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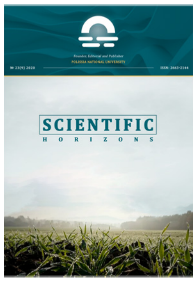

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Irrigation systems as a factor in increasing productivity in agricultural regions of Ukraine

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Abstract. The research relevance is determined by the need to analyse the efficiency of irrigation systems in the agricultural regions of Ukraine against the background of increasing climate change and moisture deficit, which affect the stability of agricultural production. The study aimed to determine the impact of irrigation on the productivity of major crops (sunflower, wheat and winter rape) and to assess the economic efficiency of introducing irrigation technologies in arid regions of Ukraine. The study used agronomic and economic methods of analysis. The irrigation efficiency was determined by comparing crop yields under different water supply regimes. The cost-effectiveness assessment included an analysis of the costs of installing and operating irrigation systems concerning the increase in yields and product quality. The study determined that the use of irrigation increased the yield of sunflower by 28-48%, winter wheat by 15-25%, and rapeseed by 25-35%. Optimal water supply contributed to an increase

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in the protein and gluten content of wheat grain and an increase in the oil level of rapeseed. An analysis of the economic efficiency of irrigation showed that the payback period depended on the type of system: drip irrigation provided the highest yield increase with minimal water consumption, while sprinklers required higher operating costs. Irrigation was substantial in increasing crop productivity in the arid regions of Ukraine. Adaptive irrigation technologies, including automated water management systems, proved to be the most effective. The introduction of modern irrigation methods will help optimise the water balance of soils, reduce the negative impact of drought and increase the economic profitability of agricultural production

Keywords: agriculture; primary sector of economy; water balance; yield; sunflower; winter wheat; winter rape; economic profitability; adaptive technologies

INTRODUCTION

The research relevance is determined by the need to improve irrigation systems in Ukraine against the backdrop of global climate change rising average annual temperatures and increasing frequency of droughts, which significantly limit crop productivity, especially in the southern regions. Water shortages and soil degradation due to excessive water consumption require the development of adaptive water management methods that would optimise the water balance of soils, reduce moisture losses and improve product quality. In addition, the destruction of hydraulic structures, such as the Kakhovka hydroelectric power plant, exacerbates the problem of water supply and requires the restoration and modernisation of irrigation infrastructure for sustainable agricultural production. The issue of efficient use of irrigation systems was widely covered in the scientific literature, in particular in the context of adapting agricultural production to climate change, optimisation of water balance and increase in the economic profitability of crops. S. Tegipko and I. Dimov (2024) studied the introduction of modern irrigation system management technologies and their impact on agricultural productivity. The researchers determined that the use of automated irrigation systems contributed to increased water use efficiency and reduced water losses, which had a positive impact on yields and product quality. The problem of distribution of irrigated land in Ukraine was analysed by N.A. Prokopenko (2023). The researcher determined that most of these areas are concentrated in regions with critical moisture levels, which required the expansion of irrigated areas to ensure stable agricultural production.

At the same time, the environmental impact of irrigation was studied by S.I. Demianenko (2022). The author noted that excessive irrigation can lead to soil salinisation and loss of soil fertility. To reduce this negative impact, it was proposed to introduce adaptive irrigation methods that would take into account the balance of water consumption and soil quality. The problem of restoring land use systems after the destruction of hydraulic structures was a key issue in the research of V.V. Yuzva (2024). The author highlighted that military operations have significantly complicated the provision of agriculture with the necessary water resources, which necessitated the development of a strategy for modernising irrigation infrastructure.

International scientific literature has also extensively studied approaches to efficient water use in irrigated agriculture. S. Attard *et al.* (2024) determined that the use of water-saving technologies in regions with developed irrigation infrastructure increased yields without increasing water consumption. Y. Heiba *et al.* (2024) demonstrated that the use of drip irrigation in combination with precise soil moisture monitoring technologies could significantly reduce water consumption and increase crop productivity at the same time. Climate change and its impact on the functioning of irrigation systems were analysed by H. Zhou *et al.* (2024). The authors proved that even with increased investment in agriculture, the instability of the water balance could decrease agricultural productivity. The effectiveness of different irrigation methods in arid regions was studied by E.T. Ebstu and M. Muluneh (2025). The study proved that drip irrigation in combination with optimised fertilisation schemes ensured maximum productivity with minimal water use. A. Cholik *et al.* (2025) conducted a study on water use in the irrigation system of the Seuseupan region. The researchers determined that effective water management could significantly reduce water consumption and increase crop yields, which is important for maintaining sustainable agricultural production.

The issue of international cooperation in the development of irrigation systems was addressed by O.M. Mohish and O.B. Myhailyuk (2024). The authors noted that the integration of advanced water conservation technologies from international experience could increase the efficiency of the Ukrainian agricultural sector and improve its competitiveness. M.S. Kavunichenko (2024) studied the impact of European integration processes on the development of agriculture in Ukraine, emphasising that the introduction of modern irrigation technologies could ensure higher production profitability and improve product quality. The consequences of the destruction of the Kakhovka hydroelectric power plant were analysed by Y. Dorosh *et al.* (2024). The authors determined that the loss of the reservoir significantly reduced the area of irrigated land in the southern regions, which required a revision of the water management strategy to adapt agriculture to new conditions. Despite the available research, the long-term environmental impacts of irrigation, the impact of different irrigation technologies on product quality, and their economic feasibility on farms of different sizes remain insufficiently understood.

