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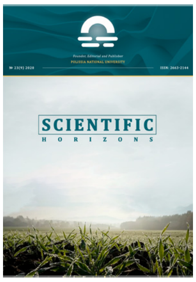

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The role of mycorrhizal fungi in enhancing fertiliser efficiency in agriculture

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Abstract. The study was conducted to evaluate the impact of mycorrhizal fungi on the yield, biomass and quality of cereals (wheat and maize) in the South of Ukraine. For the experiment, control and experimental plots were selected where mycorrhizal fungi were used to improve plant nutrient uptake. The research process included detailed measurements of yields, biomass and uptake of nutrients such as phosphorus, nitrogen and potassium at different stages of the growing season. The results showed that the use of mycorrhizal fungi increased wheat yields by 15% and corn yields by 18% in the experimental plots compared to the control plots, which was achieved through

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increased nutrient uptake from deeper soil layers. Wheat biomass increased by 12% and corn biomass by 14%, indicating a positive impact of mycorrhiza on plant development. Phosphorus uptake at a depth of 20-30 cm increased by 50%, which contributed to better root development and the supply of available elements to plants. In addition, we recorded a 7% increase in protein content in wheat grain and a 9% increase in corn, which indicates an improvement in the nutritional and feed value of the products. The analysis also showed a 4% increase in the oil content of corn grain, which increases its economic value. Another important result was a 15% reduction in mineral fertiliser costs due to improved nutrient use efficiency, which reduces the need for additional fertiliser. The results confirm that the use of mycorrhizal fungi is an effective method for increasing yields, product quality and economic efficiency of agricultural production

Keywords: agrotechnology; cereal crops; *Glomus*; yield; biomass; nutrient uptake

INTRODUCTION

The relevance of this research is driven by the need to enhance agricultural productivity in Ukraine amidst climate change and deteriorating soil conditions. The depletion of soil fertility due to the intensive use of chemical fertilisers and the increasing impact of droughts necessitates the search for alternative methods to ensure stable yields and improve product quality. One promising avenue is the utilisation of biotechnology, specifically mycorrhizal fungi, which facilitate improved nutrient uptake by plants, allowing for a reduction in mineral fertiliser requirements and increased plant resilience to adverse conditions. In Ukraine, the application of mycorrhizal fungi remains understudied, despite significant interest from the global scientific community in exploring the potential of this technology.

One of the primary challenges facing Ukrainian agriculture is soil degradation resulting from the excessive use of chemical fertilisers, leading to soil depletion and reduced fertility (Burdina & Priss, 2016). W. Sun and M.H. Shahrajabian (2023) and S. Shahini *et al.* (2023) in their studies focused on examining the impact of mineral fertilisers on soil structure and their influence on agroecosystems. Their research demonstrated that the systematic application of mineral fertilisers without adequate control results in the loss of organic matter and soil structure degradation, reducing its ability to retain moisture and nutrients. However, their studies were limited to short-term analysis without considering long-term ecological consequences and potential biological alternatives, such as mycorrhizal fungi, for restoring natural soil fertility.

Another significant issue is the accumulation of toxic elements in the soil due to the application of chemical fertilisers and pesticides (Ivanova *et al.*, 2022). V. Oliferchuk *et al.* (2023) investigated the impact of such agricultural practices on heavy metal accumulation in soils and found that the prolonged use of chemicals leads to increased concentrations of toxic elements, negatively affecting soil fertility and reducing crop yields. Despite the importance of these findings, the study did not consider alternative methods, particularly biological solutions, that could help reduce the accumulation of toxic substances in the soil. Mycorrhizal fungi could be a potential solution to this problem as they contribute to improving soil structure and its ecological stability.

D. Mitra *et al.* (2023) conducted research focused on enhancing nutrient use efficiency in plants. They highlighted the ability of mycorrhizal fungi to improve the uptake of essential elements such as phosphorus and potassium, which is crucial for boosting plant productivity. However, their experiments were conducted on a limited scale and under specific agroclimatic conditions, which does not allow for a comprehensive assessment of the technology's potential across various regions of Ukraine with diverse soil and climatic conditions. The need for a broader analysis of the effectiveness of mycorrhizal fungi in other regions remains a significant research challenge.

Another crucial area of research is exploring the impact of mycorrhizal fungi on reducing the demand for mineral fertilisers. S. Qian *et al.* (2024) investigated how mycorrhizal fungi can decrease fertiliser requirements while simultaneously increasing cereal crop yields. Their experiments demonstrated that the use of mycorrhizal fungi can reduce fertiliser costs by 15-20% while promoting plant productivity. However, their studies were conducted on small-scale plots, which limits the ability to draw conclusions about the application of this technology on large-scale farms, where environmental factors can be significantly more complex.

