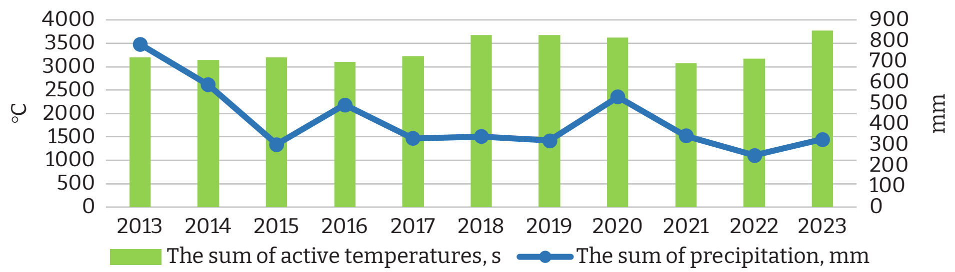

Figure 3. The sum of active temperatures and precipitation for 2013-2023
Source: compiled by the authors based on data from the meteorological station of the Institute of Horticulture NAAS

In 2023, a record maximum sum of active temperatures was recorded at 3,777 °C, enabling the unobstructed cultivation of not only peaches but also other heat-loving crops in this region. Such changes in temperature patterns have been noted by several researchers, including O.V. Shevchuk (2023), who states that during the period from 1991 to 2020, this positive anomaly (the deviation of air temperature from climatic norms) was the largest across the entire country in the history of instrumental meteorological observations.

However, for peaches, the temperature regime is significant not only during the growing season but also during the dormant period (Shoferistov & Bunchuk, 2013; Fadón *et al.*, 2020; Milech *et al.*, 2022). An analysis of long-term data on the productivity and condition of peach plantations indicates that even in the southern and southwestern regions of Ukraine, where the industrial cultivation of this plant is well established, critical conditions for the overwintering of trees periodically arise (Riabov, 2011). Approximately once every 5 to 10 years, critical conditions for plant overwintering develop, characterised by sharp fluctuations in low temperatures and their prolonged effect during the winter-spring period, especially with minimal snow cover, leading to the freezing of flower buds and wood in areas such as Transnistria, Kyiv, Zaporizhzhia, and even Crimea. O.M. Aleksieieva & I.V. Yudytska (2023) note that the most damage is often caused by temperature fluctuations in February when thaws alternate with significant drops in temperature at night. Several researchers from other countries also address spring frosts as a limiting factor in peach cultivation (Kuden *et al.*, 2018).

In a dormant state, depending on the variety and rootstock, peaches can withstand low temperatures ranging from 23 to 28°C. For swollen buds, temperatures of 18 to 19°C are detrimental, while for split buds, approximately 12°C is critical. During the flowering stage, buds are damaged at temperatures between 3 and 4°C, meaning that spring frosts can destroy a significant portion of the harvest (Feshchenko, 2004).

O.M. Aleksieieva & P.H. Bondarenko (2021) asserted that a decrease in peach yield is only observed when 75 to 80% of the floral buds are killed. Additionally, the second wave of growth, or what is referred to as premature shoots, plays a crucial role in the trees winter hardiness. It is known that flower buds exhibit the greatest winter hardiness during the phase of archeosporium (the initial formation of pollen), which occurs during the deep dormancy of the plant. In the second wave of growth, this phase lasts longer (up until the end of January), allowing the buds on these shoots to maintain frost resistance for a significantly extended period. At the same time, several researchers indicate that the yield of peaches depends on the formation and differentiation of generative buds on these growths; poor bud formation makes it impossible to achieve high yields. Bud differentiation occurs in the second half of summer and is influenced by variety, weather conditions, plant nutrition, and other factors (Li *et al.*, 2016; Beppu, 2020; Surányi, 2020).

The winter hardiness of drupes, including peaches, refers not only to their resistance to low temperatures but also to their ability to withstand a range of adverse factors during the winter period. Among these factors, the most significant are the characteristics of the temperature regime, the desiccating effect of wind, frost, and sunburn.

Drought Resistance as a Factor in Achieving Stable Yields

However, the winter hardiness of peaches is significantly influenced by the plant's development and its progression through various stages of organogenesis. Beginning in the second half of summer, processes commence within peach plant tissues to prepare for winter – shoot growth ceases, structural reorganisation occurs within the cells, and a series of physiological processes take place. These include the accumulation of starch, sugars, and phosphorus compounds, a reduction in the levels of growth stimulators, and an increase in the number of inhibitors (Opanasenko, 2005). As a result of metabolic changes, plants enter a state of dormancy, reaching a physiological condition that confers high frost resistance; however, this resistance may be insufficient in the absence of favourable weather conditions. For instance, during noticeable drought or cool, rainy weather in summer, trees may fail to complete their vegetative cycle adequately and may perish during frosts that trees cultivated under favourable summer conditions can withstand. It has been established that following drought periods, frost resistance decreases by 4-6°C (Kryvoshaka *et al.*, 2018).

Consequently, drought resistance is a crucial economically valuable trait of a variety, as it reflects adaptive properties to moisture deficiency and impacts the overall health of the plants, as well as their yield and fruit quality. Among fruit crops, peaches are classified as drought-resistant, characterised by an enhanced ability of their leaves to retain water, relatively rapid restoration of turgor after wilting, and the capacity to utilise low levels of available water in the soil (Smykov *et al.*, 2013). The resistance to drought is facilitated by a well-developed vascular system, primarily attributed to the organism's genetics, as well as the physiological, biochemical, and anatomical characteristics of the aerial organs (Liu, 2023). In this context, there is a significant reduction in moisture loss through transpiration and an increased heat resistance of the tissues, which in turn contributes to the overall high drought resistance of the organism (Bunchuk, 2013).

At the same time, to achieve high yields of market-quality produce, particularly under drought conditions, peaches require a substantial amount of water. Atmospheric precipitation constitutes the primary component of the water balance. Insufficient rainfall from May to August leads to significant crop losses, while temperature fluctuations and inadequate precipitation adversely affect plant growth and development (Silaev, 2003). Water serves as both a solvent and a medium for the movement and exchange of substances, and its high specific heat capacity helps stabilise plant temperatures (Kryvoshaka, 2012). When moisture is deficient, fruit-bearing plants cease to grow, their leaves and fruits wilt and drop, and the formation of generative buds diminishes, consequently reducing yields not only in the drought year but also in the following year (Fernandez *et al.*, 2020).

An analysis of the total precipitation from 2013 to 2023 reveals a clear trend of decreasing rainfall (Fig. 3). Previously, from 1961 to 1990, the average annual precipitation across Ukraine was 578 mm (Shevchuk, 2023); however, this figure has now dropped to 418 mm in the Kyiv Region. The year 2022 was notably the driest, with a total precipitation of 249 mm, representing a reduction of 67% compared to the long-term averages. A significant decline in rainfall has been observed since 2015 when the total was 301 mm. Moreover, not only is the total amount of precipitation decreasing, but it is also unevenly distributed throughout the growing season of the trees. A detailed month-by-month analysis indicates that the driest months are July and August, during which the future harvest is established.

Consequently, considering climate change – specifically the increase in active temperature accumulation, the reduction of minimum winter temperatures, and the development of frost-resistant peach varieties by both Ukrainian and foreign breeders – conditions are becoming favourable for cultivating this crop in the Forest-Steppe zone of Ukraine. The insufficient moisture during the growing season presents new challenges for researchers, particularly in establishing irrigation horticulture experiments in this area. It is essential to develop new methodological recommendations and provide scientific support for the establishment of perennial plantings, including peach orchards by both commercial farms and private amateur gardeners.

CONCLUSIONS

The analysis of various literary sources indicates that the peach is a widely cultivated drupe globally, with both the area under cultivation and yield continuously increasing. In contrast, Ukraine has experienced a reduction in cultivated area; however, the implementation of intensification elements has led to a 5.3-fold increase in yield, while the needs of the domestic market remain unmet. The primary objectives set for researchers and horticulturists involve expanding cultivated areas not only in the southern regions but also in more northern areas due to changing climatic conditions. Among the key factors facilitating the spread of peach cultivation into northern regions of Ukraine is the development of frost-resistant varieties that can adapt to unstable weather conditions during the winter-spring period. Additionally, the temperature regime plays a significant role, particularly the increase in active temperature accumulation during the spring-summer period, both within Kyiv Region and in other regions of Ukraine, allowing peaches and other heat-loving crops to grow and bear fruit uninterruptedly, as well as ensuring even ripening of the fruits.

At the same time, it has been established that the high temperatures and insufficient rainfall observed during the period 2013-2023 create conditions for the formation of dangerous phenomena in horticulture – air and soil droughts. Therefore, drought resistance is also an important characteristic of the crop and variety in particular, as it affects the overall condition of plants, yield, and fruit quality. Thus, considering the weather changes of recent years and the creation by breeders of new frost-resistant varieties, which has contributed to the shift in the distribution range of peach culture to more northern regions of Ukraine, it is necessary to prepare and implement special measures to adapt the horticultural industry to the cultivation of this crop in new regions for it.

It is recommended to start laying down experiments on irrigated horticulture and develop new methodological recommendations to provide scientific support for the establishment of perennial peach plantations in the conditions of the Right-Bank part of the Western Forest-Steppe of Ukraine.

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CONFLICT OF INTEREST

None.

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Передумови вирощування морозостійких сортів персика у правобережній частині Західного Лісостепу України

Анотація. Необхідність використання морозостійких сортів персика у зоні Лісостепу України обумовлена частими різкими коливаннями температури повітря у зимово-весняний період, а їх вирощування дозволить нівелювати вплив погодних умов для стабільного виробництва плодів цієї культури. Тому метою досліджень було проаналізувати перспективи вирощування персика (*Prunus persica* Mill) за інтенсивними технологіями в умовах зміни клімату. Проаналізувавши ситуацію з вирощування персика встановлено, що він є досить поширеною кісточковою культурою, як в Україні так і в світі. Виділено основні країни, що є лідерами по виробництву плодів персика: Китай, Італія, Туреччина, Греція та Іспанія. Не зважаючи на приріст валового виробництва (на 24 %) плодів персика у світі за 2013-2023 рр. відбулось і підвищення попиту на цю культуру, що провокує дефіцит і зростання рівня імпорту в Україні. За розрахунками із забезпечення науково-обґрунтованих річних норм споживання плодів персика виявлено, що нестача їх у виробництві становить 187 тис. т при нинішньому виробництві 11,2 тис. т. Виявлено фактори, що стримують розширення площ під персиковими насадженнями. Проте створення селекціонерами морозостійких сортів, придатних для вирощування в Лісостепу України, разом зі зміною погодних умов дають можливість для безпечного культивування персика в регіоні. Проведено аналіз погодних умов правобережної частини Західного Лісостепу України. Установлено, що за 2013-2023 рр. суттєво підвищилась сума активних температур, а 2023 рік відзначився максимальним значенням – 3777 °C. При цьому сума опадів знизилася на 58 % та становить всього 325 мм. Враховуючи погодні зміни і створення селекціонерами нових морозостійких сортів, що сприяло зміщенню ареалу поширення культури персика в північні регіони України, необхідна підготовка та реалізація спеціальних заходів щодо адаптації садівничої галузі до вирощування цієї культури у нових для неї регіонах з метою задоволення потреб внутрішнього ринку. Рекомендується розпочати закладання дослідів із зрошувального садівництва та розробити нові методичні рекомендації для забезпечення наукового супроводу при закладанні багаторічних насаджень персика в умовах правобережної частини Західного Лісостепу України

Ключові слова: *Prunus persica* Mill; продуктивність; ринок плодів; зміна клімату; інтенсивні технології; посухостійкість

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Impact of biopreparations on the phytopathological state of potato plants

Abstract. Given the frequent use of chemical agents for the control of potato diseases, it is crucial to explore protective measures that consider agroecological aspects. This study aimed to determine the impact of biological preparations on the development of late blight and alternariosis in potatoes. Research on the effects of biopreparations on the main diseases of potatoes was conducted over three years under field conditions at the Volyn State Agricultural Research Station of the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine. The experimental design, disease diagnosis, and assessment of the technical efficacy of biological preparations against potato diseases were performed according to established methodologies. The experiments revealed that the application of biopreparations under various conditions leads to a reduction in the intensity of late blight and alternariosis in potatoes, as well as contributing to the preservation of yield. Lower disease development and higher efficacy of biopreparations were observed

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in the context where the biodestructor Ekostern (1.2 L/ha) and the biopreparation MycoHelp (2.0 L/ha) were applied, alongside three rounds of plant spraying with various biological preparations – Agat-25K, Regoplant, PhytoHelp, and Stimpo. Among these, PhytoHelp, with an application rate of 1.0 L/ha, exhibited the highest technical efficacy. The use of biological preparations in different contexts increased potato tuber yield. Specifically, with the application of MycoHelp at 2.0 L/ha and the spraying of plants with various biological agents, the preserved yield ranged from 1.71 to 2.02 t/ha. The application of biopreparations alongside the use of Ekostern at 1.2 L/ha and MycoHelp at 2.0 L/ha contributed to yield increases across various treatments, ranging from 1.6 to 2.21 t/ha. The obtained results are deemed useful for enhancing the effectiveness of the integrated protection system for potatoes against specific diseases and for developing organic cultivation technologies for table potatoes on sod-podzolic soils

Keywords: potato blight; alternariosis; disease development; technical efficacy; potato tuber yield

INTRODUCTION

Biopreparations can provide a more environmentally safe and effective means of protecting plants from diseases due to their natural active components, which exert a lesser impact on the environment compared to chemical agents. Their application can help reduce the risk of soil and water resource contamination, as well as minimise the negative effects on beneficial organisms essential for maintaining ecological balance. Furthermore, biopreparations can decrease the risk of pathogen resistance development, a common occurrence with prolonged use of chemical treatments. In addition to their ecological benefits, biopreparations can significantly enhance crop yields and improve plant quality owing to their growth-promoting properties and ability to strengthen plant immunity. This is critically important for ensuring food security, as high yields and quality produce meet the population's needs and enhance economic stability within the agricultural sector. The study and implementation of biopreparations could be vital steps towards the development of sustainable agriculture and the introduction of new, more effective methods for combating phytopathogens.

M. Koch *et al.* (2020) highlighted the significance of potatoes (*Solanum tuberosum* L.) in agriculture due to their high yield potential and valuable nutritional properties, including minerals, vitamins, antioxidants, protein, and fibre. T. Deguchi *et al.* (2016) reported that global potato consumption is approximately 35 kg per person per year. They also found that optimal growing conditions for potatoes are in regions with average daily temperatures between 10 and 20°C. In Japan, as noted by the authors, plastic mulching is often used to accelerate planting and warm the soil more quickly. This practice is employed to achieve higher prices for early harvests, free up land for rice cultivation, and reduce the risk of late blight under conditions of heavy rainfall.

At the same time, according to T. Artyukh *et al.* (2022), the use of polyethylene film mulching in Ukraine is infrequent, despite the strategic importance of potatoes for the country's food security. As of 2021, Ukraine ranked fourth globally in potato production and second in per capita consumption at 139 kg. However, the authors highlighted that diseases affecting potatoes during growth and storage are among the key limiting factors for yield and quality.

According to M. Berhan (2021), late blight (caused by *Phytophthora infestans* (Mont.) de Bary) and alternariosis (caused by *Alternaria solani* (Ell. et Mart.) Sor.) are among the most prevalent potato diseases worldwide. S.K. Bomok & M.Y. Pikovskyi (2019) found that during storage, table potatoes often develop fungal rots such as dry fusarium, phoma, white, grey, and verticillium rots, as well as common scab and black scurf. These diseases reduce the quality of tubers, decreasing their dry matter and starch content. Research by S.K. Bomok *et al.* (2020) identified late blight and alternariosis as the most dangerous potato diseases in Ukraine. M.M. Kyryk *et al.* (2012) highlighted that late blight affects the above-ground parts of the potato plant and can also spread to tubers, while alternariosis causes leaf spot and stem necrosis.

R. Sharma *et al.* (2020) investigated the widespread use of chemical pesticides for potato disease control, highlighting the increasing pesticide load on the biosphere. They identified a lack of high-yielding varieties and the prevalence of diseases, particularly alternariosis, as major factors limiting potato yield. J. Yuen (2021) also emphasised the significant impact of *Phytophthora infestans* on food security. Due to the prolonged use of fungicides for disease control, many potato varieties require continuous chemical treatments or possess disease-resistance genes.

Given the challenges posed by chemical pesticides and the prevalence of potato diseases, there is a pressing need to explore more sustainable disease management strategies. Biological control, utilising beneficial microorganisms, offers a promising alternative. Z. Gao *et al.* (2017) demonstrated the efficacy of soil microorganisms in producing volatile organic compounds that can influence plant growth and enhance resistance to pathogens, including grey mould and late blight.

Numerous scientific studies have demonstrated the efficacy of biological control agents in managing potato diseases. Notably, isolates of *Bacillus amyloliquefaciens* and *Bacillus subtilis* have exhibited antifungal activity exceeding 50% against a broad spectrum of phytopathogenic fungi, including *Alternaria alternata*, *Rhizoctonia solani*, *Fusarium oxysporum* and *Fusarium verticillioides*, while simultaneously promoting plant growth (Azeem *et al.*, 2022).

J. Zhang *et al.* (2023) investigated the efficacy of the strain of *Bacillus subtilis* H17-16, isolated from healthy potato roots, in controlling potato late blight caused by *Phytophthora infestans*. The study found that strain H17-16 inhibited the growth of *P. infestans* mycelium and sporangia, induced disease resistance in potatoes, and promoted plant growth. Furthermore, field and post-harvest applications of H17-16 effectively reduced the incidence of potato late blight, and its combination with chitosan or chemical fungicides yielded better results than H17-16 alone. Additionally, another stain of *Bacillus subtilis*, EG21, demonstrated antagonistic activity against both *Phytophthora infestans* and *Rhizoctonia solani in vitro*.

The research aims to establish the impact of biological preparations on the development of late blight and alternariosis in potatoes.

MATERIALS AND METHODS

Research on the impact of biopreparations on the development of late blight and alternariosis in potatoes was conducted from 2021 to 2023 at the Volyn State Agricultural Research Station of the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine (NAAS). The soil at the experimental site is characterised as sod-podzolic loamy sand. The potato variety Partner was cultivated.

The experimental design, disease diagnostics, and determination of the technical efficacy of biological preparations against potato diseases were carried out according to accepted methodologies (Kononuchenko, 2002; Kyryk *et al.*, 2012). The following biopreparations were used in the studies:

1. Ekostern Classic (bacteria of the genera *Bacillus, Paenibacillus, Azotobacter, Enterobacter, Enterococcus, Agrobacterium*, and fungi of the genus *Trichoderma*; total viable effective microorganisms not less than 2.5-5.0 × 10^9 CFU/cm^3);
2. MycoHelp (a mixture of cells from *Bacillus subtilis, Azotobacter, Enterobacter, Enterococcus*, and fungi of the genus *Trichoderma*; total viable effective microorganisms not less than 1.0 × 10^9 CFU/g);
3. PhytoHelp (a concentrated mixture of live natural bacteria *Bacillus subtilis* – not less than 4 × 10^9 CFU/cm^3);
4. Agat-25K (based on soil bacteria *Pseudomonas aureofaciens* H-16; cultural substance of inactivated bacteria, titre 5-8 × 10^{10} before inactivation, bioactive substances from plant sprouts, containing macro- and micronutrients, flavonoids, as well as active fractions of pine extract);
5. Regoplant (contains metabolites of micromycetes, which are biologically active substances at a concentration of 0.3 g/L, saturated and unsaturated fatty acids (C14-C28), polysaccharides, includes 15 amino acids, as well as analogues of phytohormones of cytokinin and auxin nature, micronutrients at a concentration of

1.75 g/L, potassium salt of alpha-naphthyl acetic acid – 1 mg/L, and Aversectin C);

6. Stimpo (metabolites of micromycetes, which are biologically active substances – 1 g/L, saturated and unsaturated fatty acids (C14-C28), polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature, micronutrients at a concentration of 0.014 g/L, and Aversectin C).

In this study, mustard was used as a green manure crop, followed by incorporation into the soil either without a biodestructor or after spraying with the biodestructor Ecostern at a rate of 1.2 L/ha (Table 1).

Table 1. Experimental design for studying the impact of biological preparations on the development of potato diseases

Factor A	Factor B
Background 1. No biodestructor. Incorporation into the soil of MycoHelp, 2.0 L/ha	1. Control (no foliar application of biological preparations)
	2. Agat-25K, 100 mL/ha
	3. Regoplant, 50 mL/ha
	4. PhytoHelp, 1.0 L/ha
	5. Stimpo, 15 mL/ha
Background 2. Ecostern 1.2 L/ha. Incorporation into the soil of MycoHelp, 2.0 L/ha	1. Control (no foliar application of biological preparations)
	2. Agat-25K, 100 mL/ha
	3. Regoplant, 50 mL/ha
	4. PhytoHelp, 1.0 L/ha
	5. Stimpo, 15 mL/ha

Source: developed by the authors

Subsequently, the impact of biopesticides was studied following a soil application of MycoHelp at a rate of 2.0 L/ha (in spring, before cultivation) and three foliar spray applications of Agat-25K, Regoplant, PhytoHelp, and Stimpo on potato plant development, late blight, and alternariosis. The study adhered to the ethical guidelines outlined in the Convention on Biological Diversity (1992).