The study aimed to assess the impact of irrigation technologies on the yield and quality characteristics of crops (sunflower, winter wheat and rapeseed), as well as to determine the economic feasibility of their implementation in the arid regions of Ukraine.

MATERIALS AND METHODS

The study of the efficiency of irrigation systems in increasing crop productivity was based on an integrated approach that included agronomic, economic and environmental methods. The object of the study was irrigation systems and their impact on the yield and quality of sunflower (*Helianthus annuus* L.), winter wheat (*Triticum aestivum* L.) and winter rape (*Brassica napus* L.). The experimental plots were in the Southern Steppe zone of Ukraine at the Educational and Research Centre of Mykolaiv National Agrarian University from 2022 to 2024. The research was conducted under three irrigation regimes: no irrigation (control), optimal irrigation and excessive irrigation.

Standardised agronomic methods were used to assess crop productivity, including harvesting from the plots of record, subsequent determination of the crop weight and conversion of the data per hectare. The quality parameters of grain products were analysed in the laboratory: the protein and gluten content of wheat grain was determined by the Kjeldahl method based on the analysis of total nitrogen, while the oil content of rapeseed was estimated by the hexane extraction method with subsequent determination of the mass fraction of fat. The photosynthetic activity of plants was determined using a portable gas analyser LI-6400XT, which was used to record the level of CO_2 assimilation under different irrigation regimes, assessing the impact of water supply on the efficiency of photosynthetic processes. The cost-effectiveness of irrigation technologies was calculated based on an analysis of capital and operating costs. Capital costs included the cost of installing drip and sprinkler irrigation systems while operating costs included water supply, electricity and maintenance costs. Additional gross income from irrigation was defined as the difference between the yields on irrigated and rainfed plots multiplied by the market value of the product (1):

$$\Delta D = (Y_{germ} - Y_{rainfed}) \times P, \tag{1}$$

where ΔD – additional income, UAH/ha; Y_{germ} – crop yield under irrigation, t/ha; $Y_{rainfed}$ – crop yield on the rainfed field, t/ha; P – market price of the product, UAH/t.

The payback period of investments in irrigation systems was calculated as the ratio of capital expenditures to the average annual net profit generated by irrigation (2):

$$T_{payback} = \frac{C_{cap}C_{cap}}{P_{net}P_{net}}, \tag{2}$$

where $T_{payback}$ – payback period, years; C_{cap} – capital costs, UAH/ha; P_{net} – average annual net profit from irrigation, UAH/ha.

ROE was defined as the ratio of net profit to capital expenditure expressed as a percentage (3):

$$ROI = \left(\frac{C_{cap}}{P_{net}}\right)\left(\frac{C_{cap}}{P_{net}}\right) \times 100\%, \tag{3}$$

where ROI – return on investment ratio, %.

The environmental impact of irrigation was assessed by analysing soil salinity using a soil conductivity meter (EC-meter). The water balance of the soil was monitored using tensiometers and Decagon GS3 moisture sensors. Statistical data processing was conducted in the RStudio software environment using agricolae packages for analysis of variance (ANOVA). The difference between the groups was considered statistically significant at the level of p<0.05 by Student's t-test. The study was based on an analysis of scientific papers on the impact of irrigation on crop productivity, the economic efficiency of irrigation systems and their environmental impact. Data on sunflower, winter wheat and rapeseed yield under different irrigation regimes (non-irrigated conditions, optimal irrigation, excessive irrigation) were studied. The quality characteristics of the products, such as protein and gluten content in wheat grain and oil content in rapeseed, was emphasised. The environmental impact of intensive irrigation was also analysed, including the risk of soil salinisation and changes in the water balance.

The study compared the efficiency of different types of irrigation systems, such as drip irrigation and sprinklers. The cost-effectiveness of irrigation systems was assessed by comparing the costs of implementing and operating these technologies with the increase in yields and product quality. Environmental impact of intensive irrigation was emphasised. The prospects for the introduction of adaptive irrigation technologies that incorporate climate change and the dynamics of crop water consumption was analysed in the study. The use of precision irrigation, automated water management systems and innovative approaches to optimising soil water balance were emphasised. Adaptive irrigation systems based on energy-saving solutions and precise water management were noted to ensure an optimal balance between irrigation costs and crop yields.

RESULTS

Influence of irrigation systems on productivity and ecological balance in the Southern Steppe of Ukraine. Irrigation is one of the key factors in stabilising yields and improving the quality of agricultural products in conditions of unstable moisture. The use of irrigation systems helps to compensate for moisture deficits, which is critical in regions with an arid climate, such as the Southern Steppe of Ukraine. The rational use of irrigation optimises the water balance of plants, improves photosynthetic activity and efficient absorption of nutrients (Pichura *et al*., 2024). Modern approaches to assessing irrigation efficiency address agronomic, economic and environmental parameters. Agronomic efficiency is determined by yield growth, product quality and crop resistance to changes in water regime. The economic assessment involves analysing the profitability of technologies, including irrigation costs, additional agronomic measures and profitability gained through increased yields. The environmental component includes optimising the use of water resources, preventing secondary salinisation of soils and maintaining their fertility (Havrysh *et al*., 2020).