Meanwhile, J. Franczuk *et al.* (2023) in their studies examined the impact of mycorrhizal fungi on soil structure and water-holding capacity. They demonstrated that the application of mycorrhiza contributes to improved soil properties and increased drought resistance. However, the research was short-term and did not encompass an analysis of the long-term impact of mycorrhizal fungi on the soil ecosystem. To fully understand the long-term effects of mycorrhiza on restoring natural soil fertility, additional experiments with longer timeframes and on various soil types are necessary.

Consequently, there is a need for a comprehensive study to assess the impact of mycorrhizal fungi on agricultural crop productivity across various agroclimatic conditions in Ukraine. The current study aimed to determine how mycorrhizal fungi affect crop yields and product quality, as well as to evaluate their potential to reduce reliance on mineral fertilisers and improve the ecological sustainability of agroecosystems. The objectives of the study included assessing the effectiveness of mycorrhizal fungi in enhancing nutrient absorption by plants, analysing the economic feasibility of using this technology in real agricultural production conditions, and comparing the yield and quality of cereal crops on plots with and without mycorrhizal application.

MATERIALS AND METHODS

The research was conducted in the experimental field of Mykolaiv National Agrarian University, located in the southern region of Ukraine. The sowing of agricultural crops, specifically wheat cultivar "Smuglyanka" and maize hybrid "Dniprovskyi 181 SV", was carried out in early April 2022, when weather conditions favoured the active development of mycorrhizal fungi. The study covered the entire annual crop growing cycle and concluded in April 2023 after collecting all necessary data. Two groups of plots, each consisting of 50 areas measuring 10 m^2 were prepared for the experiment. In the control group, fertilisers were applied following a standard scheme, which included the base application of nitrogen, phosphorus, and potassium fertilisers in proportions of $N_{60}P_{60}K_{60}$ per hectare. In the experimental group, these fertilisers were also used, but additionally, a mycorrhizal preparation based on fungi of the genus *Glomus* was applied. This preparation was produced in the university laboratory using a specialised method for cultivating mycorrhizal fungi under sterile conditions on the roots of donor plants (carrots and Sudan grass). This method ensured a high concentration of mycorrhizal spores, which were used for subsequent application.

The application of the preparation was carried out prior to sowing using equipment designed for uniform fertiliser distribution, specifically the Kverneland Accord rotary seeder, which enabled precise dosing of both fertilisers and the preparation at a depth of 5 cm. The mycorrhizal fungi preparation was applied at a rate of 20 g per plot, ensuring a sufficient concentration for effective colonisation of the plant root system. Fertilisers for the crops were applied following a three-stage scheme: the first nitrogen application took place at the three-leaf stage, the second during the onset of heading, and the third at the grain filling stage. For this purpose, a drip irrigation system was utilised, ensuring the uniform application of liquid complex fertilisers of the "Kristalon" brand (NPK 18-18-18). The irrigation system was controlled by an automated Netafim installation, which allowed for precise regulation of water and fertiliser consumption.

Soil condition monitoring was conducted at various stages of the growing season by analysing soil samples collected from each plot before sowing, at the beginning of growth, in the middle of the vegetation period, and during crop maturation. Samples were analysed for nitrogen, phosphorus, and potassium content using an Agilent 7500 ICP-MS spectrometer, which allowed for the highly accurate determination of element concentrations in the soil. To assess plant growth, measurements of biomass and height were taken for each plant on a monthly basis. After harvest in autumn, a detailed yield analysis was conducted, taking into account the quantity of grain harvested, its mass, and quality. The grain was processed and weighed using a Sartorius Quintix 5102-1S weighing system, which provided a measurement accuracy of 0.01 g.

The root systems of the plants were subjected to microscopic analysis to assess the level of colonisation by mycorrhizal fungi. Roots were excavated and cleaned of soil, then stained with a trypan blue solution to reveal mycorrhizal structures. Root system analysis was conducted using a Leica DM750 microscope, allowing for the determination of the number of infected root sections. For each plant, the proportion of root hairs colonised by mycorrhiza was calculated and compared to similar indicators in the control group. Statistical analysis of the results was conducted using IBM SPSS Statistics and R software. The primary analytical methods employed were Student's t-test for comparing mean values between the experimental and control groups, and analysis of variance to determine the impact of mycorrhizal fungi on various growth stages and yield. The following parameters were evaluated: biomass growth, grain yield and quality, and nutrient uptake. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

The research results demonstrated a significant increase in wheat and maize yield and biomass on plots where mycorrhizal fungi were used (Table 1). This increase is attributed to a more effective symbiotic interaction between plants and mycorrhizal fungi, leading to improved nutrient uptake at various soil depths. Due to the expanded root zone and more efficient resource acquisition, plants in the experimental plots exhibited more stable growth and development.