Potato plants were sprayed at the following growth stages: when the canopy closed, at budding, and after flowering.

RESULTS AND DISCUSSION

Analysis of the results revealed that in Background 1 (soil application of MycoHelp, 2.0 L/ha, and three foliar spray applications with various biological agents), late blight development on the treated plots ranged from 6.8% to 9.2%, which was 5.0-7.4% lower compared to the control (Table 2). The lowest disease incidence was observed in treatments with PhytoHelp, 1.0 L/ha (6.8%), and Agat-25K, 100 mL/ha (7.9%). The development of late blight was also reduced with the use of Stimpo, 15 mL/ha, and Regoplant, 50 mL/ha, where it was 8.9% and 9.2%, respectively. In the study, the reduction in alternariosis development was 6.6-9.4% with a control disease incidence of 17.5%. The highest value was observed when using PhytoHelp at a rate of 1.0 L/ha. The development of alternariosis was practically the same with the application of Regoplant, Stimpo, and Agat-25K, with values of 10.9%, 10.8%, and 10.5%, respectively. The technical efficacy of the tested biopreparations against late blight was 35.2-52.1%. This figure against alternariosis reached 37.7-53.7%. The most effective protection of potato plants from diseases was provided by spraying with PhytoHelp at a rate of 1.0 L/ha.

Table 2. Efficacy of biological preparations against potato diseases (average for 2021-2023)

No.	Experimental variant	Disease development, %		Technical efficacy, %	
		Late blight	Alternariosis	Late blight	Alternariosis
Background 1. Incorporation into the soil of MycoHelp, 2.0 L/ha					
1.	Control (no foliar application of biological preparations)	14.2	17.5	-	-

Table 2, Continued

No.	Experimental variant	Disease development, %		Technical efficacy, %	
		Late blight	Alternariosis	Late blight	Alternariosis
2.	Agat-25K, 100 mL/ha	7.9	10.5	44.0	40.0
3.	Regoplant, 50 mL/ha	9.2	10.9	35.2	37.7
4.	PhytoHelp, 1.0 L/ha	6.8	8.1	52.1	53.7
5.	Stimpo, 15 mL/ha	8.9	10.8	37.3	38.3
	LSD_{05}	0.31	0.24		
Background 2. Ecostern 1.2 L/ha. Incorporation into the soil of MycoHelp, 2.0 L/ha					
1.	Control (no foliar application of biological preparations)	12.8	14.1	-	-
2.	Agat-25K, 100 mL/ha	6.5	8.1	49.2	42.5
3.	Regoplant, 50 mL/ha	7.9	8.5	38.3	39.7
4.	PhytoHelp, 1.0 L/ha	5.5	5.8	54.7	58.8
5.	Stimpo, 15 mL/ha	7.8	8.4	39.0	40.0
	LSD_{05}	0.21	0.26		

Source: developed by the authors

In treatment, variants in Background 2, where Ecostern (1.2 L/ha) was applied to the soil along with MycoHelp (2.0 L/ha) and foliar sprays of biopreparations during the potato growing season, late blight development decreased to 5.5-7.9% compared to the control, where the disease incidence was 12.8% (Table 2). The trend observed in Background 1 was also evident in Background 2, namely the ability of PhytoHelp (1.0 L/ha) and Agat-25K (100 mL/ha) to provide the maximum reduction in late blight development. In the variants in Background 2, the lowest alternariosis development was also observed in Variant 4 with PhytoHelp treatment, where the value was 5.8%, while in variants treated with Agat, Stimpo, and Regoplant, the value was 8.1%, 8.4%, and 8.5%, respectively.

The technical efficacy of biopesticides against late blight in Background 1 ranged from 35.2% to 52.1%, while against alternariosis, this figure was 37.7-53.7% (Table 2). For both diseases, PhytoHelp at a rate of 1.0 L/ha was the most effective. Meanwhile, in Background 2, with the application of Ecostern (1.2 L/ha), an increase in technical efficacy was observed when using biological treatments. Specifically, this figure against late blight was 38.3-54.7%, and against alternariosis – 39.7-58.8%. The highest efficacy was observed in variants with foliar application of PhytoHelp.

The application of biological preparations on different backgrounds increased potato tuber yield (Table 3). In the control, the potato tuber yield was 10.62 t/ha in Background 1 with a soil application of MycoHelp at 2.0 L/ha, while in the control of Background 2 with the use of Ecostern at 1.2 L/ha and MycoHelp at 2.0 L/ha, the yield was 11.46 t/ha. In Background 1, with a soil application of MycoHelp at 2.0 L/ha and foliar application of various biological agents, the harvested yield was 1.71-2.02 t/ha. Comparing the variants of foliar treatment of potato plants with biopreparations in Background 1, it should be noted that they differed little in potato tuber yield, which was 12.33-12.64 t/ha. The highest yield was established in Variant 4 with a soil application of MycoHelp (2.0 L/ha) and three-time treatment with PhytoHelp (1.0 L/ha).

Table 3. Potato tuber yields under the application of biological preparations (average for 2021-2023)

Experimental variant	Yield, t/ha
Background 1. Incorporation into the soil of MycoHelp, 2.0 L/ha	
1. Control (no foliar application of biological preparations)	10.62
2. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Agat-25K at 100 mL/ha during the growing season	12.35
3. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Regoplant at 50 mL/ha during the growing season	12.33

Table 3, Continued

Experimental variant	Yield, t/ha
4. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of PhytoHelp at 1.0 L/ha during the growing season	12.64
5. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Stimpo at 15 mL/ha during the growing season	12.42
Background 2. Ecostern 1.2 L/ha. Incorporation into the soil of MycoHelp, 2.0 L/ha	
1. Control (no foliar application of biological preparations)	11.46
2. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Agat-25K at 100 mL/ha during the growing season	13.08
3. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Regoplant at 50 mL/ha during the growing season	13.39
4. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of PhytoHelp at 1.0 L/ha during the growing season	13.67
5. Incorporation into the soil of MycoHelp at 2.0 L/ha + three foliar applications of Stimpo at 15 mL/ha during the growing season	13.06
LSD_{05} Factor A Factor B AB	0.07 0.11 0.15

Source: developed by the authors

The application of biological preparations on a background of Ecostern at 1.2 L/ha and MycoHelp at 2.0 L/ha contributed to a yield increase of 1.6-2.21 t/ha in various variants.

In Background 2, tuber yields for variants with foliar applications of biopreparations ranged from 13.06 to 13.67 t/ha. Similar to Background 1, the highest yield was obtained in Variant 4 (soil application of MycoHelp at 2.0 L/ha + three foliar applications of PhytoHelp at 1.0 L/ha during the growing season). Variant 3, with a soil application of MycoHelp at 2.0 L/ha and three foliar applications of Regoplant at 1.0 L/ha, had a slightly lower tuber yield of 13.39 t/ha. Meanwhile, Variants 1 (MycoHelp at 2.0 L/ha and Agat-25K at 100 mL/ha) and 5 (MycoHelp at 2.0 L/ha and Stimpo at 15 mL/ha) showed virtually no difference in tuber yield, with values of 13.08 and 13.06 t/ha, respectively.

In general, scientific literature presents findings on the varying potential of biological products in enhancing plant productivity and limiting the development of potato diseases, which depend on numerous factors requiring further study (Osei *et al.*, 2022). The current research has demonstrated the effectiveness of both biological products applied to sod-podzolic soil and those applied as foliar treatments.

The results presented indicate that the application of biopreparations under various conditions leads to a reduction in the severity of late blight and alternariosis in potatoes and contributes to increased yield. Lower disease incidence and higher efficacy of biological products were observed when a biodestructor, Ecostern (1.2 L/ha), and a biopreparation, MycoHelp (2.0 L/ha), were applied to the soil, followed by three foliar sprays of different biological agents – Agat-25K, Regoplant, PhytoHelp, and Stimpo. Among these, PhytoHelp (based on *B. subtilis* bacteria) at a rate of 1.0 L/ha exhibited the highest technical efficacy. The findings of A. Saba *et al.* (2022) confirm the effectiveness of biological control agents against potato diseases using various microorganisms. Specifically, isolates of *Bacillus amyloliquefaciens* and *Bacillus subtilis* demonstrated antifungal activity (over 50%) against a broad spectrum of phytopathogenic fungi, including *Alternaria alternata*, *Rhizoctonia solani*, *Fusarium oxysporum*, and *Fusarium verticillioides*, and also promoted plant growth.

In a study conducted by L. Stridh *et al.* (2022) under both greenhouse and field conditions, the impact of various biocontrol agents, such as *Pythium oligandrum*, *Bacillus subtilis*, and the biopreparations *Polygandron* and *Serenade*, was evaluated for the control of early blight in potatoes. These agents were used individually, in combination with each other, or conjunction with synthetic fungicides. In greenhouse conditions, the application of biocontrol agents led to a significant reduction in infection by *A. solani*, achieving efficacy rates of 50% to 95%. However, in field conditions, this effect was much less pronounced, indicating the difficulty of achieving similar results in open fields due to the influence of various external factors. In light of these results, the authors of this article conducted their own field trials, which confirmed the effectiveness of bioproducts not only in controlling common potato diseases but also in increasing overall tuber yield. This approach highlights the potential of integrating biological agents with other control methods for a comprehensive approach to improving crop productivity.

A. Alfiky *et al.* (2022) reported that EG21 metabolites exhibited a strong zoosporecidal effect on *P. infestans*. The inhibitory effect against *P. infestans* and *R. solani* infections was confirmed on potato leaves and tubers, respectively. The antagonistic potential of *Trichoderma* spp. strains against *P. infestans* were evaluated *in vitro* by A. Alfiky *et al.* (2023). In dual culture, *P. infestans* growth was suppressed by 53% to 95%.

Overall, *Pseudomonas* spp. strains exhibited varying levels of biocontrol activity against *P. infestans* in potato tuber bioassays. For instance, a study by G. Léger *et al.* (2021) demonstrated that strains of *P. orientalis* and *P. yamanorum* significantly reduced the level of late blight, exhibiting a high level of biocontrol properties. Conversely, strains of *P. synxantha* were ineffective in inhibiting pathogen growth, highlighting the need for careful strain selection for the control of *P. infestans*. These results also indicate potential variations among strains of the same genus, requiring further research to identify the most effective biocontrol agents. Moreover, in addition to the individual characteristics of strains, environmental conditions can also influence their ability to effectively protect plants from pathogens.

S. Kumar *et al.* (2023) conducted pot experiments to evaluate the efficacy of three biocontrol agents – *Trichoderma viride*, *Bacillus subtilis* and *Pseudomonas fluorescens* – individually and in a consortium, for promoting potato growth and activating defence mechanisms against *A. solani*. Results indicated that the application of a consortium of the three microorganisms significantly enhanced plant growth compared to other treatment methods. Potato plants treated with the triple-microbe consortium exhibited a substantial reduction in disease incidence compared to control plants inoculated with *A. solani* but left untreated.

N. Metz & H. Hausladen (2021) investigated the potential of *Trichoderma* spp. against *A. solani* under laboratory, greenhouse, and field conditions. They found that the choice of a specific *Trichoderma* strain can significantly influence the outcome, as even strains of the same species demonstrated varying levels of efficacy. However, a significant reduction in alternariosis in the field was recorded in only one of the four years of field trials. Furthermore, the authors were unable to find a significant correlation between *in vitro*, *in vivo*, and field data within a single year, highlighting the need for field trials to assess real-world efficacy.

Thus, both in the present research and in studies conducted by other researchers, a positive effect of biopreparations on reducing the incidence of diseases affecting table potatoes has been established. In particular, a decrease in the infectious load on plants and an increase in their resistance to pathogens have been observed. This not only improves the quality of the yield but also reduces the reliance on chemical protection agents.

CONCLUSIONS

The results of the research indicate that the use of biopreparations has a positive impact on the development of both late blight and alternariosis in potatoes. The greatest efficacy was demonstrated by the product PhytoHelp at a dosage of 1.0 L/ha, which reduced the level of late blight infestation to 5.5% and alternariosis to 5.8%, in conjunction with the application of Ekostern at 1.2 L/ha. Overall, the technical efficacy of the investigated products against late blight reached 54.7%, while against alternariosis, it reached 58.8%. Other biopreparations also contributed to the reduction of disease development, although their effectiveness was somewhat lower.

The application of biopreparations also contributed to increased potato yields. When using MycoHelp at a rate of 2.0 L/ha in combination with PhytoHelp at 1.0 L/ha, yields reached 13.67 t/ha, which is 2.21 t/ha higher than the control. Similarly high yield results were obtained with other biopreparations such as Agat-25K and Stimpo, however, PhytoHelp demonstrated the most consistent results.

The lowest disease development was observed in treatments where the biodestructor Ecostern (1.2 L/ha) and the biopreparation MycoHelp (2.0 L/ha) were applied, followed by foliar sprays with Agat-25K, Regoplan, PhytoHelp, and Stimpo at various growth stages. PhytoHelp, at a rate of 1.0 L/ha, demonstrated the highest technical efficacy, resulting in a yield increase of 2.21 t/ha. Thus, the research confirmed the high efficacy of biopreparations in controlling major potato diseases, as well as their positive impact on yield. This indicates the feasibility of their use in potato production. The results obtained suggest the need for further studies on the effects of biopreparations on different potato varieties and other crops. Additionally, the long-term effects of biopreparations on the preservation of agroecosystems should be investigated. It is also important to study the impact of these products on other pathogenic organisms that may affect potatoes. Research into the efficacy of biopreparations in other soil and climatic zones is promising.

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CONFLICT OF INTEREST

None.

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Вплив біопрепаратів на фітопатологічний стан рослин картоплі

Анотація. З огляду на часте застосування хімічних засобів для контролю хвороб картоплі, важливо шукати можливості захисту з урахуванням агроекологічних аспектів. Метою роботи було визначення впливу біологічних препаратів на розвиток фітофторозу та альтернаріозу картоплі. Дослідження впливу біопрепаратів на розвиток основних хвороб картоплі проводили протягом трьох років у польових умовах Волинської державної сільськогосподарської дослідної станції Інституту картоплярства Національної академії аграрних наук. Постановку експериментів, діагностику хвороб, визначення технічної ефективності біологічних препаратів проти захворювань картоплі проводили за загальноприйнятими методиками. Експериментами встановлено, що застосування біопрепаратів на різних фонах призводить до зниження інтенсивності розвитку фітофторозу та альтернаріозу картоплі, а також сприяє збереженню врожаю. Нижчий розвиток хвороб і вищу ефективність біопрепаратів відмічено на фоні, де вносили біодеструктор Екостерн (1,2 л/га), біопрепарат Мікохелп (2,0 л/га) та здійснювали трьох разові обприскування рослин різними біологічними препаратами – Агат-25К, Регоплант, Фітохелп і Стимпо. При цьому найвищою технічною ефективністю характеризувався Фітохелп з нормою витрати 1,0 л/га. Використання біологічних препаратів на різних фонах забезпечувало зростання врожайності бульб картоплі. Зокрема за застосування Мікохелп 2,0 л/га та обприскуванням рослин різними біологічними засобами збережених урожай становив 1,71-2,02 т/га. Внесення біопрепаратів на фоні використання Екостерн 1,2 л/га та Мікохелп, 2,0 л/га сприяло зростанню врожайності у різних варіантах від 1,6 до 2,21 т/га. Отримані результати доцільно використовувати для підвищення ефективності інтегрованої системи захисту картоплі від окремих хвороб і розробки органічних технологій вирощування картоплі столової на дерново-підзолистих ґрунтах

Ключові слова: фітофтороз картоплі; альтернаріоз; розвиток хвороб; технічна ефективність; урожайність бульб картоплі

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Density of soil composite composition in a changing magnetic field

Abstract. The advancement of technical means for determining soil density in precision (controlled) agriculture necessitates the enhancement of non-destructive flow interaction methods. There is also a need to improve methods for assessing soil density, as existing deviations from optimal values adversely affect the yield of agricultural crops. This research aims to establish the density of the composites in the granulometric composition of soil by determining the self-induction voltage in a changing magnetic field. The research methods are adapted to determine the relationships of Larmor precession under variable inductive current for the density of each composite in the granulometric soil composition. Experimental investigations were conducted by measuring the self-induction voltage of a solenoid acting as a sensor for each of the composites located within the core. The processing of experimental results was carried out according to the principles of mathematical statistics and probability theory, using approximations in the

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Excel and Statistica software packages. Based on the results of the experimental investigations, models of the relationships between the density ρ (1.0-1.5 g/cm^3) of soil composites and the self-induction voltage ε_L = 184-192 mV, with a generator voltage of 5 V and determination coefficients R^2 = 0.95-0.99, have been established. These models enable the assessment of soil density with high accuracy, thereby facilitating the optimisation of agronomic processes. It has been determined that these models can be used with a high degree of reliability as calibration characteristics for the design of technical means for flow-based non-destructive measurement of the density of the main soil types in Ukraine. Furthermore, it has been identified that future research should focus on a more in-depth investigation of the relationships between magnetic permeability and the agrophysical characteristics of soil within the locally defined inductive field of the sensor (solenoid). An applied aspect of the obtained results is the further development of adaptive machinery and monitoring systems for soil conditions, aimed at achieving optimal cultivation indicators, as well as their utilisation by research institutions and instrument-making enterprises

Keywords: soil density; magnetic permeability; self-induction; magnetisation; Larmor precession

INTRODUCTION

Determining soil density in a variable magnetic field is crucial for enhancing the precision of agrophysical characteristic measurements, which directly impacts the efficiency of agricultural processes. This method enables flow-based, non-destructive assessment of soil conditions, facilitating high-speed, intelligent cultivation and monitoring of physicochemical properties. It contributes to the optimisation of cultivation technologies, increased yields, and reduced risks of land degradation. Furthermore, this research opens up new avenues for the development of adaptive machines and control systems that utilise modern methods of continuous non-destructive soil condition assessment.

Research by G. Baranov *et al.* (2022) indicates that modern agricultural technologies are based on the use of intelligent systems for high-quality flow-based soil condition monitoring and the adaptation of machine components to achieve the desired agrophysical parameters, particularly soil density, during pre-sowing cultivation.

The normative requirements for pre-sowing soil cultivation, particularly for sugar beet, are established by DSTU 4819:2007 (2009). According to this standard, the depth of the loosened layer, depending on soil moisture, should be between 2.5 and 4 cm across the entire width of the mechanised unit and should not deviate from the set value. The density of the seedbed should be between 1.2 g/cm^3 and 1.3 g/cm^3. Deviations in soil density from the optimum lead to reduced yields. For example, experimental studies by S. Kartashov *et al.* (2012) have shown that deviations in soil density of 0.1...0.3 g/cm^3 (from the optimum) result in a decrease in yield, particularly for sugar beet, by 20-40%.

The implementation of modern sugar beet cultivation technologies using precision farming methods and electronic maps, as proposed by M. Ivaniuta *et al.* (2023), should guarantee flow-based monitoring of soil density in both time and space, considering its compositional makeup, and allow for corresponding adjustments in the operation of farming implements.

The impact of soil compositional composition on density during flow-based monitoring using electronic devices has not been sufficiently studied. According to J. Ruehlmann *et al.* (2020) and P. Panagos *et al.* (2024), the solid portion of soil is primarily composed of "physical clay" (aluminium oxide) and "physical sand" (silicon dioxide), which are classified as diamagnets and paramagnets, respectively.

Existing methods for measuring soil agrophysical characteristics, as exemplified by the research of M. Abdulraheem *et al.* (2024), rely on the soil's ability to alter its dielectric permittivity between submerged electrodes depending on its condition. These methods are effective for determining parameters such as moisture content, temperature, and cation exchange capacity, and are widely used in agricultural monitoring tools. However, despite the success of these methods in measuring these indicators, they primarily focus on agrochemical properties, neglecting other important characteristics such as soil density, which can be determined through interactions with a changing magnetic field.

In the research conducted by M. Zaouche *et al.* (2017), it was noted that to achieve results in determining agrophysical parameters using non-destructive flow-based methods, the interaction of an electromagnetic field with the soil is utilised. These methods are based on studies of eddy currents and reflectometry (radar sensing) which are applied in soil profiling tools and the determination of soil horizons.

Measurements of soil magnetic susceptibility, as proposed by F. Shirzaditabar & R.J. Heck (2022), are widely used to identify zones with elevated concentrations of contaminants. This approach allows for the effective determination of the content of ferromagnetic minerals of anthropogenic origin, such as iron oxides and heavy metals, commonly found in contaminated soils. Due to its sensitivity to changes in magnetic properties, this method is useful for environmental monitoring, however, its application is primarily limited to the detection of contamination, requiring further development for addressing agricultural tasks.

Promising directions for determining soil density, considering its compositional makeup, were proposed in the research of N. Asgari *et al.* (2018), M.O. Kanu *et al.* (2014) and S. Ayoubi *et al.* (2018), where the adaptation of Larmor precession methods for analysing the interaction of a non-homogeneous magnetic field with soil is considered. This approach involves using induction measurement methods to convert the electronic signal into electrical quantities, opening up new possibilities for the precise determination of the physical properties of soil. This is a relevant area of research, as such methods can significantly improve the accuracy of soil monitoring and cultivation.

This study aimed to investigate the dependencies of the density of the soil's composite composition on the self-induction voltage in a changing magnetic field.

MATERIALS AND METHODS

Experimental research was conducted in 2024 at the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine, a research institution located in Kyiv, Ukraine. For the study, soil composition samples optimal for sugar beet cultivation were selected, specifically sandy loam, light loamy, medium loamy, and heavy loamy.