Assessment of the long-term environmental impacts of irrigation is an important aspect of water management. The long-term use of irrigation systems in regions with a moisture deficit can lead to the accumulation of salts in the soil profile, which negatively affects its physical and chemical properties. In addition, changes in the water regime led to the transformation of agroecosystems, including changes in the species structure of vegetation and soil microbiota (Borovyk *et al.*, 2024). This requires the development of adaptive measures aimed at maintaining ecological balance under intensive irrigation.

Irrigation has a significant impact on the growth and development of sunflower, winter wheat and rapeseed. Sunflower (*Helianthus annuus* L.) is a relatively drought-resistant crop, but under conditions of limited water supply, the leaf surface area decreases, the development of the root system slows down and the period of active photosynthesis is reduced. The introduction of adaptive irrigation systems can increase the yield of this crop by 20-30% due to improved water management and longer growing seasons. Winter wheat (*Triticum aestivum* L.) has high requirements for water supply, especially in the tillering, earing and earing phases. Water deficit during these critical periods can lead to a decrease in the number of productive shoots, a reduction in ear length and a decrease in grain filling. The use of irrigation can increase the yield of winter wheat by 28-48%, as well as improve the quality characteristics of the grain, in particular the protein and gluten content (Korkhova *et al*., 2023). Winter rapeseed (*Brassica napus* L.) is a crop that responds positively to irrigation, especially in the phases of germination, germination and spring vegetation recovery. Optimal water supply contributes to the development of a powerful root system, increase of biomass and accumulation of oil in seeds. Research shows that irrigation can increase rapeseed yields by 25-35% compared to rainfed conditions, as well as increase the oil content in seeds to 45-47% (Kovalenko *et al*., 2024). Thus, irrigation increases crop productivity, especially in conditions of natural precipitation deficit. The use of modern irrigation system management technologies allows to optimise water consumption, increase photosynthesis efficiency and ensure stable production of high-quality products.

Sunflower: productivity potential under different irrigation regime. Sunflower (*Helianthus annuus* L.) is one of the leading oilseed crops in Ukraine, especially in the Southern Steppe, where climatic conditions are often characterised by insufficient moisture. The introduction of efficient irrigation systems can significantly increase the productivity of this crop, providing optimal conditions for plant growth and development. According to the study, sunflower has high plasticity and can adapt to changes in moisture supply, but lack of moisture negatively affects its productivity, which is confirmed by the study of the adaptability of different hybrids under conditions of insufficient moisture (Yeremenko *et al*., 2020). The sunflower hybrids P64HE133 and P64LE25 are highly adaptable to different growing conditions. P64LE25 is characterised by stable yields in different agroclimatic conditions, excellent resistance to root lodging and high tolerance to rust and diseases of leaves and heads. Under irrigated conditions, these hybrids demonstrate an improved morphological structure, including an increase in leaf surface area and the development of a more powerful root system. This contributes to more efficient absorption of water and nutrients and ensures higher productivity compared to rainfed conditions. At the same time, under non-irrigated conditions, there is a reduction in plant size, which can limit their yield potential.

Soil moisture levels directly affect the photosynthetic activity of sunflowers. With optimal irrigation, a stable water balance is maintained, which contributes to an increase in the intensity of photosynthesis, efficient stomatal functioning and better carbon dioxide absorption. In addition, sufficient water supply helps to reduce the temperature of the leaf surface, which has a positive effect on enzymatic processes and the overall metabolism of plants. In contrast, in dry conditions without irrigation, photosynthetic activity decreases due to stomatal closure and reduced transpiration, which is a defensive response to water deficit (Zymaroieva *et al.*, 2021). The results of the study confirm that the introduction of irrigation significantly increases sunflower yields, but the effectiveness of this measure depends on compliance with the optimal irrigation regime. The largest yield increase was noted under optimal irrigation conditions, while excessive water supply, although providing some yield increase, is accompanied by an increased risk of disease development and deterioration of seed quality. Given these factors, it is necessary to maintain a balanced irrigation regime that ensures maximum productivity gains without adverse effects on the plant organism and crop quality.

Data analysis shows that the use of irrigation systems has a significant impact on sunflower yields. Under non-irrigated conditions, plant productivity is lowest due to limited soil moisture, which negatively affects the growth and development of the plant organism. Optimal irrigation provides the highest yields, which is explained by the improvement of physiological processes, including photosynthetic activity and efficient nutrient absorption. At the same time, excessive irrigation, although leading to an increase in yields compared to natural moisture conditions, has certain negative consequences, such as reduced seed quality and an increased risk of plant disease (Table 1).

***Table 1**. Influence of different irrigation regimes on sunflower productivity in 2022-2024 on average*

Irrigation mode	Yield (t/ha)	Increase in yield (%)	Additional observations
No irrigation (control)	2.5	–	Reduced leaf surface area, lower photosynthetic activity
Optimal irrigation	3.7	48%	Increased leaf surface area, high photosynthetic activity
Excessive irrigation	3.2	28%	Increased risk of disease development, reduced seed quality

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

Thus, the introduction of rational irrigation practices is a key factor for realising the productivity potential of sunflower hybrids P64HE133 and P64LE25 in the Southern Steppe of Ukraine. Optimal water supply helps to improve physiological processes, increase photosynthetic activity and provide consistently high yields, which makes these technologies promising for increasing production efficiency.