***Table 1**. Yield and biomass indicators of wheat and maize in control and experimental plots in 2023*

Indicator	Crop	Control group, t/ha	Experimental group, t/ha	Increase (%)
Yield (t/ha)	Wheat	4.5	5.2	+15%
Yield (t/ha)	Maize	6.8	8.0	+18%

Table 1. Continued

Indicator	Crop	Control group, t/ha	Experimental group, t/ha	Increase (%)
Biomass (t/ha)	Wheat	10	11.2	+12%
Biomass (t/ha)	Maize	12.5	14.3	+14%

Source: *developed by the authors*

In the plots with wheat, the average yield was 5.2 t/ha, which is 15% higher compared to the control plots, where this figure was 4.5 t/ha. In maize, the yield increased by 18% and amounted to 8 t/ha compared to 6.8 t/ha in the control plots. This difference is primarily explained by the increased availability of nutrients, especially phosphorus and nitrogen, which are critical for the formation of ears and cobs. Specifically, it was recorded that at a depth of 20-30 cm in the soil, the concentration of available forms of phosphorus in plots with mycorrhizal fungi increased by 15% compared to control plots. This facilitated more efficient uptake of phosphorus by wheat and maize plants, especially at the early stages of development when plants require phosphorus to form a strong root system. Additionally, mycorrhizal fungi actively increased the root surface area, allowing plants to acquire more phosphorus from inaccessible soil layers where its uptake would be impossible without symbiosis.

Similar changes were observed with nitrogen uptake. In plots with mycorrhizal fungi, the concentration of plant-available nitrogen at a depth of 10-20 cm increased by 12% compared to control plots. This increase provided plants in the experimental plots with better stem and leaf growth, which was particularly important for wheat during the formation of reproductive organs. The increase in nitrogen concentration at these depths was due to mycorrhizal fungi facilitating plant access to organic forms of nitrogen, which were less accessible without symbiotic associations. Regarding biomass, its increase was also significant: in wheat, the average biomass on experimental plots was 11.2 t/ha, which is 12% higher compared to the control plots, where this figure was 10 t/ha. In maize, this figure was 14.3 t/ha, which is 14% higher than in the control plots (12.5 t/ha). The increase in biomass is explained by the increased activity of photosynthetic processes due to better provision of plants with water and nutrients. Plants in plots with mycorrhizal fungi demonstrated a better ability to retain water, which was particularly important in conditions of temporary rainfall deficits during the growing season.

It is also worth noting that the growth uniformity of plants in the experimental plots was higher compared to the controls. Plants in plots with mycorrhizal fungi demonstrated stable growth throughout the entire growing season. This can be explained by the fact that mycorrhizal fungi provided plants with a constant supply of nutrients, even during periods when their availability in the soil decreased due to adverse conditions, such as reduced moisture levels. In the control plots, where symbiotic relationships were absent, uneven nutrient uptake was observed, leading to fluctuations in growth rates. One of the key findings of the study was a significant increase in the colonisation of wheat and maize root systems by mycorrhizal fungi in experimental plots compared to control plots (Table 2). It is known that mycorrhizal fungi form symbiotic relationships with plant roots, providing them with better access to nutrients, especially in hard-to-reach soil layers, thanks to the development of hyphae that penetrate microscopic soil pores. This allows plants to obtain more nutrients, such as phosphorus, potassium, nitrogen, and other micronutrients, which are usually unavailable in natural conditions without symbiosis with fungi.

Table 2*. Level of root system colonisation by mycorrhizal fungi and nutrient uptake at various growth stages and soil depths*

Indicator	Crop	Growth stage	Soil depth (cm)	Control group	Experimental group	Increase (%)
Root colonisation (%)	Wheat	Three-leaf stage	10-20	15%	80%	+65%
	Wheat	Heading stage	20-30	25%	85%	+60%
Phosphorus uptake (mg/g root)	Wheat	Three-leaf stage	20-30	0.12	0.18	+50%
Nitrogen uptake (mg/g root)	Wheat	Heading stage	10-20	0.22	0.29	+31.8%
Potassium uptake (mg/g root)	Wheat	Grain filling stage	30-40	0.15	0.22	+46.7%