The essence of the method lies in the fact that when a voltage from a generator, ε, is applied to a solenoid with inductance L, a phase shift in the current occurs due to Larmor precession (the interaction of the magnetic field with the core), as shown in Figure 1. The characteristic of the phase shift of the current can be determined from known values of inductive reactance, X_L, by measuring the current, I, flowing through the solenoid (Fig. 2).

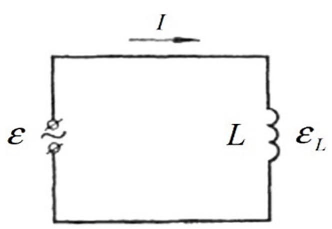

Figure 1. Diagram of connecting a solenoid (coil) with inductance L to an alternating current source

Note: ε – generator voltage, ε_L – self-induction voltage, L – solenoid inductance, I – current

Source: J. Rawlins (2000)

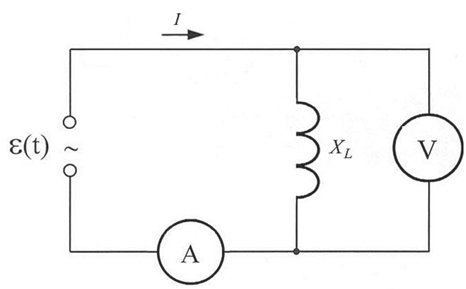

Figure 2. Diagram for determining the inductive reactance X_L

Note: ε – generator voltage, e_L – self-induction voltage, L – solenoid inductance, I – current

Source: J. Rawlins (2000)

Inductive reactance, X_L, depends on the rate of change of current, ω, and the magnetic permeability of the core, which is proportional to the inductance L (Rawlins, 2000; Chakraborty & Majumdar, 2023):

$$X_L = \omega \cdot L, \tag{1}$$

where ω is the angular frequency, *rad/s*; L is the inductance of the solenoid (coil), *H*. Alternatively:

$$X_L = 2\pi f L, \tag{2}$$

where f is the frequency of the alternating current, *Hz*. The inductance of the solenoid can be calculated from known characteristics of the construction and magnetic permeability of the core (Rawlins, 2000):

$$L = \mu \cdot \mu_0 \cdot \frac{N^2 \cdot S}{l}; \tag{3}$$

where S is the cross-sectional area of the core, mm^2, μ is the magnetic permeability of the core, μ_0 is the magnetic permeability of the vacuum, $\mu_0 = 4\pi \cdot 10^{-7}$, N is the number of turns; l is the length of the solenoid, m.

The current in the solenoid, according to Ohm's law, can be found by determining the self-induction voltage ε_L (Fig. 2):

$$I = \frac{\varepsilon_L}{X_L}. \tag{4}$$

The power P consumed by the solenoid in an alternating current circuit can be calculated by determining the self-induction voltage ε_L and the current I (Rawlins, 2000):

$$P = \varepsilon_L \cdot I. \tag{5}$$

The inductive reactance of the solenoid X_L, Ω, expressed through the magnetic permeability μ:

$$X_L = 2\pi \cdot f \cdot \mu \cdot \mu_0 \cdot \frac{N^2 \cdot S}{l}. \tag{6}$$

The power consumption P, W, used for the interaction of the solenoid's induced current with the soil in the core is determined by the relationship:

$$P = \frac{{\varepsilon_L}^2}{2\pi f \mu \mu_0 \frac{N^2 S}{l}}. \tag{7}$$

To establish the relationships between the agrophysical parameters of the soil, it is necessary to conduct research on magnetic permeability at a set magnetisation time of the core of a given density for each soil composition optimal for growing sugar beets (Table 1).

Table 1. Classification of the soil sample compositions by granulometric structure (based on N.A. Kachinsky)

Name by granulometric composition	Content of "physical clay" / "physical sand" (particles < 0.01 mm/particles> 0.01 mm), %
Sandy loam	10/20
Light loam	20/30
Medium loam	30/45
Heavy loam	45/60

Source: developed by the authors based on DSTU 4819:2007 (2009)

Optimal indicators and methods for determining and controlling soil density for sugar beet cultivation have been established by research and relevant regulatory acts, namely: DSTU ISO 11272:2001 (2001), DSTU 4362:2004 (2005), DSTU 11277:2005 (2005), DSTU 4819:2007 (2009), DSTU 7846:2015 (2016).

The soil compositions from Table 1 were pre-cleaned, dried to a moisture level of 0.5-1%, and weighed with an accuracy of 0.01 grams. The density range of 1.0-1.5 g/cm³ was artificially achieved by pressing each composition into a 50 ml volume. For conducting experimental studies, the instruments and equipment depicted in Figure 3 were used. The AC generator 9 was connected to a laboratory power supply with stabilised voltage and a coil 11 (solenoid) functioning as a sensor. The frameless coil consists of 50 turns with a diameter of 32 mm and a length of 65 mm. The AC generator was set to a frequency of 600 kHz, with the ability to generate amplitudes of 3, 4, and 5 V (Fig. 4).

Figure 3. Instruments and equipment for conducting experimental research

Note: 1 – FNIRSI 1013D oscilloscope (FNIRSI Technology Co., Ltd, China), 2 – scales (Digital Pocket, China), 3 – multimeter – DT838 (Avrora LTD, Ukraine), 4 – probes, 5 – sandy loamy soil composition; 6 – light loamy soil composition; 7 – medium loamy soil composition; 8 – heavy loamy soil composition; 9 – AC generator (author's development), 10 – syringe for forming soil composition samples (Jiangsu Zhengkang Medical Apparatus Co., LTD., China), 11 – measuring coil (solenoid) (author's development)

Source: photo by authors

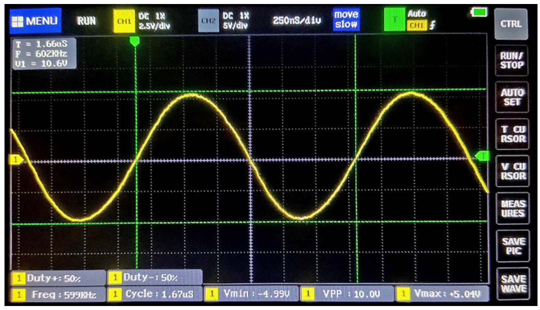

Figure 4. Oscillogram of the alternating current (voltage) of the generator *e*

Note: FNIRSI 1013D oscilloscope

Source: photo by authors

For the experimental research, a classical approach to planning was chosen, in which each factor is changed in turn until a partial maximum is determined while the values of other factors remain constant. The object of the experimental research is the relationships between magnetic permeability and the compositional composition of the soil, which is established by analytical studies of the interactions of the magnetic field with molar mass. The scientific hypothesis is the presence of relationships between the density of soil compositions and the inductive current power of the solenoid under the influence of magnetic flux interactions.

RESULTS AND DISCUSSION

In the experimental research, a *first-order* factorial design was used with independent variables $x_1 - x_6$ (density ρ) and $y_1 - y_3$ (generator voltage ε) and dependent variable z_n (self-induction voltage ε_L). (Table 2).

Table 2. Results of experimental studies of self-induction voltage ε_L

Density, g/cm³		Self-induction voltage ε_L, mV (z_n)			
x	*ρ*	Sandy loamy	Light loamy	Medium loamy	Heavy loamy
Generator voltage *ε* (y_1=3 V)					
x_1	1.0	59.3	58.5	58.3	59.2
x_2	1.1	59.3	58.5	58.8	58.8
x_3	1.2	59.0	59.2	59.2	58.7
x_4	1.3	59.3	58.9	59.2	58.5
x_5	1.4	59.0	57.7	58.3	57.3
x_6	1.5	57.6	57.0	57.9	56.9
Generator voltage *ε* (y_2=4 V)					
x_1	1.0	156.2	154.4	156.1	155.3
x_2	1.1	156.1	155.5	154.0	154.5
x_3	1.2	155.0	154.5	155.1	154.0
x_4	1.3	153.8	153.0	154.3	153.3
x_5	1.4	151.8	151.8	152.0	153.4
x_6	1.5	151.2	150.4	151.8	150.2

Table 2, Continued

Density, g/cm³		Self-induction voltage ε_L, mV (z_n)			
x	ρ	Sandy loamy	Light loamy	Medium loamy	Heavy loamy
Generator voltage ε (y_3=4 V)					
x_1	1.0	190	189	191	190
x_2	1.1	190	190	191	190
x_3	1.2	189	189	190	188
x_4	1.3	188	188	189	188
x_5	1.4	186	187	188	186
x_6	1.5	185	184	187	185

Source: developed by the authors

The results of the study of the generator amplitude of 3V determined the range of variation of the self-induction voltage ε_L = 59.3-56.9 mV for density values ρ=1.0-1.5 g/cm³ of all soil compositions placed in the solenoid core. It was established that with an increase in the density ρ of soil composition samples, the self-induction voltage ε_L decreased, which is justified by the increase in the specific energy costs of the induction field. For soil compositions, with an increase in their density ρ from 1.0 g/cm³ to 1.5 g/cm³, the self-induction voltage $\Delta\varepsilon_L$ decreased by: sandy loamy – 1.7 mV; light loamy – 2.2 mV, medium loamy – 1.3 mV and heavy loamy – 2.3 mV.

For the generator amplitude of 4V, the change in self-induced voltage ε_L was determined to be 150.2-156.2 mV for all soil compositions placed in the solenoid core within the density range ρ=1.0-1.5 g/cm³. It was established that with an increase in the density ρ of soil composition samples, the self-induction voltage ε_L decreased, which is justified by the increase in the current in the sensor (solenoid) supply circuit. For soil compositions, with a change in their density ρ from 1.0 g/cm³ to 1.5 g/cm³, the self-induction voltage $\Delta\varepsilon_L$ changed by: sandy loamy – 5.0 mV; light loamy – 5.1 mV, medium loamy – 4.3 mV and heavy loamy – 4.9 mV.

Experimental investigations using a generator amplitude of 5V revealed a range of self-induction voltage ε_L from 185 to 191 mV for all soil composition densities ρ between 1.0 and 1.5 g/cm³. Results indicated that as the density ρ of soil composition samples increased, the self-induction voltage ε_L decreased, attributable to the increased induction current required to generate the induction field. For soil compositions, as their density ρ increased from 1.0 g/cm³ to 1.5 g/cm³, the self-induction voltage $\Delta\varepsilon_L$ decreased by: sandy loamy – 5 mV; light loamy – 6 mV; medium loamy – 4 mV; and heavy loamy – 5 mV.

To investigate the influence of various factors based on the results of experimental studies, mathematical models of the parameters of their interrelationships have been developed, along with the determination of their numerical values. The mathematical model was constructed using a set of factors that characterise the conditions under which measurements were taken for each soil composition, following the current plan.

Based on the experimental results, functional relationships between self-induced induction and soil composition density (magnetic permeability) were established. Graphs were plotted to provide a preliminary visual analysis of the interactions of induction current power, resulting in second-degree polynomial equations for each soil composition (Fig. 5):

- sandy loamy:

$$\varepsilon_L = -620.7 + 36.2\rho - 12.34\rho^2 + \\ + 314\varepsilon - 30.67\varepsilon^2 - 3.3\rho \cdot \varepsilon + 0; \quad (8)$$

- light loamy:

$$\varepsilon_L = -632.7 + 66.86\rho - 23.9\rho^2 + \\ + 310\varepsilon - 30.15\varepsilon^2 - 3.5\rho \cdot \varepsilon + 0; \quad (9)$$

- medium loamy:

$$\varepsilon_L = -623.8 + 40.6\rho - 12.8\rho^2 + \\ + 313\varepsilon - 30.4\varepsilon^2 - 3.6\rho \cdot \varepsilon + 0; \quad (10)$$

- heavy loamy:

$$\varepsilon_L = -606.8 + 27.6\rho - 8.68\rho^2 + \\ + 309.45\varepsilon - 29.99\varepsilon^2 - 3.70\rho \cdot \varepsilon + 0. \quad (11)$$

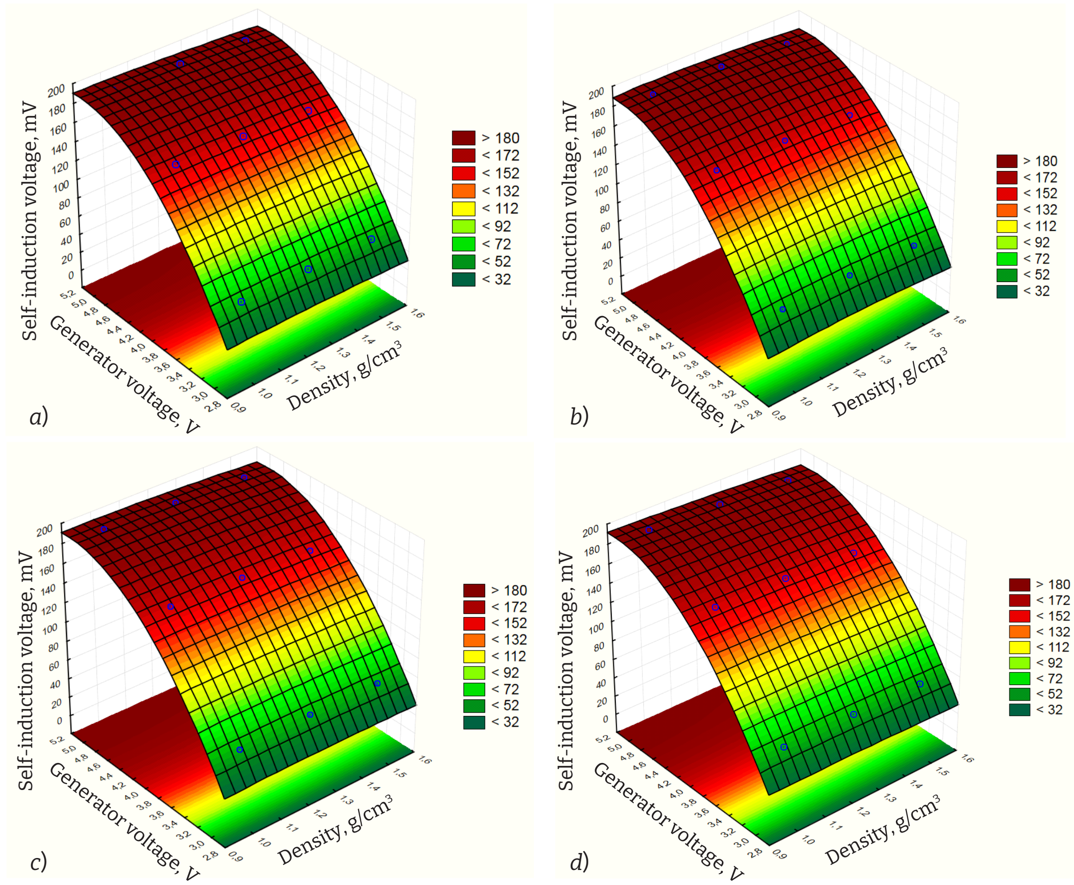

Figure 5. Surface graphs of generator voltage ε, self-induction voltage ε_L, and density ρ for soil compositions

Note: *a* – sandy loamy, *b* – light loamy, *c* – medium loamy, *d* – heavy loamy

Source: developed by the authors

Based on the surface graphs, a dominant influence of the generator voltage ε on the self-induction voltage ε_L was established about the density indicators of the soil compositions. This finding is supported by second-order analytical models of the relationships between the density values and the self-induction voltage for each voltage level of 3.4 and 5 V, with coefficients of determination $R^2 = 0.8$ - 0.98.

From the graph in Figure 6, it can be concluded that the approximation of the measurements using the least squares method (LSM) enabled the characterisation of the numerical values of the change in self-induction voltage ε_L concerning density ρ through second-order equations, yielding coefficients of determination for each soil composition: sandy loamy $R^2 = 0.81$; light loamy $R^2 = 0.89$; medium loamy $R^2 = 0.90$; and heavy loamy $R^2 = 0.95$. The percentage of variation attributed to the influence of the factor characteristics on the overall change in the outcome variable can indicate the *acceptable* prospects for the models of relationships based on the data from the experimental studies. It was established that the coefficient of determination increases as the fractional composition of the examined soil composition decreases.

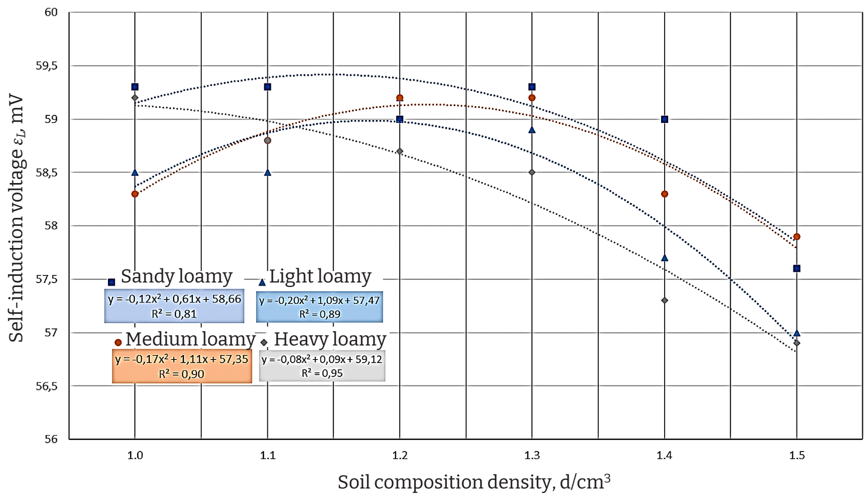

Figure 6. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 3 V)

Source: developed by the authors

As illustrated in the graph in Figure 7, the approximation of the measurements using the LSM enabled the modelling of the dependencies of self-induction voltage ε_L on density ρ through second-order equations, yielding coefficients of determination for each soil composition: sandy loamy $R^2 = 0.97$; light loamy $R^2 = 0.95$; medium loamy $R^2 = 0.99$; and heavy loamy $R^2 = 0.88$. It was established that the coefficients of determination increased with the amplitude of the alternating current for the majority of the soil compositions. The percentage of influence of the factor characteristics on the overall change in the outcome variable can indicate the *acceptable* prospects for the models of relationships based on the data from the experimental studies.

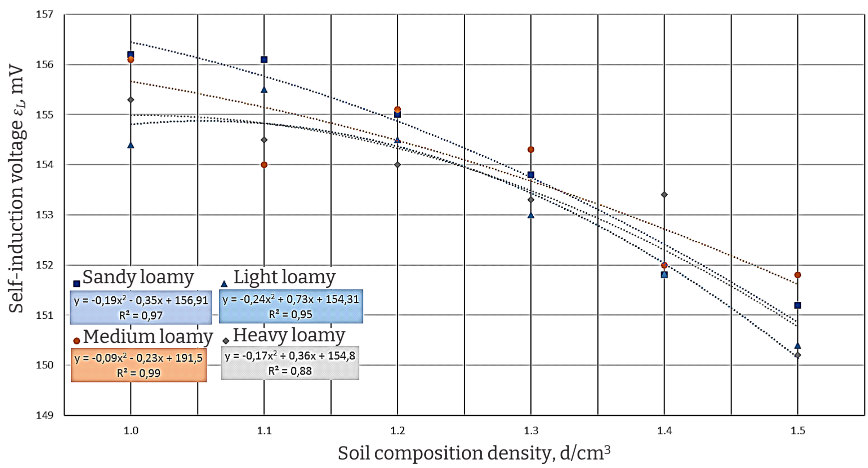

Figure 7. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 4 V)

Source: developed by the authors

The results of the graphical modelling (Fig. 8) indicate that the approximation of the determined parameters using the LSM facilitated the modelling of the relationships between self-induction voltage ε_L and density ρ through second-order equations, yielding coefficients of determination for the soil compositions: sandy loamy $R^2 = 0.98$; light loamy $R^2 = 0.97$; medium loamy $R^2 = 0.99$; and heavy loamy $R^2 = 0.95$. The percentage of influence of the factor characteristics on the overall change in the outcome variable can determine the prospects for the development of relationship models based on data from experimental studies.

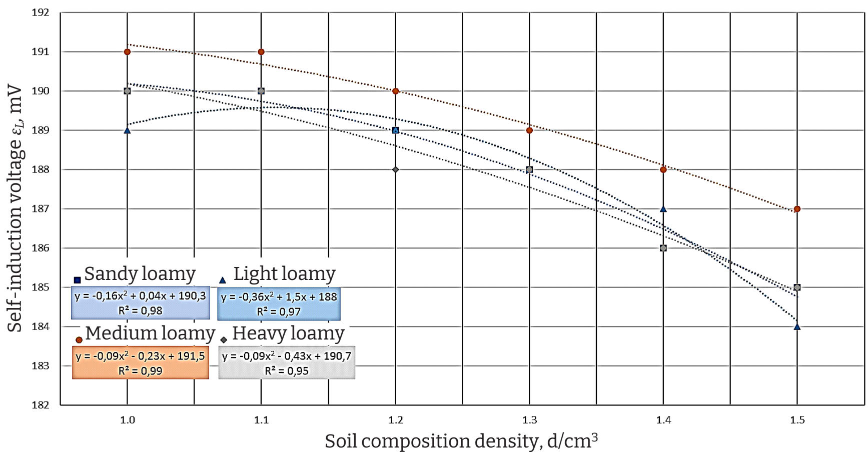

Figure 8. Results of experimental investigations into the relationships between soil composition density and self-induction voltage ε_L (amplitude 5 V)

Source: developed by the authors

Analysis of the graphs (Fig. 6-8) reveals that, with the increase in the amplitude of the generator's alternating current from 3 V to 5 V, the self-induction voltage ε_L of the solenoid (sensor) increased from 59.3 mV to 190 mV for a sandy loamy soil density of $\rho = 1.0$ g/cm³.