Winter wheat: the impact of irrigation systems on grain yield and quality. Winter wheat is one of the key grain crops in Ukraine, and its productivity largely depends on the level of water availability and the efficiency of irrigation systems. Research has demonstrated that the use of irrigation not only stabilises yields but also improves grain quality by increasing protein and gluten content (Lykhovyd, 2023). Optimal irrigation contributes to the formation of a productive stem, improves the structure of the ear and ensures a fuller grain filling. The varieties Duma Odeska and Osnova Odeska are characterised by high yields and adaptability to different growing conditions. The genetic characteristics of these varieties provide them with high resistance to lodging, which is a substantial factor in growing technologies under conditions of moisture deficit. One of the key elements of high productivity is the ability of plants to effectively use moisture during periods of moisture deficit. Studies have demonstrated that these varieties demonstrate better drought tolerance compared to other commercial wheat varieties, due to their deeper root system and better adaptive response to changes in the water regime (Korkhova *et al.*, 2023).

Irrigation has the greatest impact on winter wheat yields during the critical stages of development: tillering, earing and heading. Insufficient water supply during these periods can significantly reduce the number of productive shoots, limit plant growth and negatively affect grain fullness. The introduction of irrigation during these phases not only increases yields but also improves the quality characteristics of grain, which is a key factor in increasing its technological value for the baking industry (Pichura *et al.*, 2024). Table 2 summarises the main indicators of grain yield and quality depending on the level of moisture. The data obtained confirm that optimal irrigation provides the highest yields and improves the biochemical composition of grain and its marketable characteristics. At the same time, excessive irrigation, while contributing to yield growth, does not maximise the improvement of quality indicators, in particular protein and gluten levels, which are important for the food value of wheat.

***Table 2**. The impact of irrigation on the yield and quality of winter wheat grain in 2022-2024 on average*

Parameter	No irrigation (control)	Optimal irrigation	Excessive irrigation
Yield (t/ha)	5.2	7.8	7.2
Protein content (%)	11.8	14.5	13.9
Gluten (%)	24.5	31.2	30
Weight of 1000 grains (g)	38.5	43.2	42

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

The results confirm that optimal irrigation contributes to the most efficient use of water resources, ensuring a balance between productivity and grain quality. The high protein and gluten content of grain obtained under conditions of rational water supply is an important indicator of its suitability for bakery production. At the same time, excessive irrigation, while increasing yields, is accompanied by a decline in grain quality and can create risks of waterlogging. Thus, the use of irrigation systems in the cultivation of winter wheat can increase not only yields but also grain quality indicators. The most effective is the use of irrigation in critical phases of growth and development, which helps to maximise the genetic potential of the crop and ensures high productivity under conditions of stable water supply.

Winter rape: adaptability and productivity in irrigated conditions. Winter rapeseed (*Brassica napus* L.) is one of the leading oilseed crops in Ukraine, and its productivity largely depends on the level of water supply and the efficiency of irrigation technologies. In the Southern Steppe of Ukraine, irrigation is a critical factor that contributes not only to increasing yields but also to improving seed quality. Tempo and Clavir CL rape hybrids are highly adaptable to different levels of water supply. Tempo is characterised by rapid autumn development, which can efficiently use autumn moisture reserves and form a strong root system before entering winter. The hybrid has increased disease resistance and good winter hardiness. Clavir KL, in turn, is a high-yielding hybrid with good yield potential and high oil content. Research demonstrated that under conditions of sufficient water supply, these hybrids form an optimal crop structure with high photosynthetic apparatus productivity, which contributes to the accumulation of dry matter and increase in yield (Kovalenko *et al*., 2024).

Irrigation has a positive effect on the accumulation of rapeseed biomass, which directly affects its yield. Under optimal moisture levels, yields can increase by 20-30% compared to rainfed conditions. Irrigation also has an important impact on the quality characteristics of seeds, on the oil content. Optimal water supply allows to achieve the maximum oil content, while in dry conditions this metric is significantly reduced. One of the key factors in rapeseed productivity is the development of the root system. A deep and branched root system allows plants to use soil moisture more efficiently, reducing dependence on short-term water shortages. Irrigation conditions promote intensive growth of the root system, which ensures improved absorption of moisture and nutrients. Analysis of the data shows that optimal irrigation ensures maximum yields and improves seed quality, including oil content. At the same time, excessive irrigation, while contributing to biomass growth, leads to a decrease in the efficiency of water use, slightly reducing the oil content of seeds. It is also worth noting that an expanded root system with optimal irrigation allows plants to better withstand short-term droughts, which is an important factor in yield stability (Table 3).

Table 3. *The impact of irrigation on winter rape productivity on average for 2022-2024*

Irrigation mode	Yield (t/ha)	Oil content (%)	Root system length (cm)
No irrigation (control)	2.8	42.5	95
Optimal irrigation	4.1	46.8	125
Excessive irrigation	3.6	45.1	110

Source: *compiled by the authors*

Thus, the use of irrigation technologies in the cultivation of winter rape not only increases its yield but also improves the quality of seeds. Tempo and Clavir CL hybrids demonstrate high efficiency under conditions of optimal water supply, which is confirmed by the data on the increase in their yield and oil content. Irrigation also promotes the development of a strong root system, which provides plants with resistance to dry periods and efficient use of water resources.