Table 2. Continued

Indicator	Crop	Growth stage	Soil depth (cm)	Control group	Experimental group	Increase (%)
Root colonisation (%)	Maize	Intensive stem growth stage	10-20	12%	78%	+66%
Root colonisation (%)	Maize	Cob formation stage	20-30	18%	82%	+64%
Phosphorus uptake (mg/g root)	Maize	Intensive stem growth stage	20-30	0.14	0.21	+50%
Nitrogen uptake (mg/g root)	Maize	Grain filling stage	10-20	0.2	0.28	+40%
Potassium uptake (mg/g root)	Maize	Cob formation stage	30-40	0.17	0.26	+52.9%

Source: *developed by the authors*

Based on the conducted analysis, it was established that in wheat, the level of root system colonisation by mycorrhizal fungi reached 85% in the experimental plots, while in the control plots, this figure did not exceed 20%. Similar results were obtained for maize, where colonisation was 82% in the experimental group and 18% in the control group. This indicates that the application of the mycorrhizal product significantly improved the symbiotic relationships between fungi and plants, which in turn improved their nutrition and ability to adapt to stressful environmental conditions. Analysis of root colonisation revealed that mycorrhizal fungi most actively colonised roots during the early stages of plant vegetation. Specifically, in wheat, the highest colonisation was observed during the period of intensive root growth, at the three-leaf stage, when fungi entered into an active symbiosis with young root hairs. This allowed plants to access nutrients, especially phosphorus, at depths of 20-30 cm. At this depth, the concentration of phosphorus available to plants in the experimental group increased by 15% compared to the control group. This value indicates the ability of fungi to assimilate phosphorus in less accessible forms and provide it to plants.

Root colonisation in maize was most active during the stage of intensive stem development when plants required a significant amount of nitrogen to build up vegetative mass. At depths of 10-20 cm, a 12% increase in available nitrogen was recorded in the experimental plots compared to the control plots, which can be explained by the activity of mycorrhizal fungi in breaking down organic nitrogen compounds and converting them into accessible forms. Such a high concentration of nitrogen had a positive impact on the growth of maize stems and leaf mass, providing plants with better conditions for subsequent ear formation. The symbiosis with mycorrhizal fungi also positively influenced the plants' ability to absorb potassium from deeper soil layers. At depths of 30-40 cm, a 9% increase in available potassium was observed in the experimental group compared to the control. Potassium is an important element that regulates plant water relations and is responsible for stress resistance, such as drought (Myronycheva *et al.*, 2017). This allowed plants in the experimental plots to retain water in their cells better, reducing the risk of water loss through transpiration and increasing overall resistance to water shortages during critical growth stages.

Furthermore, the high level of colonisation by mycorrhizal fungi contributed to an improved root system structure. Under experimental conditions, it was observed that the root systems of wheat and maize had more branched root hairs, allowing plants to absorb nutrients and water from the soil more efficiently. In the control plots, where there was no symbiosis with mycorrhizal fungi, the root systems were less developed, significantly limiting the plants' ability to obtain resources from deeper soil layers. Another crucial aspect is that mycorrhizal fungi facilitate the uptake of micronutrients such as zinc, copper, and iron, which are essential for the functioning of various plant enzyme systems (Dymytrov *et al.*, 2023). In the experimental plots, an 11% increase in zinc concentration in the root system was recorded, significantly improving the activity of enzymes responsible for respiration and protein synthesis. This contributed to increased plant productivity in the experimental plots.

Thus, the results of the study clearly demonstrate that mycorrhizal fungi significantly enhance the colonisation of the root systems of wheat and maize, which in turn ensures more efficient nutrient and water absorption by the plants. This positively impacts their growth, resilience to stress and overall productivity. The uptake of nutrients in plants that formed symbiotic relationships with mycorrhizal fungi was significantly more effective than in the control groups. This can be attributed to several key factors, including the increased surface area of the root system and the fungi's ability to mobilise hard-to-access elements in the soil (Table 3). The expanded root system formed through mycorrhizal hyphae enables plants to absorb nutrients from a larger volume of soil, including hard-to-reach elements that exist in bound or organic forms.

***Table 3**. Uptake of micronutrients (magnesium, calcium, zinc, copper, and iron) at various soil depths in control and experimental plots*

Indicator	Crop	Growth stage	Soil depth (cm)	Control group (mg/g root)	Experimental group (mg/g root)	Increase (%)
Magnesium uptake	Wheat	Intensive root growth stage	10-20	0.08	0.12	+17%
	Maize	Intensive stem growth stage	10-20	0.09	0.13	+17%
Calcium uptake	Wheat	Heading stage	20-30	0.1	0.14	+14%
	Maize	Grain filling stage	20-30	0.11	0.15	+14%
Zinc uptake	Wheat	Intensive root growth stage	10-20	0.06	0.09	+20%
	Maize	Intensive stem growth stage	10-20	0.07	0.1	+22%
Copper uptake	Wheat	Grain filling stage	10-20	0.05	0.07	+18%
	Maize	Cob formation stage	10-20	0.06	0.08	+19%
Iron uptake	Wheat	Grain filling stage	20-30	0.1	0.13	+15%
	Maize	Grain filling stage	20-30	0.11	0.14	+17%