The highest coefficients of determination $R^2 = 0.95 - 0.99$ for the models describing the relationships between the density of soil compositions $\rho = 1.0\text{-}1.5$ g/cm³ and the self-induction voltage $\varepsilon_L = 184 - 192$ mV were observed at a generator voltage of 5 volts. The models featuring these relationships can be employed as calibration characteristics for technical means of non-destructive testing for determining the density of composite soil compositions.

Comparing the results obtained in this research with other similar approaches to this issue, it can be noted that density is one of the critical indicators of soil fertility. Optimal density levels facilitate the faster development of the root system (by an average of 2-3 days) and the increase in vegetative mass, ultimately contributing to higher yields. For most agricultural crops, optimal density levels fall within the range of 1.1 to 1.3 g/cm³. Overall, a deviation from the optimal density of 1.2 g/cm³ for sugar beets, as noted by S. Kartashov *et al.* (2012), by 0.1 to 0.3 g/cm³ may lead to a reduction in yield of 20 to 40 per cent.

In agricultural practice, bulk density serves as a comprehensive indicator of soil physical condition. For most crops grown on medium to heavy loamy soils, optimal growth conditions occur within a density range of $\rho = 1.0\text{-}1.3$ g/cm³, while for sandy and sandy loamy compositions, the optimal range is $\rho = 1.2 - 1.5$ g/cm³. However, existing methods often fail to provide accurate measurements of soil conditions throughout the entire plough layer, hindering the assessment of tillage equipment performance. According to V. Kravchuk *et al.* (2023), current electronic devices for flow-based density measurement lack the necessary capabilities for precision agriculture and adaptive tillage operations. Notably, non-destructive methods based on electromagnetic interactions with the soil layer are gaining prominence in modern agriculture. These methods encompass both contact and non-contact interactions, as highlighted in the research by V. Kravchuk *et al.* (2023).

One of the approaches to addressing the issues of guaranteed adaptive management of soil cultivation operations is the implementation of automated tools through the use of electronic maps with specified indicators of soil cultivation quality. An important task in designing these automated systems is the development of flow-based measurement tools for agrophysical indicators, as highlighted by I. Trinks & M. Pregesbauer (2016), as well as Y. Zhou *et al.* (2022).

However, the aforementioned tools inadequately respond to the compositional composition of sandy and clay soils, which form the basis of the physical composition according to the classification by Kachinsky, as outlined in DSTU 4730:2007 (2008), and the research conducted by J. Ruehlmann *et al.* (2020) and X. Xu *et al.* (2022).

According to this classification, the division of soils based on their granulometric composition is founded on the complexity of cultivation by the working components of soil tillage machines and the fractional composition, as confirmed by the researcher P. Sanchez (2019). Soils can be classified into light, such as sandy and sandy loamy; medium, including light and medium loams; and heavy, comprising heavy loams and clays. The granulometric composition is one of the factors that influence various physical properties of soils, including density, porosity, plasticity, permeability, swelling, shrinkage, and others.

Research by O. Kruglov *et al.* (2022) indicates that information regarding the agronomic indicators of soil forms the foundation of the modern concept of "precision" (or smart) agriculture. Soils used in agrotechnological production exhibit high levels of differentiation and dispersion. Standard agrochemical surveys do not provide adequate monitoring of the actual situation or the complete realisation of the potential fertility of the soil cover. Consequently, the measurement of magnetic permeability has been proposed as an alternative. It is important to note that conducting the necessary research using standardised agrochemical and agrophysical methods is a labour-intensive procedure, requiring significant time and financial resources to carry out the relevant analyses.

In the study of M. Hanesch & R. Scholger (2005), it is explored that the determination of the characteristics of magnetic susceptibility χ and magnetic permeability μ is a widely accepted method in soil science, particularly within the framework of molar mass magnetism, frequency dependence, and thermal behaviour of soils. Furthermore, this study confirmed that fundamental principles of magnetism can be applied to determine parameters relevant to soil contamination studies. The influence of several factors, such as mineralogical composition and particle size, on magnetic field indicators, is analysed, as well as the relationship between the magnetic susceptibility of soil and its parent lithology, climate, organic matter content, topography, sediment sources, and particle size, among others.

According to the research conducted by A. Ouallali *et al.* (2023), a simple, rapid, and cost-effective method for determining magnetic susceptibility χ is essential for the precise mapping of soil erosion. Furthermore, the studies are aimed at identifying the factors that influence the variation in soil susceptibility χ and utilising this susceptibility to assess soil erosion as an inexpensive and efficient means of tracking long-term morphological processes and sedimentation. The results confirm that land use, slope, and soil type significantly affect susceptibility χ values. Current research indicates a high efficacy of magnetic susceptibility values as a rapid, straightforward, and economically viable approach that can serve as an alternative method for assessing soil redistribution.

The research conducted by F. Shirzaditabar & R. Heck (2021) examines the relationships between the volume and bulk density of magnetic permeability μ in soil materials. The study presents a comparison of two types of instruments for measuring soil magnetic susceptibility, based on interactions in a magnetic field and electromagnetic induction (EMI). Magnetochemical investigations encompassed particle size analysis, pollutant detection, organic matter identification, paleoecological studies, archaeology, as well as soil erosion and degradation. The results indicate that the investigated devices, which utilise magnetic fields, can accurately measure the magnetic susceptibility of small soil quantities, thinly applied layers, or exposed soil, but are ineffective at measuring materials beyond 10 cm from the sensor.

The determination of individual soil properties by compositional composition is partially traced in the scientific studies of D. Robinson *et al.* (2004) and P. McLachlan *et al.* (2022), using equipment based on the principles of interaction of the electromagnetic field with the soil and are not intended to solve the goal of research aimed at developing non-destructive flow determination of agrophysical indicators and tillage management systems.

The studies made it possible to develop devices for flow-based non-destructive determination of soil magnetic permeability by measuring the values of self-induction voltage in a changing magnetic field.

CONCLUSIONS

The conducted studies of flow-based determination of soil density by the induction method concerning the compositional composition can be the basis for the development of equipment for guaranteed adaptive control of working bodies, which will ensure the achievement of the specified indicators during the operation of the unit, increase the yield and efficiency of the technological process. The obtained results made it possible to establish the expediency of determining the magnetic permeability of soil for flow-based non-destructive density determination about the compositional composition by using the interaction of the induction field.

It has been established that modern means of determining agrophysical indicators, which use the interaction of the electromagnetic field with the soil, are based on the methods of determining eddy currents and reflectometry. The disadvantages of eddy current methods in the soil during flow-based measurement are the susceptibility to electrochemical corrosion of the root layer and scattering of the probing signal depending on its structure, which complicates the use of reflectometry tools.

It is noted that the development of means for flow determination of soil agrophysical indicators by induction methods will provide an opportunity to obtain operational monitoring of the root layer and respond to changes in the state during cultivation. Studies have shown that the relationships between the density of soil compositions ρ and the self-induction voltage ε_L can be determined by second-order models with determination coefficients $R^2 = 0.80 - 0.98$ at generator voltages of 3.4 and 5 volts. The smallest error of the models of the relationships between the density of soil compositions $R^2 = 1.0 - 1.5$ g/cm^3 and the self-induction voltage $\varepsilon_L = 184 - 192$ mV was observed at a generator voltage of 5 volts.

The obtained models can be used as calibration characteristics for the design of technical means for flow-based, non-destructive determination of the density of various soil structure compositions. It has been established that to improve the accuracy of non-destructive flow-based determination of soil density by induction methods, it is advisable to use second-order models that characterise the compositional composition of the corresponding soil type.

The prospect of research is the introduction of methods for flow-based determination of agrophysical indicators in the system of guaranteed adaptive management of soil cultivation.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Щільність композиційного складу ґрунту в змінному магнітному полі

Анотація. Розвиток технічних засобів визначення щільності ґрунту в умовах точного (керованого) землеробства потребує вдосконалення методів неруйнівної потокової взаємодії. Існує також необхідність вдосконалення методів визначення щільності ґрунту, оскільки наявні відхилення від оптимальних значень, мають негативний вплив на врожайність сільськогосподарських культур. Мета досліджень спрямована на встановлення щільності композицій гранулометричного складу ґрунту шляхом визначення напруги самоіндукції у змінному магнітному полі. Методи досліджень адаптовані до визначення зв'язків прецесії Лармора за змінного індукційного струму для щільності кожної з композицій гранулометричного складу ґрунту. Експериментальні дослідження виконувались шляхом визначення напруги самоіндукції соленоїда як датчика для кожної з композицій розташованих в осерді. Обробка результатів експериментальних досліджень виконувалась відповідно до правил математичної статистики та теорії ймовірності із застосуванням апроксимації в програмному комплексі Excel та Statistica. За результатами експериментальних досліджень визначено моделі взаємозв'язків щільності ρ (1,0-1,5 г/см^3) композицій ґрунту, напруги самоіндукції ε_L = 184 - 192 мВ за напруги генератора 5 В з коефіцієнти детермінації R^2=0,95-0,99. Моделі дозволяють оцінювати щільність ґрунту з високою точністю, що сприяє оптимізації агротехнічних процесів. Визначено, що з високою вірогідністю зазначені моделі можуть бути використані як калібрувальні характеристики для проектування технічних засобів потокового неруйнівного визначення щільності основних типів ґрунтів України. Визначено також, що перспективою подальших досліджень є поглиблене вивчення взаємозв'язків магнітної проникності та агрофізичних характеристик ґрунту в місцевизначеному індукційному полі сенсора (соленоїда). Прикладним аспектом отриманих результатів є подальший розвиток адаптивних машин та засобів моніторингу стану ґрунту для досягнення показників оптимального його обробітку, а також, використаня науково-дослідними установами та приладобудівними підприємствами

Ключові слова: щільність ґрунту; магнітна проникність; самоіндукція; намагнічування; прецесія Лармора

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The impact of mineral fertilisers on the physicochemical properties of soil in maize cultivation

Abstract. The use of mineral fertilisers is a critical factor in modern agriculture, significantly influencing the physicochemical properties of soil, which in turn affects crop yield and quality. Understanding these impacts is essential for sustainable agricultural practices. This study aimed to determine the effects of different types and quantities of mineral fertilisers on the physicochemical properties of soil in the context of maize cultivation. The research involved experimental field trials with varying applications of mineral fertilisers. Soil samples were collected at different stages of maize growth and analysed for parameters such as pH, electrical conductivity, organic matter content, and nutrient availability (nitrogen, phosphorus, potassium). The study employed a range of methods to investigate the effects of mineral fertilisers on soil properties, including soil preparation, application of various types and doses of fertilisers, maize planting, plant growth monitoring, and analysis of soil physicochemical characteristics. The application of mineral fertilisers led to significant changes in soil pH, with some fertilisers causing acidification and others increasing alkalinity. Fertilised plots showed increased electrical conductivity, indicating a rise in soluble salt content. Variations in organic matter content were observed, dependent on the type and dosage of fertilisers used. It was determined that fertilised plots exhibited elevated levels of nitrogen, phosphorus, and potassium, directly correlating with the type and quantity of fertiliser applied. The highest maize yield was achieved with balanced applications of nitrogen-phosphorus-potassium (NPK) fertilisers, underscoring the importance of balanced nutrient management. These findings provide valuable insights for optimising fertiliser use, which may contribute to improved soil health, increased maize yield, and sustainable agricultural practices

Keywords: fertility; yield; growth; fertilisers; cultivation process

INTRODUCTION

Contemporary research focuses on finding a balance between high crop yields and maintaining ecological stability, taking into account regional soil and climate characteristics. In particular, attention is directed towards studying the effects of mineral fertilisers combined

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with organic fertilisers, as well as developing new formulations to reduce environmental impact. This approach supports the development of more sustainable agriculture that meets current and future demands. The use of mineral fertilisers is a primary practice in modern agriculture, influencing soil physicochemical properties and crop yield. T. Mardamootoo *et al.* (2021) indicated that nitrogen fertilisers enhance crop yields but also contribute to soil acidification. J. Jin *et al.* (2020) examined the effects of different types of phosphorus fertilisers on soil pH, finding that they can either increase or decrease acidity, depending on application conditions. Researchers such as M. Kolton *et al.* (2019) emphasised the need for balanced mineral fertiliser use to maintain stable nutrient levels in the soil, noting that excessive nitrogen fertiliser use reduces organic matter content, potentially leading to soil degradation. J. Kučerík *et al.* (2018) conducted experiments with varying doses of potassium fertilisers and found that optimal doses improve maize yield without negatively impacting the soil's physicochemical properties. They also observed that long-term application of these doses helps maintain organic matter balance and does not alter soil acidity levels, preserving soil productivity. Y. Kuzyakov *et al.* (2019) highlighted the importance of considering soil-specific conditions when selecting the type and quantity of fertilisers. They noted that adapting fertiliser use to the characteristics of a particular soil optimises their effectiveness, enhancing maize yield while minimising environmental risks. C. Nataris *et al.* (2021) examined the long-term effects of mineral fertilisers on soil biota and found that regular use of certain fertilisers can reduce microbial biodiversity. They indicated that this decline in biodiversity may negatively impact soil functions such as organic matter decomposition and nutrient availability for plants, which in turn could reduce agroecosystem productivity. Z. Guo *et al.* (2019) explored the effects of various mineral fertiliser combinations and found that balanced application of nitrogen, phosphorus, and potassium (NPK) significantly enhances soil physicochemical properties and crop yield. Overall, the research supports the need for an integrated approach to soil fertility management. Mineral fertiliser use should take into account soil-specific conditions and the requirements of particular crops. The relevance of this study stems from the need to determine optimal rates and types of mineral fertilisers to preserve soil fertility and ensure high maize yields.

This study aimed to investigate the impact of mineral fertilisers on the physicochemical properties of soil during maize cultivation and to develop recommendations for farmers on the effective use of fertilisers.

The main objectives of the study were as follows:

- to analyse the effects of different types of mineral fertilisers on soil pH and electrical conductivity;
- to examine changes in organic matter content and nutrient availability under the influence of fertilisers;
- to identify optimal fertiliser application rates to secure high maize yields.

The scientific novelty of the article lies in its comprehensive approach to studying the impact of mineral fertilisers on soil properties and maize yield, which includes a detailed analysis of soil physicochemical parameters and the development of practical recommendations for agricultural producers.

MATERIALS AND METHODS

To achieve the study's objectives, experimental field trials were conducted at the research base of the Agricultural University, specifically at the National University of Life and Environmental Sciences of Ukraine, in 2023.

The investigation into the effects of mineral fertilisers on the physicochemical properties of soil in maize cultivation utilised several methods, including soil preparation, the application of various fertiliser types and doses, maize planting, plant growth monitoring, and analysis of soil physicochemical characteristics.

Field trials. The research involved the division of plots for the application of different doses and types of mineral fertilisers. Soil samples were collected at the beginning of the experiment and during critical maize growth stages, allowing an assessment of changes in soil physicochemical properties over time.

Soil sample analysis. The content of essential nutrients (nitrogen, phosphorus, potassium) was determined using spectrophotometric methods. Soil pH was measured via an electrometric method, ensuring accuracy and reliability. Soil electrical conductivity was assessed using a conductometer, which enabled the evaluation of the soil's salt balance.

Organic matter analysis. Organic matter content was determined using Tyurin's volumetric analysis method, allowing the assessment of the impact of mineral fertilisers on soil organic composition.

Biometric indicators of maize. Measurements of plant height, leaf count, and yield were conducted to evaluate the impact of fertilisers on maize growth and development. These data enabled the establishment of correlations between the use of mineral fertilisers and crop productivity.

The experimental base of this study was conducted on chernozem soils. The trials were performed on plots of 1 m^2 for each fertiliser variant, with a total of 10 variations, including a control Plot without fertiliser application (Table 1).

Table 1. Characteristics of fertilisers and application methods for experimental plots

Plot	Fertiliser	Manufacturer (Ukraine)	Dosage	Application method	Season/Growth phase
Plot 1	NPK 15:15:15	UkrAhroNikel	200 kg/ha	Disc harrow	Pre-sowing period
Plot 2	Carbamide (Urea)	Azot	150 kg/ha	Sprayer	At the beginning of the growing season
Plot 3	Crystalline NPK 16:8:24	HidroAhro	100 kg/ha	Disc harrow	During flowering
Plot 4	Potassium nitrate	PhosAgro	120 kg/ha	Sprayer	Grain filling period
Plot 5	Superphosphate	Agroprodservice	250 kg/ha	Disc harrow	Autumn period
Plot 6	Organic fertiliser (manure)	EkoAgro	20 t/ha	In-depth application	Pre-sowing period
Plot 7	Liquid fertiliser based on humic acids	AhroKhim	50 L/ha	Sprayer	Phase 4-6 leaves
Plot 8	Balanced NPK 10:20:10	AgroZahyst	180 kg/ha	Disc harrow	Development of the root system
Plot 9	Ammonium nitrate	Fosforyt	200 kg/ha	Disc harrow	Autumn period

Source: author's own development

Each experimental variant was repeated three times to ensure the statistical reliability of the results. The use of standard soil and plant analysis methods enabled reproducibility. Data processing was carried out using software (SPSS, MATLAB, GIS systems, ANOVA) for statistical analysis, ensuring reliability and accuracy. This study can be replicated by other researchers by following the described methods and using similar materials. The study adhered to ethical standards outlined in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

RESULTS AND DISCUSSION

The cultivation of maize in modern conditions is a key component of agricultural production, as this crop serves as an important source of food, feed, and industrial raw materials. However, maize cultivation faces several challenges, particularly due to climate change, rising resource costs, and increased demands for environmental sustainability. Climate change significantly impacts maize-growing technologies, with higher temperatures, irregular rainfall, and frequent droughts requiring adaptation of both crop varieties and soil management practices. Consequently, there is growing emphasis on using drought-resistant hybrids and improving irrigation systems to sustain stable yields even in unfavourable conditions. Another critical factor is the efficient management of resources, particularly fertilisers, water, and fuel. Rising fertiliser and energy costs drive farmers to seek ways to optimise their expenditure. Precision farming and advanced agricultural technologies, such as GPS guidance for the targeted application of fertilisers and crop protection products, help reduce costs and improve efficiency. Environmental sustainability is also of high importance. Today, farmers strive to minimise their environmental impact, including reducing pesticide and chemical fertiliser use. Methods of organic farming, crop rotation, and other practices aimed at maintaining soil fertility and preventing degradation are increasingly being implemented.

Modern maize cultivation requires adaptation to emerging challenges related to climate change, economic conditions, and environmental standards. The use of innovative agricultural technologies and resource management approaches has become essential to the successful production of this vital crop.

The application of nitrogen fertilisers increases soil acidity, potentially reducing nutrient availability to plants and necessitating additional measures to maintain an optimal pH level. Conversely, phosphorus and potassium fertilisers contribute to improved soil structure by enhancing the stability of soil aggregates, thereby boosting water permeability and aeration. This is particularly beneficial for maize, which requires well-structured, well-drained soils for optimal growth. Additionally, mineral fertilisers significantly raise the levels of essential nutrients in the soil, promoting increased maize yields. However, prolonged and uncontrolled use of fertilisers can lead to excessive accumulation of these elements in the soil, negatively impacting long-term soil fertility and posing environmental risks, such as groundwater pollution. Therefore, the use of mineral fertilisers in maize cultivation should be balanced and carefully monitored to maximise benefits while safeguarding soil resources and the environment.

The impact of mineral fertilisers on the physicochemical properties of soil in maize cultivation is a significant issue in contemporary agricultural production, as the application of fertilisers largely determines not only crop yield but also the ecological condition of the soils. Numerous studies have been conducted to date, revealing a variety of results concerning the changes in the physicochemical properties of soil under the influence of mineral fertilisers.

One of the key indicators altered by mineral fertilisers is the soil acidity level (pH). Numerous studies have demonstrated that intensive application of mineral fertilisers, particularly nitrogenous ones, leads to soil acidification. For instance, applying 150-200 kg/ha of nitrogenous fertilisers can decrease pH by 0.5-1.0 units within a few years of continuous application. Consequently, this affects the bioavailability of nutrients and the activity of microorganisms involved in organic matter transformations (Hwang *et al.*, 2021).

Another critical aspect is the alteration of soil organic matter content. The consistent application of mineral fertilisers can lead to a decrease in humus content in the topsoil. According to AgroTimes (2020), applying 150 kg/ha of nitrogen-phosphorus fertilisers can reduce humus content by 5-10% over a 10-15-year period. This is because mineral fertilisers stimulate microbial activity, leading to a more rapid decomposition of organic matter. However, without adequate replenishment through organic fertilisers or green manures, this can result in soil degradation.

Furthermore, it is important to consider changes in soil structure. Research by M. Hünninghaus *et al.* (2019) indicates that mineral fertiliser application can affect the water and physical properties of soil, including its permeability and aeration. For instance, prolonged use of high doses of mineral fertilisers (exceeding 200 kg/ha) can lead to soil compaction, deteriorating its structural condition. This reduces the soil's capacity to hold water and air, which in turn negatively impacts plant root systems. Consequently, it is recommended to adhere to optimal mineral fertiliser application rates and combine them with organic fertilisers to maintain soil fertility. Additionally, applying mineral fertilisers at rates not exceeding 100-150 kg/ha is optimal, allowing for the maintenance of a stable pH level and preventing soil degradation (SuperAgronom, 2022). In such cases, the negative impacts on soil structure and humus content are minimised while maize yields remain high.