Physiological and biochemical parameters of crops under irrigated conditions.Irrigation affects the fundamental physiological and biochemical processes of plants, including photosynthetic activity, transpiration and dry matter accumulation. Ensuring an optimal water regime helps to improve the efficiency of assimilation processes, which directly affects crop productivity. Photosynthetic activity is a key indicator of plant productivity, as it determines the rate of organic matter synthesis (Oliynyk *et al.*, 2020). Studies have shown that irrigation helps to maintain the optimum level of photosynthetic potential through improved water supply. The chlorophyll content (Chl a+b) in sunflower leaves under irrigation increased by 15-22%, in winter wheat by 18-25%, and in rapeseed by 20-27% compared to rainfed conditions. This indicates the maintenance of a stable state of chloroplasts and an increase in the activity of the photosynthetic apparatus. The intensity of photosynthesis in irrigated crops increased by an average of 20-35%, depending on the crop. The largest increase in this indicator was observed in rapeseed and winter wheat, due to their high sensitivity to soil moisture. Improved water supply contributed to active carboxylation, increased productive leaf apparatus and a general increase in photosynthetic productivity.

Transpiration is an important process that maintains plant temperature and regulates the absorption of mineral elements (Boiko *et al.*, 2024). Data analysis demonstrated that under irrigation conditions, the average transpiration rate for sunflowers was 5.8-6.5 mmol/m^2/s, which is 10-15% higher than in rainfed crops. In winter wheat, this figure reached 4.2-5.1 mmol/m^2/s, and in rapeseed 5-5.8 mmol/m^2/s. The increased intensity of transpiration with sufficient moisture indicates active water exchange and improved regulation of the heat balance of plants. This is an important factor in increasing the resistance of crops to high temperatures, which is typical for arid regions. The accumulation of dry matter is an integral indicator of the efficiency of growth processes. Irrigation promotes more intensive synthesis of organic compounds, which has a positive impact on the structure of the crop. The dry matter content of irrigated sunflower crops was 44-48%, which is 8-12% higher than under rainfed conditions. In winter wheat, this figure increased to 56-62%, ensuring better grain filling. In rapeseed, the dry matter content increased to 40-44%, which contributed to an increase in seed oil content (Pichura *et al*., 2024). Thus, the use of irrigation contributes to the improvement of the physiological and biochemical parameters of crops, providing optimal water supply, increased photosynthetic activity and improved crop quality. The use of efficient irrigation systems reduces drought stress, increases plant resilience and ensures high productivity under unstable water conditions.

Comparative assessment of the economic efficiency of irrigation. Irrigation is a strategically important factor in agriculture, especially for water-scarce regions such as the Southern Steppe of Ukraine. Its implementation helps to increase yields, improve product quality and reduce risks associated with climate change. At the same time, the use of irrigation systems requires significant financial investments, which requires a comprehensive analysis of their economic efficiency. The calculation of the costs of installing and operating different irrigation systems shows that drip irrigation, although requiring a higher initial investment, is more cost-effective in the long run due to reduced water and electricity consumption. Sprinkler systems, in turn, have lower capital costs but are more expensive to maintain (Table 4).

Table 4*. Estimated cost of installation and operation of irrigation systems*

Parameter	Drip irrigation	Sprinkler systems
Installation cost (thousand UAH/ha)	45-60	75-90
Annual operating costs (thousand UAH/ha)	5-8	12-15
Water consumption (m^3/ha)	2,500-3,500	5,000-7,000
Electricity consumption (kWh/ha)	450-600	1,000-1,400
Average yield increase (%)	20-35	15-30

Source: *compiled by the authors*

The impact of irrigation on yields depends on the crop. The largest increase in productivity is observed in winter wheat, where the yield increase reaches 2.3-2.8 t/ha. For rapeseed, this figure is 1.2-1.7 t/ha, and for sunflower – 1-1.5 t/ha. Accordingly, the economic effect of using irrigation also varies depending on the crop, which is confirmed by the calculations of additional profit (Table 5).

Table 5*. The impact of irrigation on yields and profitability*

Crop	Yield with irrigation, Y_{germ} (t/ha)	Yield without irrigation, $Y_{rainfed}$ (t/ha)	Price (UAH/t)	Additional yield (t/ha)	Additional income (UAH/ha)	Payback period (years)	ROI (%)
Winter wheat	7.8	5.2	7,000	2.6	18,200	2.75	36.4
Sunflower	3.7	2.5	21,000	1.2	25,200	1.98	50.4
Winter rape	4.1	2.8	15,000	1.3	19,500	2.56	39

Source: *compiled by the authors*

Regarding the obtained indicators, it is determined that the payback period of irrigation systems is one of the key factors in deciding on their implementation. The fastest payback period for drip irrigation is 1.7-2.4 years on average, while for sprinklers this period is 3-4.4 years (Table 6).