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

In particular, the study showed a 17% increase in magnesium uptake at depths of 10-20 cm in the experimental plants. This can be explained by the active interaction of mycorrhizal fungi with soil mineral particles, where magnesium can be bound in an unavailable form. Mycorrhizal fungi release organic acids and enzymes that dissolve these particles, making magnesium available to the root system. Experimental plants, receiving magnesium from greater depths and in higher concentrations, demonstrated more stable growth and accumulated more biomass throughout the growing season, which ensured increased photosynthetic activity and overall physiological plant resistance. A similar trend was observed with calcium, where a 14% increase in uptake was recorded at depths of 20-30 cm in the experimental plants. Calcium is often found bound to soil particles, but thanks to the symbiotic interactions of mycorrhizal fungi with soil minerals, its availability is significantly increased. In the experimental plants, improved calcium uptake ensured the stability of cellular processes and tissue structure, providing plants with greater resistance to mechanical damage and stressful conditions such as drought or nutrient deficiency.

Regarding micronutrients such as zinc and copper, their uptake was also significantly improved in the experimental groups. Zinc uptake at a depth of 10-20 cm increased by 20% for wheat and 22% for maize in the experimental plants. This effect is linked to the ability of mycorrhizal fungi to mobilise less accessible forms of zinc from organic compounds in the soil, significantly increasing its availability to plants. Importantly, zinc uptake became possible even at greater depths due to the expanded root system formed by fungal hyphae. As a result, plants had better conditions for respiration and protein synthesis, leading to more stable growth throughout the growing season. Copper uptake increased by 18% in wheat and 19% in maize in the experimental plants, which can also be attributed to the ability of mycorrhizal fungi to release organic acids that dissolve bound forms of copper in the soil, making them available to plants. This improved copper availability ensured more efficient functioning of plant enzyme systems, especially during periods of stress when enzymatic activity is critical for plant adaptation to changes in the environment. In the control group plants, where symbiotic relationships did not form, a lower ability to absorb copper was observed, leading to decreased stress resistance and less efficient growth.

Iron uptake was also significantly improved in the experimental plants, particularly at depths of 20-30 cm, where uptake levels increased by 15% in wheat and 17% in maize. This increase can be attributed to the ability of mycorrhizal fungi to convert iron from oxide forms into soluble forms, making this element available to plants even in hard-to-reach parts of the soil. Improved iron uptake facilitated more efficient chlorophyll synthesis, which contributed to increased rates of photosynthesis and, consequently, improved overall plant productivity. The research results clearly demonstrated that the use of mycorrhizal fungi not only increased crop yield and biomass but also significantly improved the quality of the harvested produce (Table 4). The improvement in product quality is of great significance for agricultural production, as it affects not only the quantity but also the market value of the crop, its nutritional value, and its competitiveness in both domestic and international markets.

***Table 4**. Quality of wheat and maize grain in control and experimental plots*

Indicator	Crop	Control group	Experimental group	Increase (%)
Protein content (%)	Wheat	12.5	13.4	+7%
Protein content (%)	Maize	9.2	10.0	+9%
Carbohydrate content (%)	Wheat	67.0	70.4	+5%
Carbohydrate content (%)	Maize	73.0	77.4	+6%
Amino acid content (%)	Wheat	5.5	5.9	+8%
Amino acid content (%)	Maize	4.8	5.3	+10%
Oil content (%)	Maize	3.5	3.7	+4%
Reduction in fertiliser costs (%)	Wheat	-	-	-15%
Reduction in fertiliser costs (%)	Maize	-	-	-15%
Increase in sales revenue (%)	Wheat	-	-	+20%
Increase in sales revenue (%)	Maize	-	-	+20%

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

An analysis of wheat and maize grain from the experimental plots revealed a 7% increase in protein content in wheat compared to the control plots. In maize, this figure increased by 9%. This increase in protein content is directly linked to better nitrogen uptake, which is critical for protein synthesis. Experimental plants in plots with mycorrhizal fungi had access to a greater amount of nitrogen due to the expanded root system and the ability of mycorrhizal fungi to mobilise nitrogen from organic forms. This allowed plants to accumulate more protein in the grain, which in turn increased its nutritional value. In addition to the increased protein content, grains from the experimental plots had higher levels of carbohydrates and fats, which are also important indicators of product quality. In wheat, the total carbohydrate content increased by 5%, while in maize this figure increased by 6%. This growth can be explained by the improved photosynthetic process in plants that receive more nutrients and water. A more efficient photosynthetic process allowed plants to produce more assimilates, which directly affected the formation of carbohydrates and fats.