Mineral fertilisers are a crucial component of modern agriculture, but their use requires careful management. Systematic monitoring of soil physicochemical properties, such as pH, humus content, and water and physical properties, is essential to prevent the adverse effects of long-term fertiliser application. Adhering to agronomic recommendations regarding fertiliser rates and combining them with organic practices is key to maintaining soil fertility and sustainable maize production.

The impact of mineral fertilisers on the physicochemical properties of soil in maize cultivation is a significant topic, as their correct application can significantly increase yields but also affect the soil and environment. The use of nitrogenous fertilisers, such as ammonium nitrate, can lead to increased soil acidity. Research by SuperAgronom (2020) shows that regular application of these fertilisers can decrease soil pH by 0.1-0.3 units per year. When growing maize using complex mineral fertilisers (nitrogen, phosphorus, and potassium), an increase in soil organic matter content of 10-15% is observed compared to control plots where no fertilisers are applied. The application of potash fertilisers can improve the water-holding capacity of the soil. Statistical data from SuperAgronom (2020) shows that the use of potash fertilisers increases this indicator by 5-8%, which positively affects maize growth, especially under drought conditions. The use of mineral fertilisers in maize fields on average increases yields by 20-40%. For example, the application of nitrogenous fertilisers can increase maize yields to 8-10 t/ha compared to 5-6 t/ha on control plots. Excessive use of mineral fertilisers can lead to the accumulation of nitrates in the soil, which in turn contributes to their leaching into groundwater. According to some data, the concentration of nitrates in the soil can increase by 30-50 mg/kg with excessive use of nitrogenous fertilisers. These statistics highlight the importance of a balanced approach to the use of mineral fertilisers to ensure sustainable maize production and maintain long-term soil health.

A study investigating the impact of mineral fertilisers on the physicochemical properties of soil during maize cultivation revealed significant changes in soil parameters and crop yield. The results were statistically analysed using ANOVA and are presented in Table 2.

Table 2. Effect of mineral fertilisers on soil pH

Plot	Initial pH	pH after application
Plot 1	6.5	5.9
Plot 2	6.5	5.8
Plot 3	6.5	6.1
Plot 4	6.5	6.2
Plot 5	6.5	6.3
Plot 6	6.5	6.4
Plot 7	6.5	6.0
Plot 8	6.5	6.1
Plot 9	6.5	6.0
Control	6.5	

Note: data presented with a mean error of ±0.1
Source: compiled by the author based on research

The plot treated with carbamide (Plot 2) exhibited the greatest decrease in pH, from 6.5 to 5.8, indicating a high acidifying effect of nitrogenous fertilisers. Plot 5, where superphosphate was used, also showed a slight decrease in pH from 6.5 to 6.3, suggesting a weak acidifying effect of phosphorus. Potassium nitrate (Plot 4) reduced pH to 6.2, demonstrating a moderate acidifying effect of potassium. The complex NPK 15:15:15 fertiliser (Plot 1) lowered pH from 6.5 to 5.9, indicating a moderate acidifying effect, although less pronounced than that of pure nitrogenous fertilisers.

The results obtained demonstrate a significant impact of different types of mineral fertilisers on the physicochemical properties of the soil. Specifically, the application of nitrogen (N) fertilisers led to a decrease in soil pH, which is consistent with the findings of T. Hirvilammi & M. Koch (2020), who noted a similar effect of nitrogen on soil acidity. The application of phosphorus (P) and potassium (K) fertilisers showed a less pronounced effect on soil pH, which corresponds to the results of studies by M. Dusenge *et al.* (2019).

The data presented in Table 3 indicate that the application of fertilisers, particularly nitrogen-based ones, significantly enhances maize yield, which can be beneficial for optimising agronomic practices. The use of mineral fertilisers increases yields by 20-40% compared to plots without fertiliser. For instance, yields can reach 8-10 tonnes per hectare on fertilised plots compared to 5-6 tonnes per hectare on control plots. The application of mineral fertilisers significantly improves the growth and development of maize, resulting in higher yields and better plant growth indicators.

Table 3. Plant height, leaf number, and yield on experimental plots

Plot	Plant height (m)	Number of leaves	Yield, t
Plot 1 (NPK 15:15:15)	2.4	15	9.0
Plot 2 (Carbamide)	2.5	16	9.5
Plot 3 (Crystalline NPK 16:8:24)	2.3	14	8.5
Plot 4 (Potassium nitrate)	2.2	15	8.8
Plot 5 (Superphosphate)	2.0	13	7.0
Plot 6 (Manure)	2.1	14	7.5
Plot 7 (Liquid fertiliser based on humic acids)	2.2	15	8.0
Plot 8 (Balanced NPK 10:20:10)	2.3	15	9.2
Plot 9 (Ammonium nitrate)	2.4	16	9.0
Control	1.9	12	5.5

Source: author's own development

Overall, the comprehensive study demonstrated that the application of mineral fertilisers significantly increased the content of essential nutrients in the soil, positively affecting maize growth and development. The spectrophotometric analysis confirmed a substantial increase in nutrient content, but it was also found that intensive application of nitrogenous fertilisers led to an increase in soil acidity, as confirmed by pH measurements using an electrometric method. Conductivity measurements indicated that high doses of fertilisers could increase the risk of soil salinisation, as elevated conductivity values were observed. Analysis of organic matter using the Tyurin method showed that prolonged use of mineral fertilisers can reduce organic matter content, which in turn negatively impacts long-term soil fertility.

Increased soil electrical conductivity following fertiliser application indicates an increase in soluble salt content, as confirmed by the findings of R. Fang *et al.* (2020). In particular, a decrease in soil organic matter content was observed under the influence of high doses of nitrogenous fertilisers, which aligns with the conclusions of L. Domeignoz-Horta *et al.* (2020).

A significant finding of this study is the determination of the optimal fertiliser combination to increase maize yield. The highest yield was achieved when balanced nitrogen-phosphorus-potassium (NPK) fertilisers were applied, confirming the importance of a balanced approach to plant nutrition, as noted in the research of H. Das *et al.* (2023).

Comparing the results of this study with those of the aforementioned researchers allows us to conclude that a comprehensive approach to soil fertility management is necessary. The use of mineral fertilisers should be adapted to specific soil conditions and crop requirements, ensuring not only increased yields but also long-term soil health.

Determining optimal rates of mineral fertiliser application is a key factor in achieving high maize yields. The correct selection of nitrogen, phosphorus, and potassium fertiliser dosages allows not only for increased yields but also for maintaining soil health, preventing soil depletion and degradation (Chi *et al.*, 2020).

To achieve high maize yields, it is necessary to consider soil type, climatic conditions, and the specific characteristics of the maize variety.

Nitrogen fertilisers are typically the most important for maize growth, as nitrogen is a primary component required for protein synthesis, which is essential for plant growth and development. The optimal nitrogen fertiliser rate is 120-180 kg/ha, depending on the level of natural soil fertility and organic matter content. Phosphorus fertilisers are also important, especially in the early stages of maize development. They promote root development and improve plant resistance to adverse conditions. The optimal phosphorus fertiliser rate is typically 60-90 kg/ha of active ingredient. Potassium fertilisers improve plant water relations and increase their resistance to drought, pests, and diseases. For maize, it is recommended to apply potassium fertilisers at a rate of 80-120 kg/ha. It is also important to integrate fertilisers, taking into account the plant growth stage. For example, the main portion of nitrogen fertilisers should be applied before sowing or during the early growth stages to ensure maximum nitrogen availability during critical growth periods. Phosphorus and potassium are best applied before primary ploughing or before sowing to ensure their uniform distribution in the soil (Ukrainian agro-industrial group, 2024).

The impact of mineral fertilisers on maize cultivation is a critically important topic in modern agriculture. This is because maize is one of the most significant crops for both food and feed industries. It occupies vast areas in many countries worldwide, including Ukraine, which is a leading producer of this crop. However, to ensure stable yields and maintain soil fertility, mineral fertilisers must be applied correctly, taking into account specific soil characteristics and plant needs. It is crucial to note that mineral fertilisers undoubtedly increase maize yields by providing essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients. However, the misuse of fertilisers can lead to soil degradation, reduced fertility, and even negative environmental consequences, such as water pollution due to nitrate leaching. Therefore, the judicious and balanced use of mineral fertilisers is essential for ensuring the sustainable development of agriculture.

A key recommendation for successful maize cultivation is to consider the specific characteristics of the soil and its agrochemical composition. According to T. Hao *et al.* (2020), it is essential to conduct a soil analysis before applying fertilisers to determine pH level, organic matter content, and available nutrients. This allows for the correct selection of fertiliser types and rates required for a particular field. For example, on acidic soils, attention should be paid to liming to correct acidity, which will ensure better nutrient uptake and healthy maize growth.

Exceeding recommended doses of mineral fertilisers does not always lead to increased yields and can sometimes even have negative consequences. Excessive fertiliser concentrations can reduce plant nutrient uptake efficiency and also adversely affect soil structure, water and physical properties, and the activity of soil microorganisms. Optimal doses should be selected according to agronomic recommendations, considering soil conditions and climatic factors.

Combining mineral fertilisers with organic ones is crucial. The combined application of organic fertilisers, such as compost, manure, or green manure, helps to maintain and even increase soil humus levels, contributing to long-term soil fertility improvement. Organic fertilisers also enhance soil structure, increase its water-holding capacity, and promote better uptake of mineral fertilisers. It is also important to consider the correct timing of fertiliser application. The most effective approach is to apply fertilisers during growth stages when maize has the highest nutrient requirements, such as during the period of active growth and root development. Failure to adhere to these timing recommendations can lead to inefficient fertiliser use when the plant cannot fully utilise them.

Finally, it is essential to consider changing climatic conditions that affect maize yields. Under changing climate conditions, it is necessary to adapt agricultural practices to new conditions, including the optimisation of fertiliser application. It is important to pay attention to long-term changes in weather patterns, such as rising average annual temperatures and changes in precipitation patterns, which affect the timing and methods of fertiliser application. Researchers A. Ali *et al.* (2020) have established that the correct and balanced use of mineral fertilisers is a key factor in ensuring high maize yields and maintaining soil fertility. The application of a comprehensive approach, including soil analysis, optimal dosing, combination with organic fertilisers, and consideration of climatic conditions, will minimise negative impacts and ensure the stability of agricultural production.

Therefore, optimal rates of mineral fertiliser application to ensure high maize yields should be tailored to specific growing conditions, considering the balance between nitrogen, phosphorus, and potassium components, as well as the plant growth stage. Such an approach allows for maximum fertiliser use efficiency and the achievement of consistently high yields.

CONCLUSIONS

Mineral fertilisers have the potential to significantly enhance maize yields, but their use must be balanced and well-considered. This approach not only ensures high productivity but also preserves the ecological state of soils, a crucial aspect of sustainable agriculture. The results of this study confirm the importance of balanced mineral fertiliser application for optimising soil physicochemical properties and increasing maize yields. The obtained data demonstrate a positive impact of fertilisers on maize growth and development, leading to high productivity. Fertiliser application resulted in a significant increase in the concentration of essential nutrients in the soil, particularly nitrogen, phosphorus, and potassium, which is critical for maintaining optimal plant growth conditions.

Research has shown that the application of nitrogen fertilisers significantly increases crop yields, however, potential negative consequences such as soil acidification must also be considered. This underscores the need for soil pH monitoring and regular soil health assessments to prevent a decline in nutrient availability for plants. Further research should focus on developing recommendations for optimal fertiliser application rates based on soil type and agroclimatic conditions, helping farmers to effectively manage maize production and maintain soil fertility. In particular, determining the optimal timing of fertiliser application based on plant growth stages will allow for maximum utilisation of their nutrient potential. Studies also indicate the risk of soil salinisation with excessive use of mineral fertilisers, highlighting the need to adhere to recommended doses to maintain soil health and prevent negative impacts on the ecosystem. Timely fertiliser application and the correct choice of fertilisers can form the basis for sustainable agriculture, which requires an integrated approach to resource management.

Future research could focus on investigating the long-term impact of different types of mineral fertilisers on the physical and chemical properties of soils under varying climatic conditions and soil types. It is particularly important to explore optimal fertiliser application rates to ensure high maize yields without negatively affecting the environment.

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CONFLICT OF INTEREST

None.

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Вплив мінеральних добрив на фізично-хімічні властивості ґрунту при вирощуванні кукурудзи

Анотація. Використання мінеральних добрив є критичним фактором у сучасному сільському господарстві, який значно впливає на фізико-хімічні властивості ґрунту, що, в свою чергу, впливає на врожайність та якість культур. Розуміння цих впливів є важливим для сталих сільськогосподарських практик. Метою дослідження було виявлення впливу різних типів та кількостей мінеральних добрив на фізико-хімічні властивості ґрунту в контексті вирощування кукурудзи. Дослідження включало експериментальні польові випробування з різними варіантами внесення мінеральних добрив. Зразки ґрунту збиралися на різних стадіях росту кукурудзи і аналізувалися за такими параметрами, як pH, електропровідність, вміст органічної речовини та доступність поживних речовин (азоту, фосфору, калію). У дослідженні впливу мінеральних добрив на фізико-хімічні властивості ґрунту при вирощуванні кукурудзи використовувалися ряд методів, що включали підготовку ґрунту, застосування різних типів і доз добрив, висаджування кукурудзи, моніторинг росту рослин та аналіз фізико-хімічних характеристик ґрунту. Основні результати дослідження внесення мінеральних добрив призвело до значних змін рівня pH ґрунту, при цьому деякі добрива викликали закислення, а інші – підвищення лужності. На удобрених ділянках була відзначена підвищена електропровідність, що свідчить про збільшення вмісту розчинних солей. Спостерігалися зміни у вмісті органічної речовини, зумовлені типом та дозуванням використаних добрив. Визначено, що удобрені ділянки показали підвищені рівні азоту, фосфору та калію, що безпосередньо корелює з типом та кількістю внесеного добрива. Найвища врожайність кукурудзи була досягнута при збалансованому застосуванні азотно-фосфорно-калійних (NPK) добрив, що демонструє важливість збалансованого управління поживними речовинами. Отримані результати надають цінну інформацію для оптимізації використання добрив, що може сприяти покращенню здоров'я ґрунту, підвищенню врожайності кукурудзи та сталим сільськогосподарським практикам

Ключові слова: родючість; урожайність; ріст; добрива; процес вирощування

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Crown gall of grapevine and prospects for its biological control

Abstract. The relevance of this study is conditioned by the spread of bacterial diseases of grapes in the south of Ukraine and the necessity of improving methods of pathogen identification and protection. The purpose of this study was to establish the area of bacterial grape cancer in Odesa

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region and to develop preventive measures based on the biological method. The study involved the inspection of industrial plantations for symptoms of the disease and its spread in the field. The molecular biological method of real-time polymerase chain reaction (PCR) was employed to identify the crown gall pathogen. The study was conducted following a certified methodology. PCR laboratory equipment was used to identify phytopathogens. As a result of the phytosanitary inspection of grape plantations of various farms in Odesa region, the study found grape bushes with characteristic symptoms of crown gall, with tumorous tissue growths in various parts of the plants: on the branches, stem, and grafting sites. Overall, grape crown gall is characterised by a wide distribution in the study area. According to the findings of the phytosanitary survey, the spread of bacterial grape cancer on different varieties ranged between 0.3-35%. The causative agent of the disease, *A. tumefaciens*, was identified in real time by PCR. The disease manifested itself in the form of characteristic symptoms and developed in a latent form. The developed multiplex PCR allowed for the simultaneous analysis of multiple strains of pathogenic agrobacterial isolates. Two isolates of agrobacteria were identified among the majority of isolates that were subsequently tested for tumour suppression: ILVM1 and ILVM2, which had elevated levels of antagonistic properties against the crown gall pathogen. The pathogenicity of the isolated agrobacteria on test plants of tomato and sunflower confirmed the findings of these properties obtained *in vitro*. The isolates of ILVM1 and ILVM2 agrobacteria considerably inhibited the growth of tumours on the stems of test plants compared to the pathogenic strain, and therefore they can be used in the future against the crown gall pathogen and to protect grape plants from secondary infection by the pathogen from the soil. The findings can be used to improve methods of biological plant protection against bacterial infections

Keywords: grape diseases; polymerase chain reaction; *Agrobacterium tumefaciens*; antagonist bacteria; biological protection

INTRODUCTION

Crown gall of grape, caused by *Agrobacterium tumefaciens* (Smith et Townsend 1907) Conn 1942, is a systemic, chronic disease. There is almost no means of protection against it, and control is mainly based on the prevention of plant damage, prompt diagnosis and identification of the pathogen. The disease causes a 10-20% decrease in yield and an average 15-20% decrease in sugar content (Sawant, 2023). It also impairs vine ripening. The factors contributing to plant damage include frost damage, mechanical damage, infection of planting material, soil infection, and high rates of disease transmission. As a result of the development of crown gall, industrial grape growing technologies may face difficulties in obtaining high-quality products.

As indicated by Y. Noutoshi *et al.* (2020) and I.A. Kovaleva *et al.* (2022), fungal, viral, and bacterial diseases are widespread and harmful in various grape growing regions. Among the latter, crown gall is characterised by high harmfulness in vineyards. This disease can spread rapidly among plants, especially under favourable conditions for bacteria, which significantly complicates the fight against it. As a result of crown gall, the overall productivity of vineyards and the quality of the crop are reduced, which leads to serious economic losses. The study by A. Konup *et al.* (2019) found that among the various infectious diseases in the vineyards of certain districts of Odesa region, crown gall accounts for about 25%. These statistics highlight the relevance of the problem and the importance of developing effective measures to control and treat this disease. Furthermore, the high prevalence of crown gall in the region requires attention from plant protection specialists and researchers to monitor the condition of vineyards and take prompt action. According to M.G. Thompson *et al.* (2020), symptoms of the disease are more likely to occur on bush boles, especially after damage by abiotic factors. This suggests that stressful conditions, such as drought, excessive humidity, or temperature fluctuations, can substantially weaken plants, making them more vulnerable to infections. Therefore, monitoring environmental conditions and their impact on the condition of grape bushes is a crucial aspect in preventing the development of crown gall. T. Nguyen-Huu *et al.* (2020) noted that crown gall weakens grapevines, causes a sharp decline in yield, and in some cases leads to partial or complete plant death. This highlights the need for prompt diagnosis and treatment of the disease, as a delay in its detection can lead to major economic losses for viticulturists. Additionally, agronomic measures to strengthen plants, such as improved nutrition and water management, can help reduce the damage caused by crown gall. T. Meyer *et al.* (2019) also found that the danger of crown gall is that the bacterium, accumulating in the soil, can later cause root infection in new plantations of grape plants.

Notably, bacterial plant diseases are generally challenging to control. According to L.M. Yepes *et al.* (2019), copper bactericides and antibiotics are ineffective, while disease prevention by planting pathogen-free planting material is complicated by the vegetative propagation of infected, asymptomatic vines. Under such conditions, according to A.T. Wong *et al.* (2021), it is promising to use non-pathogenic strains of Rhizobium (synonym for Agrobacterium) by co-inoculation with pathogenic bacterial isolates to reduce the damage to grapevine seedlings.

The purpose of this study was to conduct a phytosanitary inspection of grape plantations in the Odesa region to determine the spread of crown gall and identify the causative agent. For this purpose, it was necessary to extract and screen agrobacterial isolates for their antagonistic properties against *A. tumefaciens.*

MATERIALS AND METHODS

The study was conducted at the Laboratory of Virology and Microbiology of the National Scientific Centre "Institute of Viticulture and Winemaking named after V.E. Tairov" of the National Academy of Agrarian Sciences (NAAS) of Ukraine. The study followed the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). The grape plantations were inspected at the research farms of the National Scientific Centre "Institute of Viticulture and Winemaking named after V.E. Tairov" and industrial farms in Odesa region according to DSTU 3355:1996 (1997) and DSTU 4390:2005 (2006). Visual phytosanitary inspection and assessment of the degree of crown gall infection was based on the examination of plants in the plantations. Samples of grape plants of Cabernet Sauvignon, Merlot, and Chardonnay varieties were selected based on external symptoms: the presence of tumours in certain areas of the plants, as well as asymptomatic plants to detect the latent form of the disease. The grape plant samples were collected, stored, and prepared according to ISO 16578:2022 (2022). Classical polymerase chain reaction (PCR) was used to identify *A. tumefaciens*.