Table 6*. Payback calculation*

System	Capital expenditures, C_{cap} (UAH/ha)	Net profit, P_{net} (UAH/ha)	Payback, $T_{payback}$ (years)	ROI (%)
Drip irrigation	50,000	21,000	2.38	42
Sprinkler irrigation	35,000	15,000	2.33	43

Source: *compiled by the authors*

Thus, the results of the analysis demonstrated that although the introduction of irrigation systems requires significant financial resources, they are economically justified due to the steady increase in yields and incomes. The most efficient option for farms with limited water resources is drip irrigation, which provides a quick payback and minimises water and electricity consumption. Sprinkler systems may be appropriate for large areas where flexibility in water supply is required, but their cost-effectiveness is lower due to higher operating costs. The choice of the optimal system should be based on the agricultural and climatic conditions of the region, the financial capacity of the farm and the availability of water resources.

Environmental impact analysis of irrigation systems. The use of irrigation has a significant impact on the ecological state of agricultural landscapes, changing the physical and chemical properties of the soil, its microbiological composition and water balance. Rational water management helps to maintain soil productivity, while inefficient irrigation methods can lead to soil degradation, salinisation and structural disruption. Studies of the impact of irrigation on soil microbiota have shown that under conditions of regular moisture, the activity of microorganisms increases. In particular, the content of nitrogen-fixing bacteria increased by 12-18% compared to rainfed conditions, which contributed to the accumulation of available nitrogen for plants. At the same time, excessive moisture created a favourable environment for the development of fungal infections, which could negatively affect the phytosanitary condition of crops (Merza *et al*., 2023; Zamani *et al*., 2021).

Changes in the chemical composition of the soil under irrigation were manifested in an increase in the electrical conductivity of the soil solution, which indicated the accumulation of salts. Depending on the source of irrigation water, after 3-5 years of intensive use of irrigation, the salinity level increased by 20-30%, which led to a decrease in the availability of phosphorus and potassium, as well as deterioration of soil structural properties. One of the positive aspects was the stabilisation of the humus content: constant moisture supply contributed to the uniform decomposition of organic matter and active humification, which had a positive effect on soil fertility (Cepeda *et al*., 2024; Corwin, 2021). The dynamics of soil moisture content depended on the irrigation technology used. The analysis showed that drip irrigation ensures an even distribution of moisture in the arable layer (0-30 cm) at the level of 70-80% of the lowest moisture capacity, which is optimal for most crops. At the same time, the use of sprinklers resulted in uneven moisture, especially in the upper soil horizons, where the moisture content was 55-65% of the lowest moisture capacity. This caused uneven water consumption by plants and contributed to increased evaporation, which reduced irrigation efficiency (Khondoker *et al*., 2023).

Thus, the implementation of irrigation systems requires comprehensive environmental monitoring to prevent soil degradation. The optimal solution is to use drip irrigation, which minimises the risk of salinity, promotes even moisture distribution and maintains the stability of the microbiological environment. The use of water with a controlled salinity level and adaptive irrigation regimes helps to reduce the negative impact on ecosystems and maintain soil fertility in the long term.

International experience and prospects of adaptive irrigation. Studying international experience of using irrigation systems in regions with similar climatic conditions is important for optimising water use in Ukraine. In the United States (California, Texas), Spain, Israel and Australia, modern irrigation technologies are actively used to increase yields and reduce water consumption. Precision irrigation methods, remote soil moisture monitoring, and automated irrigation systems that ensure even distribution of moisture and optimise water consumption are highly effective (Didkovska, 2023). The introduction of such technologies could become a promising area for the agricultural regions of Ukraine. Increased climate change, rising average annual temperatures, changes in precipitation distribution and an increase in the frequency of droughts necessitate the introduction of adaptive water management systems (Shahini, 2024). Such technologies are already being actively used in Spain and Australia, where deficit irrigation is practised, which involves optimising irrigation rates without reducing yields. Israel has implemented systems for the reuse of treated water, which can reduce freshwater consumption by 40-50%. Similar approaches can be effective in Ukraine, especially in the southern regions with limited water resources.

Drip irrigation, automated systems and soil moisture sensors play an important role in improving irrigation efficiency. Drip irrigation, which is widely used in the US and Spain, can reduce water losses by 30-50%, ensuring that the root zone of plants is moistened. Automated monitoring systems that evaluate soil moisture, evaporation and weather conditions can reduce water use without sacrificing yields. Studies show that the use of such technologies can increase yields by 15-30%, depending on the crop and growing conditions. For example, in the United States, the introduction of precision irrigation has increased corn yields by 20-40%, and in Spain – wheat productivity by 15-30% (Ivaniuta *et al*., 2020). In addition, such systems have a positive impact on the physical and chemical properties of soils, contributing to the preservation of humus and reducing the risk of secondary salinisation.

The results of the study show that the efficiency of irrigation technologies in Ukraine is in line with general international trends. However, to increase the productivity and efficiency of water use, it is necessary to adopt the world's advanced technologies: precision irrigation and remote humidity monitoring will help optimise water consumption, and the use of energy-saving irrigation systems will reduce electricity consumption by 20-30%, and the introduction of deficit irrigation will reduce irrigation volumes with minimal impact on yields. Another promising area is the use of treated wastewater for irrigation, which is actively used in Israel and Spain and could be useful for Ukraine, especially in industrial regions with water shortages. Thus, international experience confirms the effectiveness of modern irrigation systems and the feasibility of their implementation in Ukraine. The use of precise water management, adaptive irrigation regimes and water reuse technologies will reduce the pressure on water resources and ensure stable yields in the face of climate change.