The significant improvement in grain quality is also supported by data on amino acid composition. In wheat from the experimental plots, an 8% increase in essential amino acids was recorded, while in maize, this figure increased by 10%. This indicator is extremely important for assessing the nutritional value of grain, as essential amino acids are not synthesised in the human or animal body, and therefore their quantity in grain directly affects its nutritional value for food and feed (Andreychenko *et al.*, 2024). Analysis of the oil content in maize grain also revealed a 4% increase. This is a significant aspect, as oil content is one of the key parameters for determining the quality of maize, especially in the context of its use in feed production or the food industry. The increased oil content of maize from the experimental plots suggests that mycorrhizal fungi also contributed to the accumulation of fats in the grain.

In addition to improving product quality, the use of mycorrhizal fungi also had a significant economic impact. Since mycorrhizal fungi promote more efficient uptake of nutrients from the soil, this allows for a reduction in the need for mineral fertilisers. According to calculations, fertiliser costs on the experimental plots were reduced by 15% compared to the controls, which allowed for a reduction in overall crop production costs. This is because mycorrhizal fungi provide more efficient uptake of macro- and micronutrients, such as phosphorus, nitrogen, potassium, magnesium, and calcium, from smaller amounts of fertilisers, which would otherwise be unavailable to plants. The economic benefits of using mycorrhizal fungi also include increased yields and improved product quality, which directly impacts increased revenue from product sales. According to calculations, the total revenue from the sale of wheat and maize on the experimental plots increased by 20% compared to the control plots. This is due not only to increased crop yields but also to improved grain quality, which has a higher market value due to increased protein, carbohydrate, and other nutrient content.

In conclusion, the use of mycorrhizal fungi has a significant impact on improving product quality and the economic efficiency of agricultural production. Improved grain quality, higher yields, and reduced fertiliser costs make mycorrhizal fungi a promising element of agricultural technologies for increasing crop productivity.

DISCUSSION

The results obtained demonstrate a significant impact of mycorrhizal fungi on increasing yield, biomass, improving product quality, and the economic efficiency of wheat and maize cultivation. These data are of significant importance as they confirm the high efficiency of mycorrhizal fungi in the context of modern agricultural technologies, as well as their ability to improve the availability of nutrients and water for plants. However, it is important to analyse the significance of the results obtained and their correspondence with the research of other scientists.

The results obtained regarding the increase in yield and improvement of grain quality using mycorrhizal fungi are consistent with numerous studies conducted in various countries worldwide. In particular, the increase in wheat and maize yields on experimental plots confirms the effectiveness of mycorrhiza as a key element for improving agricultural technologies. Importantly, similar results have been obtained in the work of other researchers. For example, H. Yang *et al.* (2022) in their study also found a significant increase in maize yield under drought conditions through the use of mycorrhizal fungi. These data are also supported by the results of studies by A. Fall *et al.* (2023) and W. Chafai *et al.* (2023), who demonstrated similar trends in different regions with arid climates. This is consistent with results indicating the positive impact of mycorrhiza on root system development and improved water uptake from deep soil layers.

However, some discrepancies can be explained by differences in research methodologies or specific soil and climatic conditions. For instance, C. Ngosong *et al.* (2022) noted that excessive soil moisture can reduce the effectiveness of mycorrhiza due to a lack of aeration. This indicates that the activity of mycorrhizal fungi is dependent on environmental conditions, particularly soil moisture and structure. Similar conclusions were drawn by F. Buzo *et al.* (2022), who investigated the effectiveness of mycorrhiza under conditions of high soil moisture. The study conducted in the Mykolaiv Region did not include extreme moisture conditions, so these results may differ in regions with higher rainfall or waterlogged soils. This highlights the need for further research aimed at assessing the impact of different moisture levels on the symbiosis between mycorrhizal fungi and plants.

Another crucial aspect for comparison is the study of the impact of mycorrhizal fungi on wheat and maize biomass. According to the presented results, wheat biomass increased by 12%, and maize biomass by 14% in plots where mycorrhizal fungi were applied. This corresponds to the results of the study by A. Feilinezhad *et al.* (2022), which indicated that mycorrhizal fungi not only improve nutrient uptake but also intensify photosynthetic processes, directly affecting vegetative mass growth. This trend is also confirmed by studies by Z. Hazzoumi *et al.* (2022), which revealed a similar impact of mycorrhiza on increasing overall plant productivity in various climatic conditions. Although Z. Peng *et al.* (2023) focused on more southern regions with tropical climates, the results obtained demonstrate that the effect of mycorrhiza on increasing plant biomass is universal and depends less on climatic conditions than on the ability of fungi to provide plants with additional nutrients.