The study employed the method of semi-selective nutrient media for the determination of agrobacteria, original and modified methods for the isolation of DNA of the crown gall pathogen, and PCR for the identification of *A. tumefaciens*. Bacteria were isolated from grape tissues according to the Lehoczky method (Lehoczky, 1971). Tumour, ripened vine, strands, or roots were used as samples for detection of the crown gall pathogen. The average sample of vines was formed from 1-3 two-year-old shoot fragments from several different parts of the bush, which were selected as close to the perennial wood as possible. For the extraction of agrobacteria, discs 0.2-0.5 cm tall were cut from each fragment; 15-20 discs of the average sample were placed in 3-5 ml of sterile distilled water. The agrobacteria were isolated from the samples under aseptic conditions using sterile dishes, instruments, and culture media. Agrobacteria were isolated on semi-selective nutrient medium (Roy and Sasser medium) of the following composition per 1,000 ml: $MgSO_4$ – 0.20 g, K_2HPO_4 – 0.9 g, KH_2PO_4 – 0.7 g, adonitol – 0.4 g, yeast extract – 0.14 g, NaCl – 0.2 g, boric acid – 1.0 g, agar – 15 g, pH – 7.2. After autoclaving and cooling to +50°C, the following were added: triphenyltetrazolium chloride – 0.08 g, trimethoprim – 0.02 g, d-cycloserine – 0.02 g, cycloheximide – 0.25 g. The colonies of agrobacteria obtained on the medium in Petri dishes were inoculated into tubes with bevelled agar and incubated for 1 day in a thermostat at +28°C. Subsequently, isolates of agrobacteria were identified by PCR (Abolmaaty *et al.*, 2000). The plasmid

DNA of *A. tumefaciens* was isolated using cetavlon, thermal method or alkaline lysis, and the resulting preparations were stored at −20°C. For PCR, reagents qualified as "for molecular biology", sterile solutions, and glassware were used. PCR was performed following the certified methodology No. MVV 002-85/3 – 2006.

To detect *A. tumefaciens*, specific primers were used for the ipt isopentenyltransferase gene: ipt1/ipt2 GATCG(G/C)GTCCAATG(CT)TGT/GATATCCATCGATC(TC)CTT and for the VirD2 endonuclease gene of the pathogenicity plasmid: virD2A/virD2C ATGCCCGATCGAGCTCAAGT/TCGTCTGGCTGACTTTCGTCATAA (Haas *et al.*, 1995). Primers were synthesised by Fermentas (Lithuania). Real-time PCR was performed using forward and reverse primers, fluorescently labelled DNA probes, reaction mixture in the amount of 20 µl (H_2O_2 – 8.5 µl; 10×PCR buffer – 2.5 µl; 4mM dNTP – 2.5 µl (1.76 mM – 2.84 µl); pr1 – 0.5 µM; pr2 – 0.5 µM; fluorescent probe – 0.1 µM, Taq polymerase (2.5 u/µl) (*Pfu DNA, Fermentas, Lithuania*) – 0.25 µl; Mg^{2+} – 3.0 mM and 5 µl of NCS, or PCS, or internal control, or test sample (at the bottom of the tube). The concentrations of forward and reverse primers and fluorescent DNA probes were selected empirically. To control the reaction, the study used a negative control sample (NCS) – 1×PCR buffer and a positive control sample (PCS) – the reference strain Fa-2 of the crown gall pathogen. Amplification was performed in a programmable thermocycler Rotor-Gene 6000 (Corbett Research Pty Ltd., Australia), which provided a temperature range within +40-100 °C, in the following mode:

1. Denaturation 95°C – 30 sec;
2. Annealing 60°C – 1 min;
3. Elongation – 72°C – 1 min (30 cycles);
4. Final elongation – 72°C – 10 min.

The solution with the amplification products was stored at −20°C. Initial denaturation was 95°C for 12 min. Fluorescence signal accumulation was measured for 4 channels, respectively: FAM/Green (470 nm/510 nm) for the identification of the crown gall pathogen, JOE/Yellow/HEX (530 nm/555 nm), ROX/Orange (585 nm/610 nm), Cy5/Red (625 nm/660 nm, and Cy3.5/Orange (585 nm/610 nm) for the endogenous internal control signal. The analysis results were recorded, and threshold cycles were calculated using Rotor-Gene 6000 Series Software 1.7. The amplification products were detected by increasing the fluorescence of the intercalating dye when it forms a complex with the double-stranded DNA of the crown gall pathogen. A positive sample was considered the one that showed an increase in the fluorescent signal on one of the colour channels of the amplifier.

To determine the pathogenicity of the extracted agrobacteria, test plants were used: tomatoes (*Solanum lycopersicum* L.) and sunflower (*Helianthus annuus* L.). The plants were inoculated with a suspension of these agrobacteria in the amount of 10^9 CFU/ml by cutting the internode of the stem at the level of 2-3 leaves. The wound was covered with Parafilm film (USA) to prevent drying of the bacterial suspension. The inoculated plants were incubated for 14-28 days at +25°C. Uninfected plants inoculated with sterile distilled water were used as a negative control. The positive control included plants inoculated with the reference *A. tumefaciens* pathogenic strain Fa-2 (isolated from grape roots; kindly provided by Dr T.J. Burr, USA).

Infection of plants by pathogenic bacteria *A. tumefaciens* occurs in the soil through damaged roots. To investigate the antagonistic effect of non-pathogenic isolates of *A. tumefaciens* ILVM1 and ILVM2, the cut roots of grape seedlings were soaked for one hour in a cell suspension (10^9 CFU/ml). After soaking, the treated grape seedlings were planted in pots with soil inoculated with a mixture of three strains of *A. tumefaciens*: Fa-2, 271, and IDI with a final concentration of 10^8 CFU/g soil and were grown in greenhouses. The development of tumours formed on the roots and stems of plants was studied.

RESULTS AND DISCUSSION

During the inspection of plantations in the industrial viticulture zone in the Odesa region, tumours typical of crown gall were found on grape bushes (Fig. 1). The tumours were identified by PCR analysis. The latent infection with the crown gall of grape pathogen on individual grape varieties ranged within 0-30%, depending on the susceptibility of the variety and the origin of the planting material.

Figure 1. Symptoms of crown gall on the grape plant
Source: photograph taken by the authors of this study

In studies, symptoms of the disease were observed on seedlings with latent infection as early as 1-2 years after planting. With the affected planting material, the crown gall pathogen enters the soil, and the infected area can continue to be a reservoir of *A. tumefaciens* for a long time.

A visual inspection of the vineyards in the study area revealed the presence of varying degrees of crown gall on young and fruiting plantations. The degree of development of the disease on technical varieties was as follows: Cabernet Sauvignon – up to 35%, Merlot – 25%, Chardonnay – 15%, which suggests the need to develop and improve crown gall control measures. Y. Wang *et al.* (2018) found that all grape varieties may be at risk of infection with the crown gall pathogen to some extent, and there are no varieties entirely resistant to this pathogen.

The use of antagonist microorganisms as part of a biological method of disease control is promising. Specifically, in the studies of H. Pan *et al.* (2022), the *Bacillus megaterium* L2 strain exhibited antibacterial activity against *A. tumefaciens* T-37, as its biologically active substances can destroy the integrity of the cell membrane, damage cellular structures, affect cellular metabolism, and inhibit protein synthesis. In the study by G.E. Qing *et al.* (2024), *Bacillus amyloliquefaciens* strain KN-527 had an inhibitory effect on *Agrobacterium vitis* in the early stages of crown gall development. At the same time, it is also interesting to use other isolates of agrobacteria against grape crown gall.

To search for antagonist bacteria, 50 bacterial isolates were isolated from soil in vineyards. The grown bacteria had a characteristic pink-red colour with a white border when cultivated on Roy and Sasser medium. The pathogenicity of the agrobacterium isolates was tested by real-time PCR (Fig. 2).

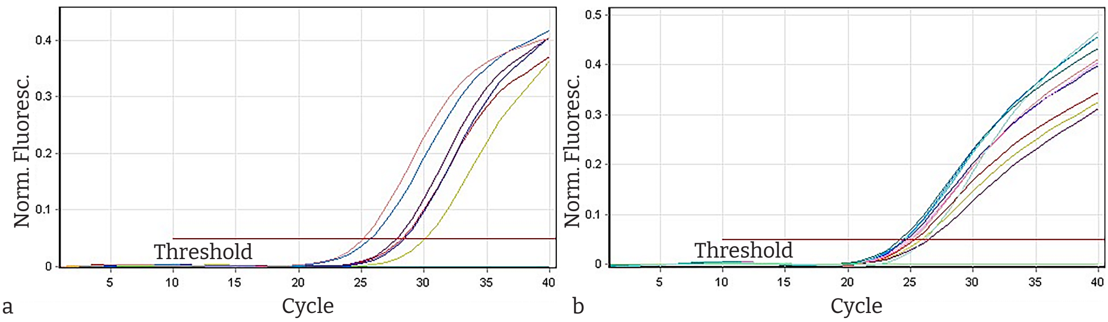


Figure 2. Results of testing isolates of agrobacteria for pathogenic properties
Note: a – bacterial isolates recovered from the soil in the vineyard aisles; b – bacterial isolates from the rhizosphere of grape bushes: 1 – positive control sample (PCS), reference strain Fa-2; 2 – negative control sample (NCS), PCR buffer, curves – pathogenic isolates
Source: developed by the authors of this study

It was found that most of the agrobacteria isolated from samples of grape plants collected in the vineyards of Odesa region contained fragments of *virD2* and *virF* genes simultaneously, which indicates their high virulence. To determine the antagonistic properties, non-pathogenic agrobacteria were used, which showed a zone of growth retardation of the test object at the level of 17-22 mm on the nutrient medium (Fig. 3). The screening for antagonistic properties revealed two isolates of *A. tumefaciens* ILVM1 and *A. tumefaciens* ILVM2, which had an elevated level of *in vitro* activity.

Screening tests for the presence of antagonistic properties of agrobacterial isolates on test plants (*S. lycopersicum, H. annuus*) confirmed the results of determining these properties obtained *in vitro*. It was found that most of the isolates tested for tumour inhibition had minor antagonistic properties and suppressed the disease by 20-30% compared to the positive control, but isolates of agrobacteria ILVM1 and ILVM2 considerably inhibited tumour growth on the stems of test plants (96%) compared to the pathogenic strain Fa-2 (Fig. 4; 5).

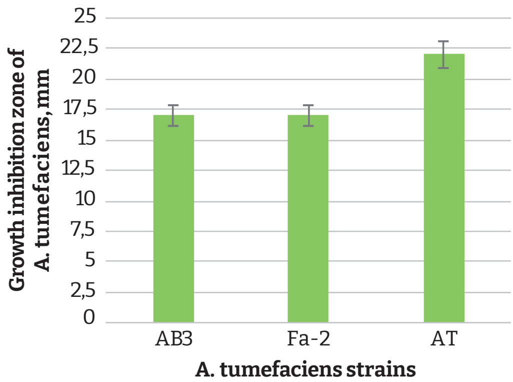
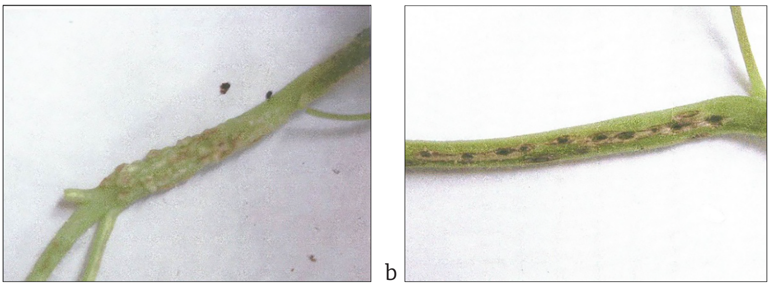
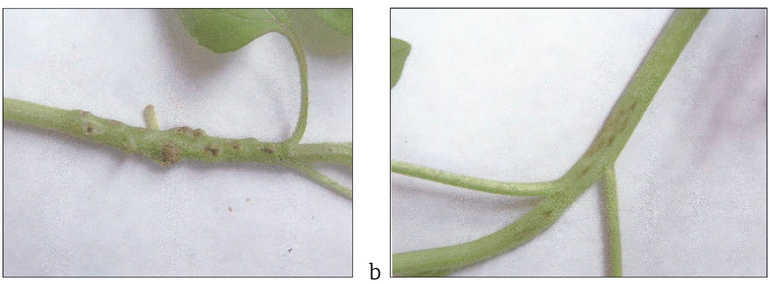


Figure 3. Antagonistic activity of a non-pathogenic isolate of ILVM 1 against reference plant pathogenic strains of *A. tumefaciens*
Source: developed by the authors of this study



a b

Figure 4. Influence of *A. tumefaciens* bacterial isolates on the manifestation of crown gall on *S. lycopersicum*
Note: a – disease symptoms after inoculation of the test plant with a suspension of bacteria of the *A. tumefaciens* pathogenic strain Fa-2 (10^9 CFU/ml); b – no disease symptoms after joint inoculation of the *S. lycopersicum* stem with a suspension of a mixture of non-pathogenic isolate ILVM1 and *A. tumefaciens* pathogenic strain Fa-2 (10^9 CFU/ml)
Source: photograph taken by the authors of this study



a b

Figure 5. Effect of *A. tumefaciens* bacterial isolates on the manifestation of crown gall of *H. annuus*
Note: a – disease symptoms after inoculation of the test plant with a suspension of the *A. tumefaciens* pathogenic strain Fa-2 (10^9 CFU/ml): b – no disease symptoms after inoculation of the *H. annuus* stem with a suspension of a mixture of non-pathogenic isolate ILVM2 and *A. tumefaciens* pathogenic strain Fa-2 (10^9 CFU/ml)
Source: photograph taken by the authors of this study

The results of the experiment were recorded 30 days after inoculation. It was found that in the places of inoculation of the stems of test plants *S. lycopersicum* and *H. annuus* with the *A. tumefaciens* pathogenic strain Fa-2, characteristic tumours appeared (Fig. 4a and 5a), which were not observed on test plants inoculated with a suspension of a mixture of non-pathogenic bacterial isolate ILVM2 and *A. tumefaciens* pathogenic strain Fa-2 (Fig. 4b and 5b).

The authors of the present study believe that the absence of symptoms of crown gall in test plants treated with a mixture of pathogenic and antagonist bacterial isolates is caused by the inhibition of *pehA* gene expression, which ensures the virulence of *A. tumefaciens*. It is probable that this process inhibits the transformation of host cells, thereby preventing tumour formation. At the same time, this hypothesis requires more detailed molecular biological research.

Treatment of the roots of different grape seedling varieties with ILVM1 isolate resulted in a 53-86% reduction in the percentage of plants with disease symptoms. The greatest effect was observed on Chardonnay plants (Fig. 6).

The efficacy of ILVM2 isolate was slightly higher and amounted to 66-87% in the varieties under study (Fig. 7). Thus, it was confirmed that preliminary inoculation of grape seedling roots with isolates of ILVM1 and ILVM2 was effective in reducing the damage to the root system by the crown gall pathogen.

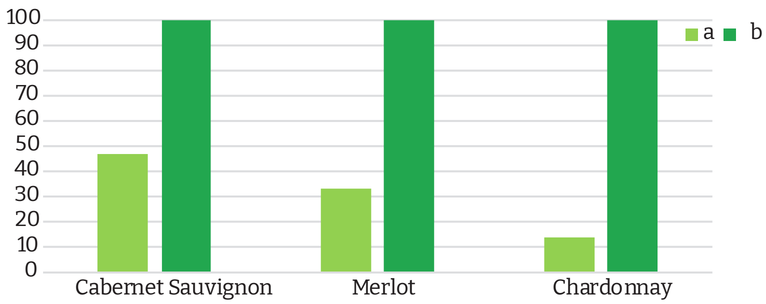


Figure 6. The effect of treatment of grape roots of different varieties with ILVM isolate on the susceptibility of seedlings to crown gall

Note: a – number of plants, %, affected by *A. tumefaciens* after treatment with ILVM1; b – control, number of plants, %, affected by *A. tumefaciens* without treatment with non-pathogenic isolate

Source: developed by the authors of this study

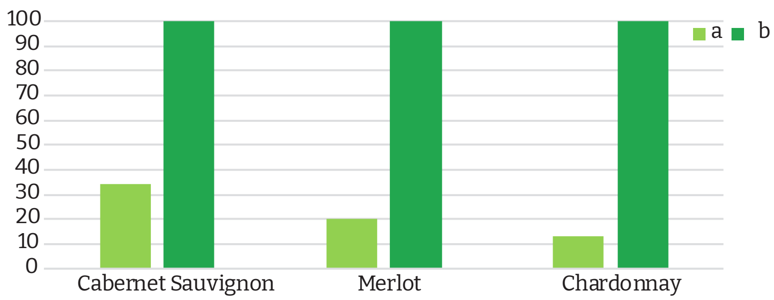


Figure 7. The effect of treatment of grape roots of different varieties with ILVM 2 isolate on the susceptibility of seedlings to crown gall

Note: a – number of plants, %, affected by *A. tumefaciens* after treatment with ILVM1; b – control, number of plants, %, affected by *A. tumefaciens* without treatment with non-pathogenic isolate

Source: developed by the authors of this study

The positive results obtained in the laboratory prompted field trials of the antagonistic effect of ILVM1 and ILVM2 isolates. These studies are a vital part of recent developments, especially in the search for biological defence products. Although positive results may be obtained in laboratory experiments, field trials often fail to produce the expected results, which necessitates such experiments.

To protect grape seedlings from secondary infection by pathogenic agrobacteria that are soilborne, the roots were treated with a mash of clay and a mixture of ILVM1 and ILVM2 isolates at a concentration of 10^9 CFU/ml. The effectiveness was evaluated in a year. It was found that in the variants with a mixture of non-pathogenic isolates of agrobacteria, the number of plants affected by *A. tumefaciens* ranged within 10-27%, which suggests a decrease in the spread of crown gall by 73-90%, depending on the grape variety (Fig. 8). The analysis showed the absence of pathogenic isolates of agrobacteria in the rhizosphere soil.

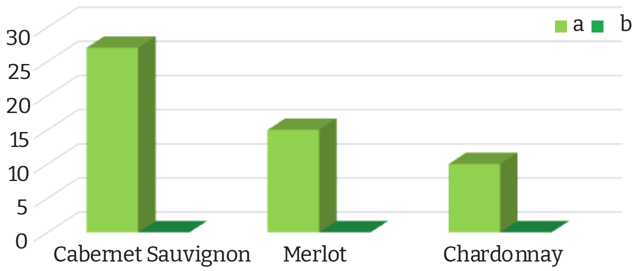


Figure 8. Influence of combined use of agrobacterium antagonist isolates on the presence of crown gall pathogen in grape plants of different varieties and in rhizosphere soil

Note: a – number of plants, %, affected by *A. tumefaciens* after treatment of seedlings with ILVM1 + ILVM 2 mixture; b – presence, %, of *A. tumefaciens* in the rhizosphere after treatment of seedlings with ILVM1 + ILVM2 mixture

Source: developed by the authors of this study

The unique action of *A. tumefaciens* lies in the possibility of its use as a tool during plant reproduction (Ben Abdallah *et al*., 2015). The use of an agrobacterium not only shortens the conventional process of plant propagation, but also allows the introduction of completely new genes into the plant, which are not typical for the plant, through genetic engineering (Lacroix & Citovsky, 2019; Guo *et al*., 2019).

According to T. Tzfira *et al.* (2017), *A. tumefaciens* is one of the most interesting and important bacteria for the detailed investigation of its antagonistic properties. It can be used to control crown gall. This is the first and most successful example of biological protection of grapes from a disease (Frikha-Gargouri *et al*., 2017).

Other scientists conducted comparable studies on biological control of the disease. V. Stockwell *et al.* (1996) found that *Agrobacterium radiobacter* strain K84 controls the disease caused by *A. tumefaciens* by producing the plasmid agrocin 84, an antibiotic with specific activity against certain strains of the pathogen. In S. Chopra *et al.* (2016), several non-pathogenic strains also helped to reduce infection, but especially *A. radiobacter* K84, which completely prevented the disease when added to the wound sites at a 1:1 ratio with *A. tumefaciens* cells.

According to R. Peñalver *et al.* (2000), *Agrobacterium radiobacter* strain K84 has been a biological control agent for crown gall for many decades worldwide. Despite its demonstrated efficacy, the greatest risk of failure with the K84 strain is the possibility of transferring the pAgK84 plasmid to pathogenic Agrobacterium strains. Later, the second generation of the K84 strain was obtained and the genetically modified strain was named K1026. It contains a deletion in the pAgK84 transfer region. A considerable amount of research has also been conducted to compare the two strains in terms of their ability to control disease, plasmid transfer, antibiotic production, root colonisation, and rhizosphere survival.

Q. Wei *et al.* (2009) indicated that *Agrobacterium vitis* E26 is a promising potential biocontrol agent for crown gall of grapevine. However, its safety and environmental risks should be understood. According to the findings of the study, the researchers found that the *A. vitis* E26 strain does not contain the virA and virG determinants. This suggests that this strain is unlikely to cause symptoms in both host and non-host plants.

Y. Hao *et al.* (2011) found that the avirulent strain of *A. tumefaciens* D3 contains a putative structural gene for ACC deaminase (acdS) and a regulatory gene (acdR = lrpL). Studies revealed that under gnotobiotic conditions, wild-type *A. tumefaciens* D3 can promote root elongation, while the acdS and lrpL double mutant *A. tumefaciens* strain D3-1 lost this ability. When co-inoculated with the virulent *A. tumefaciens* strain C58, both *A. tumefaciens* D3 wild type and *A. tumefaciens* D3-1 mutant were found in damaged castor oilseed rape plants, which can substantially suppress the development of crown gall caused by *A. tumefaciens* C58.

A. Kawaguchi *et al.* (2017) identified a non-pathogenic *Agrobacterium vitis* strain ARK-1 and found it to be effective in suppressing tumour formation on grapevines. Further studies of the *Rhizobium vitis* ARK-1 strain in the field showed its therapeutic effect and a decrease in the number of grape plants with symptoms of crown gall. According to A. Kawaguchi *et al.* (2019), co-inoculation of *R. vitis* ARK-1 with the pathogenic strain Ti VAT03-9 in a 1:1 cell ratio in grapevine shoots resulted in a significantly lower expression of the virulence genes virA, virD3, and virG of VAT03-9.