DISCUSSION

A study of the effectiveness of irrigation systems in the Southern Steppe of Ukraine confirmed their importance for stabilising yields and improving product quality under conditions of natural moisture deficit. The results correlate with the findings of other scientific studies on the impact of irrigation on agricultural productivity and its environmental impact. The results of this study confirmed that the use of irrigation technologies helps to increase the yield of sunflower, winter wheat and winter rapeseed by 15-35%, depending on the crop and the level of water supply. Similar trends were observed in the study by P. Lykhovyd (2021), which noted that the lack of precipitation in Ukraine significantly affects the yield of major crops, and an increase in irrigated areas is needed to ensure stable production. At the same time, according to a study by X. Cao *et al.* (2021), the efficiency of water use in the agricultural sector is closely related to the level of implementation of modern irrigation technologies, in particular drip and differentiated irrigation, which can significantly improve the economic performance of farms.

The study confirmed that optimal irrigation contributes to an increase in photosynthetic activity, root system development and product quality. T. Zhang *et al.* (2021) also demonstrated that the use of different irrigation methods in arid regions affects grain quality and corn yields, and the most effective were drip and subsurface irrigation systems, which reduce water consumption and ensure uniform plant development. Similar conclusions were reached in this study, as excessive irrigation led to waterlogging of the soil, increased risk of disease development and reduced economic efficiency of crops. The cost-effectiveness analysis demonstrated that irrigation is a justified measure in arid regions, but the cost of its implementation can be a significant limiting factor. A study by N. Merza *et al.* (2023) confirmed that the profitability of irrigated agriculture depends not only on yield growth but also on the level of water supply costs, which can reduce economic feasibility in farms with insufficiently developed infrastructure. This study also determined that excessive irrigation costs can lead to a decrease in the level of profitability, therefore it is necessary to introduce resource-saving water management methods to increase economic efficiency.

The environmental impact assessment confirmed that excessive irrigation contributes to the accumulation of salts in the soil profile, which can negatively affect its fertility in the long term. Similar conclusions were drawn by M. Khondoker *et al.* (2023), noting that the increase in soil salinity due to the excessive use of irrigation systems is one of the global problems of agriculture, which requires adaptive approaches to water use, particularly the use of desalination technologies. The findings of this study also confirmed that to prevent soil degradation, it is necessary to implement adaptive management of irrigation systems that incorporate the balance between crop productivity and environmental sustainability. The use of modern irrigation technologies has a positive impact on the productivity of agricultural systems (Yeraliyeva *et al.*, 2017). The study by Y.V. Cepeda *et al.* (2024) confirmed that technical modernisation of irrigation systems can significantly increase the efficiency of water use, reduce moisture loss and improve the environmental situation. This study also determined that the rational management of irrigation systems helps to stabilise yields and minimise water losses, which is important in regions with limited water resources.

The analysis of the economic efficiency of irrigation confirmed that optimal water supply provides the highest profitability of agricultural production, but excessive irrigation can lead to higher water supply costs and reduced economic feasibility. Similar findings were obtained in the study by O. Zamani *et al.* (2021), stating that the implementation of water conservation policies and efficient water pricing is an important tool for increasing the productivity of the agricultural sector. The study established that the efficiency of water use directly depends on the optimisation of irrigation technologies and the rational use of water resources. An analysis of the environmental impacts of irrigation has shown that excessive water use contributes to soil salinity, which can negatively affect long-term land fertility. A study by D.L. Corwin (2021) also confirmed that climate change and intensive irrigation are causing an increase in soil salinity, which requires adaptive approaches to water use. The study determined that to prevent soil degradation, it is necessary to use methods of optimal water balance and integrated water management.

An assessment of promising irrigation methods has confirmed that the use of alternative energy sources for water supply can help improve the economic efficiency of irrigation systems. The study by J. Rana *et al.* (2021) demonstrated that the use of solar energy for irrigation systems can significantly reduce electricity costs and increase the financial sustainability of agricultural enterprises. Similar conclusions were obtained in this study, as the economic efficiency of irrigation significantly depends on the level of energy and water supply costs. Rational management of irrigation systems requires the introduction of modern technologies for monitoring and automated control of soil moisture. S. Alharbi *et al.* (2024) confirmed that the use of technological solutions, such as remote soil moisture monitoring and automated irrigation systems, increases water use efficiency and minimise moisture losses. The study also noted that the introduction of precision irrigation and automated water management systems is a promising area for optimising water use in arid regions.

The results of the study are consistent with the findings of B. Golla (2021), stating that agricultural production in arid regions largely depends on water use efficiency, and the use of adaptive irrigation technologies helps to improve crop productivity. This paper confirmed that optimisation of irrigation technologies can ensure stable production in the face of climate change and reduced natural moisture. The obtained results confirm that the introduction of modern irrigation methods contributes to the optimal distribution of moisture in the soil, reducing its evaporation and improving the overall condition of agrocenoses. Similar conclusions were drawn by S. Lin *et al.* (2024), noting that the combination of drip irrigation with mulching not only improves the water supply of plants but also increases the efficiency of fertiliser use, which has a positive impact on cotton yields. This study also confirmed that the optimal combination of water and mineral nutrition helps to maximise crop potential while reducing unproductive water losses. A comparison of the results obtained with previous scientific studies confirmed that further development of irrigation systems should be aimed at introducing energy-efficient and environmentally friendly irrigation technologies. Optimisation of the water regime and adaptation of irrigation technologies to specific agricultural and climatic conditions will ensure a stable level of crop productivity without a negative impact on the environment.