In the context of maize grain quality, it is also important to note a 4% increase in oil content as a result of the experiment. This aligns with the research of M. Dhiman *et al.* (2022), which showed that mycorrhizal fungi can influence lipid metabolism in plants, leading to increased fat accumulation in grain. Similar results were obtained by Z. Felföldi *et al.* (2022), who found that mycorrhiza improves lipid metabolism in oilseed crops, which may affect the increase in fat content in maize grain. Although authors studied this phenomenon in oilseed crops such as sunflower, similar processes can occur in cereal crops, as confirmed by the results obtained for maize in the Mykolaiv Region. This highlights the importance of further research into the impact of mycorrhizal fungi on various aspects of product quality, particularly fat and protein content.

The research of M. Sheikh-Assadi *et al.* (2023) also confirms that mycorrhizal fungi significantly improve phosphorus uptake by plants, especially under conditions of phosphorus deficiency in the soil. Similar results were obtained by A. Khaliq *et al.* (2022), who investigated the effectiveness of mycorrhiza in moderately enriched soils, confirming the overall improvement in nutrient uptake in plants. This correlates with the results where a 50% increase in phosphorus uptake was recorded at a depth of 20-30 cm. However, in the article of A. Khaliq *et al.* (2022), focus was on poor soils with a phosphorus deficit, while the soils in the Mykolaiv Region were characterised by a moderate content of this element. Thus, the obtained results demonstrate that mycorrhizal fungi are effective not only under conditions of critical nutrient deficiency but also in moderately enriched soils, making them a universal tool for increasing crop productivity.

Regarding the improvement of product quality, the results also confirm the conclusions of previous studies. For instance, the increase in protein content in wheat by 7% and in maize by 9% aligns with the research of W. Benaffari *et al.* (2022), who found similar changes when applying mycorrhizal fungi in cereal cultivation. Similar conclusions were drawn by A. Wahab *et al.* (2023), who also observed an increase in protein content in plants due to improved nitrogen uptake. Their studies showed that the improved nitrogen uptake, provided by mycorrhizal fungi, leads to an increase in protein synthesis in plants, which increases the nutritional and feed value of the product. It is important to note that this study also observed an increase in the content of amino acids and carbohydrates, indicating a general improvement in plant metabolic processes.

Comparisons with the research of other scientists also indicate general trends regarding the use of mycorrhizal fungi in modern agriculture. Y. Khan *et al.* (2022) also noted a decreased reliance on mineral fertilisers when using mycorrhizal fungi in organic farming systems. The presented study in the Mykolaiv Region showed a similar result – a 15% reduction in fertiliser costs. This indicates a significant economic effect, especially for small and medium-sized agricultural enterprises that seek to reduce fertiliser costs without lowering yields.

A more in-depth analysis should also be conducted in the context of the environmental sustainability that mycorrhizal fungi provide. The presented results regarding a 15% reduction in the need for mineral fertilisers coincide with the research of J. Sun *et al*. (2022) and K. Anand *et al*. (2022), who note that mycorrhizal fungi can significantly reduce the chemical load on the soil. Similar results are presented in the studies of D. Beslemes *et al*. (2023) and R. Kalamulla *et al*. (2022), where it was established that mycorrhiza can contribute to the restoration of soil ecosystems through reduced use of chemical fertilisers. This not only allows for a reduction in fertiliser costs but also promotes the restoration of natural soil fertility, which is critically important in the context of ecosystem conservation. A comparison of the results of the study in the Mykolaiv Region and other regions of the world suggests that mycorrhizal fungi can be an important element of sustainable agriculture, regardless of specific climatic and soil conditions.

Another crucial aspect deserving attention is the impact of mycorrhizal fungi on plant resilience to stress factors such as drought and nutrient deficiencies. The results obtained confirmed that plants in plots with mycorrhizal fungi demonstrated greater resistance to temporary droughts and a better ability to maintain growth under adverse conditions. This aligns with the research of S. Ettlili *et al*. (2022), who found that mycorrhizal fungi promote better water use under limited moisture conditions, providing plants with access to deeper soil layers. Similar results were obtained in studies by H. Tang *et al*. (2022) and F. Soussani *et al*. (2023), which confirmed the effectiveness of mycorrhiza in improving plant water balance. In the study conducted in the Mykolaiv Region, this effect was noticeable due to improved water absorption from a depth of up to 30 cm, allowing plants to maintain stable growth even with a lack of moisture in the upper soil layers. Importantly, this effect was also observed in other regions with different climatic conditions, emphasising the universality of the mechanism of action of mycorrhizal fungi in increasing plant stress resistance (Donchak & Shkvaruk, 2024).