A. Wong *et al.* (2021) tested the non-pathogenic *R. vitis* strain ARK-1 (isolated in Japan) against four pathogenic *R. vitis* isolates from grapevines in Virginia (USA). Specifically, co-inoculation with ARK-1 significantly reduced the occurrence of disease symptoms and the average size of growths, except for the ACME15 isolate.

Scientists are also investigating other areas of biological protection of grapes against crown gall. D. Ferrigo *et al.* (2017) conducted experimental trials to assess the effectiveness of treatments based on non-pathogenic endophytes. Two-year *in planta* trials conducted on rootstocks treated with endophytic isolates showed the effectiveness of two bacterial endophytes from the genus Curtobacterium and a fungal isolate from the genus Acremonium. They led to a reduction in the development of disease symptoms. The researchers also noted the effectiveness of commercial biological control agents based on *B. subtilis* SR63 and *T. asperellum* T1 strains against *A. vitis*.

In Ukraine, N. Lemanova & M. Magher (2019) investigated the biological preparation "Paurin" based on the bacteria *Pseudomonas fluorescens* CNMN-PsB-04. For this, the biological preparation was used by treating apple MM-106 rootstock cuttings and fruit seeds before planting them in the soil. This method helped to reduce the damage to plants by crown gall by 2.0-2.5 times.

N.V. Limanska *et al.* (2019) investigated the effect of *Lactobacillus plantarum* bacteria on tumour formation and survival of *A. tumefaciens* pJZ on plant surfaces and tissues. The experimental results showed that the number of test plants (of different species) with disease symptoms in the presence of *L. plantarum* in the inoculum decreased by 85-100%. The average weight of tumours was reduced by 2-12 times compared to the control. On grapes, inoculation with a mixture of *A. tumefaciens* and *Lactobacillus* caused stimulation of plant growth, which was manifested in an increase in the number of buds that opened, an increase in the average length of shoots and an increase in the average area of the leaf apparatus.

The findings of the experiments presented in this study demonstrated a wide range of antagonistic activity of the studied isolates ILVM1 and ILVM2 against the reference agrobacterium *A. tumefaciens.* This points to the possibility of expanding the scope of practical use of these strains to create a potential effective biological product as a means of controlling the pathogen of crown gall in the south of Ukraine. In the future, the development and use of a product based on these bacteria will help reduce the percentage of plants affected by soil infection and prevent the spread of the disease, which will considerably increase the economic level of seedling production, increase the quantity, and improve the quality of the crop.

CONCLUSIONS

The study investigated the spread of crown gall in Odesa region, screened the antagonistic activity of non-pathogenic isolates of *A. tumefaciens in vitro* and *in vivo*, and determined their ability to control the disease in the field.

According to the findings of the phytosanitary inspection of grape plantations in Odesa region, the disease prevalence ranged within 15-35% (on Chardonnay, Merlot, and Cabernet Sauvignon varieties). Using the real-time PCR method, pathogenic isolates of agrobacteria were identified, and non-pathogenic isolates were also recovered. The latter were tested for antagonistic properties against the crown gall pathogen. Thus, *in vitro* on nutrient medium, the growth inhibition zone of the test object was 17-22 mm. As a result of the antagonistic properties study, two isolates of *A. tumefaciens* ILVM1 and *A. tumefaciens* ILVM2 were identified, which had a pronounced activity level. It was proved that non-pathogenic isolates of agrobacteria ILVM1 and ILVM2 inhibited the development of crown gall *in vitro* and *in vivo* on test plants *S. lycopersicum* and *H. annuus*.

The obtained findings on plants of different grape varieties allowed establishing the effectiveness of treatment of seedling roots with isolates of non-pathogenic agrobacteria ILVM1 and ILVM2. Specifically, the ILVM1 isolate led to a 53-86% reduction in the percentage of plants with disease symptoms. The effectiveness of ILVM2 isolate was 66-87%. The lowest number of diseased plants was observed on plants of the Chardonnay variety.

With the combined use of non-pathogenic isolates of agrobacteria, the number of plants affected by *A. tumefaciens* ranged within 10-27%, which indicates a decrease in the spread of crown gall by 73-90%, depending on the grape variety.

Thus, isolates of agrobacteria ILVM1 and ILVM2 showed antagonistic properties to the pathogen of grape crown gall, which in the future allows using them to develop biological means of protection against this dangerous disease.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Бактеріальний рак виноградної лози та перспективи його біологічного контролю

Анотація. Актуальність дослідження обумовлена поширенням бактеріальних хвороб винограду на півдні України та необхідністю удосконалення методів ідентифікації патогену й засобів захисту. Метою було роботи було встановити ареал бактеріального раку винограду в Одеській області та розробити профілактичні заходи на основі біологічного методу. У роботі проводили обстеження промислових насаджень на наявність симптомів хвороби та її поширення у польових умовах. Використовували молекулярно-біологічний метод полімеразної ланцюгової реакції (ПЛР) у реальному часі для ідентифікація збудника бактеріального раку. Дослідження проводились відповідно до атестованої методики. Для ідентифікації фітопатогенів використовували обладнання ПЛР-лабораторії. У результаті фітосанітарного обстеження виноградних насаджень різних господарств в Одеській області були виявлені кущі виноградних рослин з характерними симптомами бактеріального раку, з пухлинними наростами тканини в різних місцях рослин: на рукавах, штамбі, місцях щеплення. Загалом у районі проведення досліджень бактеріальний рак винограду характеризується широким ареалом. За результатами фітосанітарного обстеження поширення бактеріального раку винограду на різних сортах становило від 0,3 до 35 %. У режимі реального часу методом ПЛР було ідентифіковано збудника хвороби – *A. tumefaciens.* Хвороба проявлялася у вигляді характерних симптомів, а також розвивалася у латентній формі. Розроблена мультиплексна ПЛР дозволяє одразу аналізувати різні штами патогенних ізолятів агробактерій. Серед більшості виділених ізолятів, які в подальшому були протестовані на пригнічення пухлин, було виявлено два ізоляти агробактерій: ІЛВМ1 і ІЛВМ2, які мали високі показники антагоністичних властивостей щодо збудника бактеріального раку. Перевірка патогенності вилучених агробактерій на тест-рослинах томатів і соняшнику підтвердили результати визначення цих властивостей, отриманих і*n vitro*. Ізоляти агробактерій ІЛВМ1 і ІЛВМ2 значно інгібували ріст пухлин на стеблах тест-рослин порівняно з патогенним штамом, тому їх в подальшому можна використовувати проти збудника бактеріального раку і захисту виноградних рослин від вторинного ураження патогеном із ґрунту. Результати можуть бути використані для вдосконалення методів біологічного захисту рослин від бактеріальних інфекцій

Ключові слова: хвороби винограду; полімеразна ланцюгова реакція; *Agrobacterium tumefaciens*; бактерії-антагоністи; біологічний захист

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The effectiveness of intercropping in the Forest-Steppe zone of Ukraine

Abstract. Intercropping of agricultural crops offers a valuable technological solution for resource conservation and improved crop yield, essential to global food security. This study aimed to assess the effectiveness of intercropping maize and soybeans. Scientific methods were employed for conducting field and laboratory research, with experimental findings analysed statistically and interpreted. The study established that intercropping maize variety RAGT Zanetikks with soybean varieties Sirelia and Sakuza provides several advantages over monoculture cropping, especially in terms of yield formation. Maize demonstrated efficient utilisation of additional soil nitrogen fixed by soybeans in mixed plantings, resulting in significant maize yield gains across all fertiliser levels and even without fertilisation. The increase in maize yield in intercropped systems, compared with monoculture, ranged from 10.3% to 19.3%, depending on the fertiliser rate. The highest maize yield was achieved with $N_{90}P_{60}K_{60}$ fertilisation: 10.26 t/ha in monoculture and 12.19-12.24 t/ha in intercropped systems. Although soybean yield declined in intercropped plantings, the combined yield of both crops in intercropping systems showed a substantial increase, reaching 14.51-14.70 t/ha under $N_{90}P_{60}K_{60}$ conditions. The yield was strongly correlated with the leaf area index (r = 0.93-0.99). Soil nitrate nitrogen content was higher under soybean but decreased under intercropping systems.

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Soil biological activity increased with $N_{60}P_{45}K_{45}$ fertilisation in maize and soybean monocultures (39.4 and 47.2 mg CO_2/kg soil/day, respectively) and reached 52.6-55.1 mg CO_2/kg soil/day in intercropped plantings. These findings have significant practical implications for production, promoting resource conservation and increasing gross grain production

Keywords: leaf area index; photosynthetic potential; soil biological activity; soil nitrate nitrogen content; yield

INTRODUCTION

The efficient use and conservation of natural resources, coupled with the optimisation of technological inputs in crop production within the Forest-Steppe zone of Ukraine, has become increasingly pressing given the need to bolster food production. Intercropping, a method that combines different crops within the same planting space, has the potential to significantly enhance the efficiency of land use and reduce the need for additional inputs aimed at boosting yields. This approach contributes to a decrease in the use of fertilisers and pesticides, mitigating negative impacts on soil and water, and also helps to reduce greenhouse gas emissions associated with conventional agricultural practices. P. Manasa *et al.* (2020), through a comprehensive analysis of yield structure, productivity, competitiveness, and economic efficiency of intercropping maize with legumes, demonstrated the high effectiveness of such plantings. E.S. Jensen *et al.* (2020) indicated that the share of intercropping in European agriculture is increasing to develop more sustainable agriculture and create efficient food production systems.

E. Gillbard (2022) demonstrated that, for intercropping systems, the mechanism for increasing yield is primarily focused on nutrient optimisation. A. Wysokiński & B. Kuziemska (2019) dedicated their research to the shared use of resources and the increased proportion of fixed nitrogen through transport from the legume crop to the partner crop. W. Wang *et al.* (2022) proved that intercropping soybean with cereals demonstrates a positive interaction, significantly increasing the productivity of maize and wheat by 18.1-20.9%. The authors showed that biomass accumulation increased in intercrops: in monoculture systems, the average above-ground biomass of corn was 22.9 t/ha, soybean – 8.1 t/ha, and wheat – 11.8 t/ha; in intercrops, biomass increased by 14.5 and 17.9%, and the maximum instantaneous growth rate of corn and wheat increased by 29.4 and 34.0%, respectively. As indicated by S. Maitra *et al.* (2020), the system of intercropping was widely used in semi-arid regions due to its high and stable productivity, and efficient resource use.

In Ukraine, research on intercropping systems for forage production has been ongoing for an extended period. The results obtained by V.I. Dudchenko (2017) confirmed the effectiveness of optimal species selection, which contributes to increased vegetative mass formation and dry matter accumulation. In connection with the growing demand for biofuels, research has emerged on the intercropping of energy crops with partner crops to effectively utilise wide row spacing and produce additional plant products. Such studies have been conducted on the selection of combinations of energy crops with other species. V.O. Dekovets & M.I. Kulyk (2023) showed that the highest biomass yield of miscanthus is formed when intercropped with lupin and using the mycorrhizal preparation Mycofriend to feed energy crops – 20.7 t/ha. At the same time, research on intercropping cereal and legume crops grown for grain production in Ukraine is only beginning and requires unconditional expansion. A. Shuvar *et al.* (2019) studied the formation of productivity of agrocenoses of spring cereals and legumes when grown on the sloping lands of the Carpathian region. It was established that when sowing mixtures of cereals and legumes, yield indicators increased compared to monocultures and depended on the fertiliser background.

The study aimed to establish the effectiveness of intercropping maize and soybeans in terms of increasing total crop production, enhancing nitrogen utilisation, improving soil biological activity, and optimising the functionality of the crops' photosynthetic surface.

The research objectives were to: assess the impact of intercropping maize and soybeans on gross agricultural production; investigate nitrogen utilisation efficiency and soil biological activity under intercropped maize and soybean conditions; and substantiate the specific features of photosynthetic surface function in intercropped systems, aiming to develop agrocenoses with greater resilience to stress conditions.

MATERIALS AND METHODS

The research was conducted in the educational and scientific laboratory of the Department of Crop Growing at a separate subdivision of the National University of Life and Environmental Sciences of Ukraine (NULES) "Agronomic Research Station" (Pshenychne village, Kyiv Region) on typical low-humus chernozems in 2022-2024. Laboratory analyses were carried out in the "Analytical Studies in Crop Production" laboratory, also part of the Department of Crop Growing at NULES. The experiments were set up following standard methodologies for field research (Rozhkov, 2016). The field experiment employed a split-plot design with two factors. First-order blocks were allocated to field crops, including both monoculture and intercropped plantings, while second-order blocks focused on fertilisation treatments. Each plot measured 100 m^2, with a net harvested area of 80 m^2. The experiment included four replications.

The planting scheme and seeding rate for each crop were aligned with the experimental design (Table 1). In monoculture, the seeding rate for soybeans and maize corresponded to the zonal recommendations of the originator. In intercrops, the seeding rate for soybeans was reduced by 50%. The sowing depth for maize was 4-5 cm, and for soybeans, 2-3 cm.

Table 1. Experimental design: Factor A – monocultures and intercrops

No.	Crop/Intercrop, *Factor A*	Variety/Hybrid	FAO/CHU	Seeding rate (thousands of seeds)
1	Maize	RAGT Zanetikks	FAO 340	70
2	Soybean	Sirelia	CHU 2300	450
3	Soybean	Sakuza	CHU 2600	450
4		RAGT Zanetikks + Sirelia		70 thousand/ha+225
5		RAGT Zanetikks + Sakuza		70 thousand/ha+225

Source: compiled by the authors

Factor B – *fertilisation, kg/ha of active substance (a.s.):*

1. No fertilisation – control (C)
2. $N_{60}P_{45}K_{45}$.
3. $N_{90}P_{60}K_{60}$.

Sowing methods: monocultures – maize with a row spacing of 70 cm, soybeans – 19 cm; intercrops – maize 70 cm, with one row of soybeans sown between the rows. All crops were sown at the same time. Sowing was carried out using seed drills with press wheels – specifically, Kinze and Great Plains.

During the experimental research, the following observations and measurements were conducted, following the methodologies outlined by A.O. Rozhkov (2016):

- *Phenological observations* recorded dates for emergence, duration from emergence to flowering, and from flowering to full grain maturity. Plant counts were conducted on two-metre sections of rows at 2 to 4 evenly spaced points along the diagonal lines of each plot. The initial seedling phase was recorded when 15% of plants had emerged in the plot, and full emergence when 75% of plants had emerged, with rows clearly visible across the plot.
- *Linear measurements* – during the tasselling phase of maize, the leaf area of the plants' assimilation apparatus was measured in both monoculture and intercropped plantings.

Leaf area was determined using the "cutting" method:

$$S = (M^*n^*k)/m, \quad (1)$$

where M is the mass of leaves in the sample, g; n is the area of one cutting, cm^2; k is the number of cuttings, pcs; m is the mass of cuttings, g.

- *Photosynthetic activity of maize crops* measured as the photosynthetic potential (PP). The photosynthetic potential of the crop (PP) is calculated as the product of the average leaf assimilation area (S_L) and the duration of the active growing period (tGRW):

$$PP = S_L {}^* tGRW, m^2 \cdot days/ha. \quad (2)$$

In maize, 1000 units of PP provide for the formation of 3-5 kg of grain, and in soybeans, 0.81.5 kg of seeds.

- *Nitrate nitrogen content in the soil* was determined using a photometric method with disulphophenolic acid according to DSTU 4729:2007 (2007). This method is based on the ability of nitrates to react with this acid to form trinitrophenol, which in an alkaline medium forms yellow ammonium trinitrophenolate. The intensity of the colour is proportional to the nitrogen content. Photometric analysis of the solution was performed to determine the nitrate content.
- *CO_2 emission intensity per 1 m² per hour* was determined using the method developed by V.I. Shtatnov.
- *Biological grain yield of maize* – as maize has a high pre-harvest grain moisture content, the yield was recalculated to dry grain using the formula (3):

$$Y = Ym \cdot (100 - m)/(100 - Sm), \text{centner/ha}, \quad (3)$$

where Y is the grain yield at standard moisture, centner/ha; Ym is the grain yield at actual moisture, centner/ha; m is the actual moisture content of the grain (at harvest), %; Sm is the standard moisture content, %.

- *Biological seed yield of soybeans* – the number of plants per 1 m^2 was determined in several locations within the field. Plants were counted in 4-8 adjacent rows, ensuring that the total area, including row spacing, measured 1 m^2. The biological yield was calculated using the formula (4):

$$Y = N \cdot P \cdot S \cdot W/10^5, \quad (4)$$

where N is the number of plants per 1 m^2; P is the average number of developed pods per plant, pcs; S is the average number of seeds per pod, pcs; W is the 1,000-grain weight, g.

- *Agricultural techniques for field research* – maize seed was treated with a fungicideinsecticide complex, specifically Maxim XL (1.0 L/ton) + Poncho (2.7 L/ton). Soybean seed was treated with the fungicide Standak Top (10 L/ton) and the inoculant HiCoat (1.4 L/ton) – an inoculant in liquid formulation with an extender (*Bradyrhizobium japonicum* bacteria, strain 532C).

The research was conducted following the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992). Winter wheat was the preceding crop in the experiment. The wheat grain yield was 6.2 t/ha, and accordingly, 7.8 t/ha of by-products were returned to the soil. Soil cultivation involved stubble harrowing at a depth of 10-12 cm and ploughing at a depth of 25-27 cm. According to the experimental design and the mineralisation of plant residues, FERTIS NPK (10-20-20+S+ME) fertiliser was applied before primary tillage, and the remaining nitrogen fertilisers in the form of ammonium nitrate (34.4%) were applied during pre-sowing cultivation. At the stage of physical maturity of the soil, early spring moisture conservation was carried out. Two weeks later, cultivation was performed, and pre-sowing cultivation was carried out when the soil was consistently warmed to a depth of 10 cm to +10°C.

Before pre-sowing cultivation, the soil herbicide Primextra TZ Gold (4.5 L/ha) was applied. At the 3-5 leaf stage of maize, which coincided with the 1-3 trifoliate leaf stage of soybeans, the rescue herbicide Bazagran (3.0 L/ha) + surfactant Metolat (1.0 L/ha) was applied. The spray volume was 200 L/ha.

Harvesting and determination of biological yield were carried out at full maturity of the crops using modern methods – based on yield components recalculated to a basic moisture content of maize 14% and soybeans 12%.

RESULTS

Maize and soybeans are leading crops in Ukraine in terms of production. Innovative approaches to growing maize and soybeans are taking their production to a new level of economic, agricultural, and environmental efficiency. Intercropping of legumes and cereals has several advantages for partner crops, but at the same time, several questions require further research. Intercropping alters the cenoctic relationships in agrocenoses compared to monocultures of similar hybrids and varieties, which is reflected in various biological and morphological development traits of the crops and the formation of their productivity (Feng *et al*., 2020).

The phenology of growth and development in plants within intercropped and monoculture agrocenoses differs significantly and is also heavily influenced by fertiliser rates (Table 2).

Table 2. Duration of the growing season for monoculture and intercropped maize and soybeans, in days, average for 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s					
	No fertiliser (control)		$N_{60}P_{45}K_{45}$		$N_{90}P_{60}K_{60}$	
	Duration of growing season, days					
	M	S	M	S	M	S
RAGT Zanetikks, control	115	–	118		122	–
Sirelia	–	95	–	98	–	106
Sakuza	–	105	–	110	–	118
RAGT Zanetikks + Sirelia	117	98	121	103	125	114
RAGT Zanetikks + Sakuza	117	110	122	114	127	124

Note: M – maize, S – soybean, a.s. – active substance
Source: compiled by the authors

The duration of the growing season in both monoculture and intercropped plantings increases with higher rates of mineral fertilisers. In monoculture maize crops, an increase in fertiliser rates leads to a 3-7-day extension of the growing period, while in intercropped systems, the duration is extended by 4-8 days. However, the extension of the maize growing period in intercropped systems under similar fertilisation regimes is only 2-3 days. The extension of the growing season for soybean varieties in monoculture, with increased fertiliser rates, ranged from 3 to 13 days depending on the fertiliser rate and soybean variety, while in intercropped systems, the extension was 3-8 days, again depending on the fertilisation background and variety.

Intercropping maize with legumes, in contrast to monoculture planting, makes more efficient use of natural resources, particularly light. This is because the stems and leaves of the cereal and legume plants are arranged in different layers, allowing for more effective utilisation of solar energy. The intensification of photosynthesis presents new opportunities for increasing yield.

The productivity of photosynthesis in a crop is determined by two main factors: the total leaf surface area and the intensity of photosynthetic processes per unit of leaf area. The stratification of maize and soybean plants in mixed plantings led to differences in the formation of the assimilatory surface area, compared to monoculture plantings (Table 3).