CONCLUSIONS

Irrigation is a key factor in stabilising yields and improving product quality in conditions of unstable water supply. Optimal water supply increases the photosynthetic activity of plants (by 20-35%), increases the chlorophyll content (by 15-27%) and improves the water regime, which has a positive impact on their productivity. The study demonstrated that the use of irrigation ensures optimal absorption of nutrients and the development of a powerful root system, which contributes to the increase of crops' resistance to drought conditions. The study determined the use of irrigation provides an increase in yield: for sunflower – optimal irrigation by 48%, excessive irrigation by 28%; winter wheat – by 15-25%, winter rape – by 25-35%. In addition, the content of dry matter and oil in the seeds increases, which improves the quality of the products. Studies have confirmed that irrigation can reduce the impact of stress factors associated with moisture deficit while maintaining the productive potential of plants.

The economic evaluation of irrigation systems confirmed their financial feasibility. It was found that the average payback period for irrigation is 1.7-4.4 years, depending on the type of system and crop. The use of adaptive water management technologies allows optimising irrigation costs, which increases the overall profitability of production. At the same time, the study determined that excessive irrigation can be accompanied by increased water supply costs and an increased risk of secondary soil salinisation. An analysis of the environmental impacts demonstrates the need for rational water management. It has been established that intensive irrigation without appropriate control causes accumulation of salts in the soil (by 20-30%), changes in its physical and chemical properties, and disruption of the water balance. At the same time, the use of adaptive irrigation methods stabilised the humus balance, improve the microbiological activity of the soil and maintain its fertility in the long term.

Comparison with international experience has confirmed the effectiveness of modern irrigation technologies, including precision irrigation, automated moisture monitoring and deficit irrigation, which are actively used in the US, Spain, Israel and Australia. These technologies help to minimise water consumption, increase irrigation efficiency and reduce the burden on water resources. Adaptation of such approaches, including the introduction of energy-saving systems, precision irrigation using moisture sensors, as well as the use of reuse and recycling technologies for irrigation, is promising for Ukraine. The results of the study compiled recommendations for the further development of irrigated agriculture. The rational management of irrigation systems should be based on the principles of adaptive water use, considering the needs of specific crops and agroclimatic conditions. It is advisable to introduce automated humidity control systems, apply deficit irrigation and use precise water supply systems to optimise water resources. Further research could conduct an empirical verification of the identified patterns in the field and developing integrated approaches to managing irrigation systems in the face of climate change. A promising direction is the integration of modern technologies for moisture monitoring, precision agriculture and economic optimisation of irrigation to ensure sustainable development of the agricultural sector of Ukraine.

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CONFLICT OF INTEREST

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Зрошувальні системи як фактор підвищення продуктивності в аграрних регіонах України

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Анотація. Актуальність дослідження зводиться до необхідності аналізу ефективності зрошувальних систем в аграрних регіонах України на фоні посилення змін клімату та дефіциту вологи, що впливають на стабільність сільськогосподарського виробництва. Метою дослідження було визначити вплив зрошення на продуктивність основних сільськогосподарських культур (соняшника, пшениці та ріпаку озимих) та оцінити економічну ефективність впровадження зрошувальних технологій у посушливих регіонах України. У дослідженні використовувалися агрономічні та економічні методи аналізу. Визначення ефективності зрошення здійснювалося шляхом порівняння врожайності культур за різних режимів водозабезпечення. Оцінка економічної ефективності включала аналіз витрат на встановлення та експлуатацію зрошувальних систем у співвідношенні до приросту врожайності та підвищення якості продукції. Було встановлено, що застосування зрошення дозволило підвищити врожайність соняшника на 28-48 %, пшениці озимої – на 15-25 %, а ріпаку – на 25-35 %. Оптимальне водозабезпечення сприяло збільшенню вмісту білка та клейковини у зерні пшениці, а також підвищенню рівня олії в насінні ріпаку. Аналіз економічної ефективності зрошення показав, що термін окупності залежав від типу системи: краплинне зрошення забезпечувало найвищий приріст врожайності при мінімальних витратах води, тоді як дощувальні установки потребували більших експлуатаційних витрат. Зрошення відіграло важливу роль у підвищенні продуктивності сільськогосподарських культур у посушливих регіонах України. Найбільш ефективними виявилися адаптивні технології зрошення, що включали автоматизовані системи управління водними ресурсами. Впровадження сучасних методів зрошення сприятиме оптимізації водного балансу ґрунтів, зменшенню негативного впливу посухи та підвищенню економічної рентабельності агровиробництва

Ключові слова: сільське господарство; первинний сектор економіки; водний баланс; врожайність; соняшник; пшениця озима; ріпак озимий; економічна рентабельність; адаптативні технології