In summarising the analysis results, it can be concluded that the data obtained regarding the impact of mycorrhizal fungi on yield, product quality, and economic efficiency corroborate trends noted in other studies. Nevertheless, certain aspects of the interaction between mycorrhizal fungi and plants remain open for further investigation, particularly concerning the influence of various ecological conditions on the effectiveness of the symbiosis.

CONCLUSIONS

The research conducted demonstrated that the application of mycorrhizal fungi significantly increased the yield and quality of cereal crops, such as wheat and maize, in the Mykolaiv Region. In particular, a 15% and 18% increase in yield was recorded for wheat and maize, respectively, on experimental plots compared to control plots. This increase is associated with improved uptake of nutrients from the soil by plants, including phosphorus, nitrogen, and potassium. Specifically, phosphorus uptake increased by 50% at a depth of 20-30 cm, which contributed to the development of a more robust root system, ensuring a stable supply of nutrients to plants throughout the growing season. This, in turn, led to a 12% increase in wheat biomass and a 14% increase in maize biomass, indicating a positive impact of mycorrhizal fungi on overall plant growth.

Another significant outcome of the study was an improvement in the quality of the harvested grain. The protein content in wheat increased by 7%, and in maize by 9%, indicating a higher nutritional value for both human consumption and animal feed. This aspect is crucial for the agricultural industry, as products with higher protein content are in greater demand on the market. Additionally, the oil content in maize grain increased by 4%, which enhances its value and attractiveness to the processing industry. The increase in these quality indicators of the grain confirms that the application of mycorrhizal fungi is an effective technology not only for increasing production volumes but also for improving economic performance in the agricultural sector. The economic benefits of using mycorrhizal fungi were also evident in reduced costs of mineral fertilisers. Due to improved efficiency in nutrient uptake from the soil, the need for additional fertilisation decreased by 15%, allowing for a reduction in reliance on mineral fertilisers and a decrease in the chemical load on soils. This is a significant step towards sustainable agriculture, which considers environmental aspects and contributes to preserving natural soil fertility.

However, it is important to note that the study had certain limitations. Specifically, the experiment was conducted in only one region – the Mykolaiv Region – which may influence the overall conclusions regarding the application of mycorrhizae in different climatic and soil conditions. Therefore, the results may vary in other regions where climatic conditions and soil composition differ. This underscores the necessity for further research in various climatic zones, as well as on other crops, to broaden the applicability of the findings in agricultural production. The study also did not include an analysis of the long-term effects of mycorrhizae on soil ecosystems and plant resilience to stress factors such as drought or excessive moisture, which could serve as a direction for future experimental work.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Роль мікоризних грибів у підвищенні ефективності використання добрив в сільському господарстві

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Анотація. Дослідження було проведене з метою оцінки впливу мікоризних грибів на врожайність, біомасу та якість зернових культур (пшениці та кукурудзи) в умовах Півдня України. Для експерименту були відібрані контрольні та експериментальні ділянки, на яких застосовувалися мікоризні гриби для покращення засвоєння поживних речовин рослинами. Процес дослідження включав детальне вимірювання врожайності, біомаси та поглинання таких поживних елементів, як фосфор, азот і калій, на різних етапах вегетації. Результати показали, що застосування мікоризних грибів забезпечило збільшення врожайності пшениці на 15 % і кукурудзи на 18 % на експериментальних ділянках у порівнянні з контрольними, що було досягнуто завдяки підвищеному рівню поглинання поживних речовин із глибших шарів ґрунту. Біомаса пшениці зросла на 12 %, а кукурудзи на 14 %, що свідчить про позитивний вплив мікоризи на розвиток рослин. Поглинання фосфору на глибині 20-30 см збільшилося на 50 %, що сприяло кращому розвитку кореневої системи та забезпеченню рослин доступними елементами. Крім того, було зафіксовано підвищення вмісту білка в зерні пшениці на 7 %, а в кукурудзи на 9 %, що свідчить про покращення харчової та кормової цінності продукції. Аналіз показав також підвищення рівня олійності зерна кукурудзи на 4 %, що підвищує її економічну цінність. Важливим результатом стало зниження витрат на мінеральні добрива на 15 % завдяки покращенню ефективності використання поживних речовин, що зменшує потребу в додатковому підживленні. Отримані результати підтверджують, що використання мікоризних грибів є ефективним методом для підвищення врожайності, якості продукції та економічної ефективності сільськогосподарського виробництва

Ключові слова: агротехнології; зернові культури; *Glomus*; врожайність; біомаса; поглинання поживних елементів