Table 3. Leaf surface area of monoculture and intercropped plantings, in the tasselling phase, thousand m2/ha, 2022-2024

Hybrid + Variety	Leaf surface area*, thousand m²/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	37.2	–	37.2	42.1	–	42.1	44.4		44.4
Sirelia	–	32.1	32.1	–	34.2	34.2	–	36.7	36.7
Sakuza	–	32.9	32.9	–	35.4	35.4	–	37.2	37.2
RAGT Zanetikks + Sirelia	35.4	19.5	54.9	38.6	20.8	59.6	41.2	22.2	63.4

Table 3, Continued

Hybrid + Variety	Leaf surface area*, thousand m²/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks + Sakuza	35.2	21.3	56.5	41.1	22.0	63.1	42.7	23.1	65.8
Correlation coefficient** (r)	0.99	0.97	0.93	0.99	0.97	0.96	0.99	0.94	0.95

Note: * – M – maize; S – soybean; M+S – maize and soybean together; ** – correlation coefficient for "leaf surface area" and "yield", a.s. – active substance, c – control
Source: compiled by the authors

In monoculture plantings, the leaf surface area of individual crops was greater than in intercropped systems, specifically 37.2-44.4 thousand m²/ha for maize and 32.1-37.2 thousand m²/ha for soybean, increasing with higher fertiliser rates. At the same time, intercropping maize and soybean together resulted in a larger total leaf surface area – in the combination of Zanetikks + Sirelia – 54.963.4 thousand m²/ha; Zanetikks + Sakuza – 56.5-65.8 thousand m²/ha.

The photosynthetic potential of the crop (PP) more fully characterises the photosynthetic activity of field crop plantings, reflecting the efficiency of the leaf apparatus over the period during which the assimilatory apparatus remains physiologically active (Table 4).

Table 4. The photosynthetic potential of monoculture and intercropped maize and soybean, million m²*days/ha, 2022-2024

Hybrid + Variety	Leaf surface area, thousand m²/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	2.34	–	2.34	2.71	–	2.71	2.96	–	2.96
Sirelia	–	1.67	1.67	–	1.83	1.83	–	2.13	2.13
Sakuza	–	1.89	1.89	–	2.13	2.13		2.40	2.40
RAGT Zanetikks + Sirelia	2.26	1.05	3.31	2.55	1.17	3.72	2.81	1.38	4.19
RAGT Zanetikks + Sakuza	2.25	1.28	3.53	2.75	1.37	4.12	2.96	1.56	4.52

Note: M – maize; S – soybean; M+S – maize and soybean together, a.s. – active substance, c – control
Source: compiled by the authors

Providing plants with essential nutrients is a crucial component in the formation of yield and grain quality. Adequate nitrogen levels in the soil ensure proper growth and development of plants, making it one of the key indicators of soil fertility. Nitrogen in its nitrate form is easily absorbed by plants, and thus this indicator reflects the soil's mineral nitrogen content. In mixed crops, with a specific ratio of components, maize is the primary consumer of nitrogen (Table 5).

Table 5. Nitrate nitrogen (NO_3) content in the 0-30 cm soil layer, at the 9-10 leaf stage of maize, mg/kg of soil, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	12.1	13.5	13.7
Sirelia	14.5	15.1	15.6
Sakuza	14.2	15.3	15.8
RAGT Zanetikks + Sirelia	13.5	14.7	15.0
RAGT Zanetikks + Sakuza	13.6	14.5	14.8

Note: a.s. – active substance
Source: compiled by the authors

The nitrate nitrogen content in the soil varied depending on whether monoculture or mixed crop cultivation was used, as well as the fertilisation practices. The highest nitrate nitrogen content in the soil at the 9-10 leaf stage of maize was observed in monoculture soybean cultivation, ranging from 14.2 to 15.8 mg/kg of soil. According to the grading system, this level is considered high. Maize has two critical periods concerning the uptake of mineral nutrients. The first, which coincides with the phase between seedling emergence and the 5-7 leaf stage, is critical for phosphorus nutrition. The second critical period is during the period of intensive growth and development (9-10 leaf stage to tasselling), during which maize plants consume approximately 70% of their total nitrogen, thus influencing the soil's nitrate nitrogen reserves (Table 6).

Table 6. Nitrate nitrogen (NO_3) content in the 0-30 cm soil layer at the tasselling stage of maize, mg/kg of soil, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser (c)	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	10.4	12.9	13.2
Sirelia	14.2	14.8	15.3
Sakuza	14.4	14.9	15.5
RAGT Zanetikks + Sirelia	12.1	13.4	14.1
RAGT Zanetikks + Sakuza	12.1	13.2	14.2

Note: a.s. – active substance
Source: compiled by the authors

At the tasselling stage of maize, the highest levels of nitrate nitrogen reserves were recorded in monoculture soybean crops. In mixed crops, the nitrate nitrogen content was lower, which is attributed to the significant nitrogen absorption by the maize plants. With the application of $N_{90}P_{60}K_{60}$, the nitrate nitrogen content in the mixed crop of RAGT Zanetikks + Sakuza was 14.2 mg/kg of soil, indicating a high level of nitrogen availability. Research into soil biological activity provides a broader understanding and reveals patterns in the processes of organic matter transformation, taking into account the anthropogenic impact on the soil and its properties (Table 7).

Table 7. Total biological activity of the soil, mg CO_2/kg soil/day, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser (c)	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	33.1	39.4	37.4
Sirelia	44.6	47.2	43.2
Sakuza	44.6	47.5	42.8
RAGT Zanetikks + Sirelia	40.6	52.6	50.5
RAGT Zanetikks + Sakuza	42.5	55.1	51.3

Note: a.s. – active substance
Source: compiled by the authors

Observations of soil respiration intensity over time revealed that the highest values of this indicator occurred in the middle and latter stages of the growing season, while the lowest values were observed at the beginning. A positive effect of the interaction between maize and soybean in intercropping was established. In intercropping, maize hybrid RAGT Zanetikks with soybean varieties Sirelia and Sakuza resulted in significant increases in maize yield across all fertiliser treatments and the control variant, indicating additional nitrogen supply to the maize through nitrogen fixation by soybeans (Table 8).

Table 8. Yield of monoculture and intercropped maize and soybean, t/ha, 2022-2024

Hybrid + Variety	Yield, t/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	7.21	–	7.21	9.32	–	9.32	10.26	–	10.26
Sirelia	–	2.24	2.24	–	3.32	3.32	–	2.78	2.78
Sakuza	–	2.55	2.55	–	3.47	3.47	–	2.64	2.64
RAGT Zanetikks + Sirelia	7.95	1.81	9.76	10.74	2.59	13.33	12.19	2.32	14.51
RAGT Zanetikks + Sakuza	8.02	1.95	9.97	10.92	2.73	13.65	12.24	2.46	14.70
LSD, t/ha	0.38	0.12	0.42	0.43	0.14	0.43	0.44	0.14	0.46
LSD for any means, t/ha	0.88								

Note: M – maize; S – soybean; M+S – maize and soybean together, a.s. – active substance, c – control
Source: compiled by the authors

The yield increase of maize in intercropped systems, compared to monoculture, was 0.74-0.81 t/ha (10.3-11.2%) in the variant without fertiliser application; 1.42-1.60 t/ha (15.2-17.2%) with the application of $N_{60}P_{45}K_{45}$; 1.93-1.98 t/ha (18.8-19.3) with the application of $N_{90}P_{60}K_{60}$. At the same time, the yield of soybean varieties in intercropped systems decreased compared to monoculture.

DISCUSSION

Innovative approaches to maize and soybean cultivation technologies are taking their production to a new level of economic, agricultural, and environmental efficiency. Intercropping of legumes and cereals has several advantages for partner crops, but at the same time, several questions require further research. In modern intensive production, intercropping is of great importance for many agricultural production systems, which is based on self-sufficiency of crops in nutrients under resource-limited conditions. The agroecological practice of intercropping, which involves growing two or more crop species or genotypes together, while they coexist for a certain period of time, is now becoming widespread (Mthembu *et al.*, 2018; Allison, 2022).

In Ukraine, research on intercropping of cereals and legumes is insufficient and many questions remain unanswered. In this regard, an ongoing study was conducted in 2022-2024 in the Right-Bank Forest-Steppe region of Ukraine on typical chernozems with intercrops of maize and soybean.

According to the research of L. Feng *et al.* (2020), intercropping changes the coenotic relationships in the agrocenosis compared to monoculture agrocenoses of similar hybrids and varieties, which is manifested in several biological and morphological features of crop development and the formation of their productivity. In the current study, a change in the duration of the growing period of crops was also established depending on mono- or two-component sowing, combinations of soybean varieties with a maize hybrid, and the influence of nutrition on the rate of passage of the growing period. An increase in the duration of the growing period of soybean varieties was established when sown in intercrops. Increasing fertiliser rates further prolongs the growing period. The range of variation in the duration of the growing period in the soybean variety Sirelia was 95114 days and in the variety Sakuza – 105-124 days; for the maize hybrid RAGT Zanetikks – 115-127 days. It should be taken into account that maize with FAO 320-350 in intercrops is advisable to grow with mid-season soybean varieties that require 2,300-2,400°C of active temperatures for crop ripening, which will ensure the correspondence of the development stages of partner crops and reduce interspecific competition.

Intensifying photosynthesis is one of the primary goals in agriculture, offering qualitatively new opportunities to increase crop yields. According to M. Baslam (2020), this issue must be addressed considering the trends of climate change on the planet, and the increasing concentration of CO_2 in the atmosphere, which can positively impact the productivity of C3-plant species, especially in arid regions and drought-prone areas. The current study revealed competition between crops in intercropping for vital factors in the first and second tiers of maize and the entire soybean plant. The hybrid RAGT Zanetikks has a clearly expressed erectophile leaf type, which contributes to reducing competition for vital factors and can be recommended for growing this hybrid in intercrops. The leaf surface area increased with increasing fertiliser rates: by 19.4% when growing the maize hybrid RAGT Zanetikks; 14.3% for the soybean variety Sirelia; 13.1% for the soybean variety Sakuza; 15.5% for intercropping RAGT Zanetikks + Sirelia; 16.5% for intercropping RAGT Zanetikks + Sakuza. W. Wang *et al.* (2022) also demonstrated that intercropping improves photosynthetic rate, instantaneous growth rate, water use efficiency for each species, and increases the land equivalent ratio. Photosynthetic potential characterises the intensity of photosynthesis and the accumulation of dry matter. The results of current research showed that the photosynthetic potential of crops for an individual culture was higher in monocultures, however, in total, it was higher in intercrops. With the application of fertilisers, photosynthetic potential increases and for the combination of RAGT Zanetikks + Sakuza it amounts to a total of 4.12 and 4.52 million m^2*days/ha and, in particular, for maize, the indicator corresponds to the potential in monocultures. Intercropping maize with legumes, unlike monocultures, uses natural resources more efficiently, especially light, since the stems and leaves of cereals and legumes located at different tiers ensure fuller utilisation of solar energy. Light intake by legumes can be improved by choosing the appropriate plant type and its architecture, in connection with which research on creating a crop with a certain selection of crops and their placement is extremely important. Studies by W. Wang *et al.* (2022) have shown that intercropping cereals with legumes contributes to a greater accumulation of dry matter and an increase in grain yield compared to monoculture, including due to photosynthetic activity.

Sufficient soil nitrogen content is essential for optimal plant growth and development, making it a key indicator of soil fertility. One of the primary benefits of intercropping maize with legumes is the additional nitrogen supply to maize plants through nitrogen fixation by legumes. One of the earliest studies by R.W. Willey (1979) revealed that legumes grown between crops can provide an additional 40 kg/ha of nitrogen for maize yield formation. Thus, legumes are a stable source of nitrogen in cereal-legume cropping systems. K. Fujita *et al.* (1992) demonstrated the mechanism of biological nitrogen fixation in intercrops of cereals and legumes. The transfer of nitrogen from legumes to cereals increases system yield and its use efficiency. The introduction of nitrate-tolerant legumes, whose biological nitrogen fixation is believed to be minimally affected by the application of combined N, can increase the amount of N available to the cereal component (Moshira *et al.*, 2014; Zhang *et al.*, 2014).

In this study, the content of nitrate nitrogen in the soil varied depending on the cultivation of mono- and intercrops of maize and soybeans, and fertilisation. At the maize tasselling stage, the highest reserves of nitrate nitrogen were observed in monocultures of soybeans. In intercrops, its content was lower, which is associated with significant nitrogen uptake by maize plants. When growing intercrops of maize with soybeans, the content of nitrate nitrogen in the soil of the control variant was lower – 14.5-14.7 mg/kg of soil. The content of nitrate nitrogen in the soil when growing maize in a monoculture was 12.1 mg/kg of soil.

Under conditions of limited nitrogen availability, biological nitrogen fixation is the primary source of nitrogen in mixed legume-cereal systems (Adeleke & Haruna, 2012). Patterns of soil nitrogen use by intercrops depend on the nitrogen source and legume species. The efficiency of nitrogen use by crops in intercropping depends on their correct selection. Thus, in the studies of A. Wysokiński & B. Kuziemska (2019), it was shown that under conditions of intercropping at a low background of nitrogen fertilisers (30 kg/ha), regardless of the proportion in the sown seed mixture, the main source of nitrogen for lupin was the atmosphere and soil reserves – 65.2% in total nitrogen uptake, and for triticale – 68.8%.

The intercropping of legumes and maize, as explored by M. Dahmardeh *et al.* (2010) and J. Nasar *et al.* (2020), results in higher overall yields compared to growing either crop individually. With an ideal population ratio, intercropping can yield greater gross returns. The current study confirms that maize responds positively to increasing fertiliser rates. With the application of $N_{90}P_{60}K_{60}$, higher maize yields were obtained, both in monocultures and intercrops. In monoculture, maize yield was 10.26 t/ha, while in intercropping maize RAGT Zanetikks and soybean Sakuza – 12.24 t/ha. The surplus yield of maize in intercrops was 1.98 t/ha (16%). Calculations of nitrogen removal by the maize yield increase indicate the use of additional nitrogen by maize at a level of about 53.7 kg/ha. The gross yield in intercropping for this combination was 14.7 t/ha. With the application of $N_{60}P_{45}K_{45}$, maize yield was 9.32 t/ha in monoculture and 10.92 t/ha when intercropping the maize hybrid RAGT Zanetikks and soybean variety Sakuza. The gross yield in intercropping when sowing this combination of hybrid and variety was 13.65 t/ha.

There is a positive correlation between crop diversity and productivity. Numerous studies have been conducted on intercropping in irrigated areas and regions with abundant rainfall (Tsubo *et al.*, 2005; Hassan, 2014). However, as highlighted by W. Wang *et al.* (2024), there is a significant lack of research in semi-arid regions, despite the urgent need for ecological approaches to enhance crop yields and water use efficiency in such conditions.

For soybeans, it was established that the increase in yield in monoculture occurred with the application of $N_{60}P_{45}K_{45}$, compared to the control variant and with the application of $N_{90}P_{60}K_{60}$. The yield increased by 35.1% and 48.2% for the Sirelia and Sakuza varieties, respectively. With the application of $N_{90}P_{60}K_{60}$, the yield decreased. However, in intercrops, while the soybean yield decreased in the control variant compared to monoculture, the yield increased with an increase in the fertiliser application rate, which may indicate the joint use and redistribution of nutrients between crops. The current study also established a positive effect of the interaction of intercropping maize and soybeans. Calculations of nitrogen removal by the increase in maize yield indicate the use of additional nitrogen by maize at a level of about 53.7 kg/ha.

During 2022-2024, the current study established that the highest efficiency of microbiological processes occurred with the application of $N_{60}P_{45}K_{45}$. Thus, in monocultures of maize and soybeans, the biological activity of the soil was 39.4 and 47.2 mg CO_2/kg soil/day, respectively, indicating more intensive respiration under soybean crops. In mixed crops, an increase in this indicator was observed, which is associated, in addition to the symbiotic ability of soybeans, also with a welldeveloped root system of maize, and as a result, an increase in the coefficients of the utilisation of mineral nutrients. It should be noted that the higher biological activity of the soil in mixed crops is due to its temperature regime. The maize hybrid has an erect leaf arrangement, which at high air temperatures contributes to an increase in soil temperature, leading to unproductive water losses and impaired nitrogen uptake. Studies have established that the availability of nitrogen from the soil depends on its temperature. If the soil temperature is 20-25°C, then the sequence of nutrient consumption by plants is as follows: nitrogen-phosphorus-potassium. With an increase in temperature to 28°C and above, the sequence changes as follows: phosphorus-potassium-nitrogen. Current studies have established that the difference between the soil temperature in the rows of monocultures and mixed crops was 8-10°C in favour of the former. Therefore, due to the decrease in soil temperature in mixed crops, soil-forming microbiological processes proceeded more intensively, nitrogen consumption by plants was better, and, accordingly, a higher overall biological activity of the soil was recorded.

CONCLUSIONS

Intercropping of maize and soybeans has significant potential for expansion due to the efficient use of environmental factors. Photosynthetic activity of crops and yield are closely correlated (r=0.93-0.99). The leaf area of maize and soybean crops individually is formed larger in monocultures; in intercrops of maize and soybeans, a decrease in the leaf area of individual components was noted, but the total leaf area of the intercrop increased compared to monocultures. With the application of increasing fertiliser rates, the leaf area increased in monocultures and intercrops by 13.1-19.4%.

The photosynthetic potential of crops characterises the intensity of photosynthesis and the effective accumulation of dry matter. The photosynthetic potential of intercrops RAGT Zanetikks + Sakuza is 2.96 million m^2*days/ha, indicating a high positive interaction of crops in the accumulation of dry matter per unit of leaf area.

The content of nitrate nitrogen in the soil was higher in soybean monocultures – 14.9-15.1 mg/kg of soil; maize – 10.4-13.2 mg/kg; in intercrops of maize and soybeans, a decrease in its content was recorded, which is due to the additional use of nitrogen by maize – 12.1-14.1 mg/kg. The effectiveness of microbiological processes varies depending on the rates of fertiliser application and the composition of crops. Soil biological activity was higher with the application of $N_{60}P_{45}K_{45}$ in maize and soybean monocultures – 39.4 and 47.2 mg CO_2/kg soil/day, respectively. In intercrops, an increase in soil biological activity was observed up to 52.6-55.1 mg CO_2/kg, which confirms the positive interaction of maize and soybeans.

An integral indicator of crop cultivation efficiency is their yield. When intercropping maize RAGT Zanetikks with soybean varieties Sirelia and Sakuza, significant increases in maize yield were obtained on all fertiliser backgrounds and without fertilisers, indicating additional nutrition for maize due to nitrogen fixation by soybeans. The increase in maize yield in intercrops, compared to monoculture, was 10.3-19.3% depending on the fertiliser rate. The highest maize yield was formed with the application of $N_{90}P_{60}K_{60}$: in monoculture – 10.26 t/ha; in intercropping – 12.19-12.24 t/ha. Soybean yield increased by 35.1% and 48.2% for the Sirelia and Sakuza varieties, respectively, with the application of a lower fertiliser rate – $N_{60}P_{45}K_{45}$. The gross yield in intercrops reached 14.5114.70 t/ha against the background of $N_{90}P_{60}K_{60}$.

The perspective for further research lies in the need for interdisciplinary studies to establish the mechanisms of interaction of all structural components of the agroecosystem formed by intercropping and the management of processes of agroecosystem productivity formation, microbiological studies of the soil, which can explain the mechanisms of interaction of the root system of two species in the plane of symbiotic fixation and the use of nutrients.

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CONFLICT OF INTEREST

None.

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Ефективність міжвидових посівів в Лісостепу України

Анотація. Сумісні міжвидові посіви сільськогосподарських культур є важливим технологічним рішенням, яке забезпечує збереження ресурсів, підвищення валової урожайності культур, що є актуальним для забезпечення продовольчої безпеки людства. Метою дослідження було встановлення ефективності сумісних, міжвидових посівів кукурудзи та сої. При проведені досліджень були використані наукові методи проведення польових та лабораторних досліджень. Результати експериментальних досліджень були статистично обраховані та інтерпретовані. Встановлено, що міжвидові посіви кукурудзи ‹РЖТ Занетіккс’ з сортами сої ‘Сірелія’ і ‘Сакуза’ мають низку переваг порівняно з одновидовими посівами і в першу чергу щодо формування урожайності. Кукурудза досить ефективно використовувала додатковий азот ґрунту фіксований соєю в сумісних посівах – отримано суттєві прирости урожайності кукурудзи на всіх фонах добрив і без добрив. Приріст урожайності кукурудзи в сумісних посівах, порівняно з одновидовим посівом, склав 10,3-19,3 % залежно від норми добрив. Найбільша врожайність кукурудзи формувалася при внесенні $N_{90}P_{60}K_{60}$: в одновидовому посіві – 10,26 т/га; сумісному посіві – 12,19-12,24 т/га. Урожайність сої в сумісних посівах знижується, однак валова урожайність двох культур в сумісних посівах суттєво зростає і сягає 14,51-14,70 т/га на фоні $N_{90}P_{60}K_{60}$. Урожайність тісно корелює з площею листкової поверхні посівів ($r = 0{,}93$-$0{,}99$). Вміст нітратного азоту в ґрунті був вищим під соєю, однак знижувався під міжвидовими посівами. Біологічна активність ґрунту зростала за внесення $N_{60}P_{45}K_{45}$ в одновидових посівах кукурудзи і сої – 39,4 і 47,2 мг CO_2/кг ґрунту/добу; сумісних посівах – 52,6-55,1 мг CO_2/кг ґрунту/добу. Результати досліджень мають значне практичне значення для виробництва з огляду на ресурсозбереження та зростання валового виробництва зерна

Ключові слова: площа листкової поверхні; фотосинтетичний потенціал; біологічна активність ґрунту; вміст нітратного азоту в ґрунті; урожайність

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