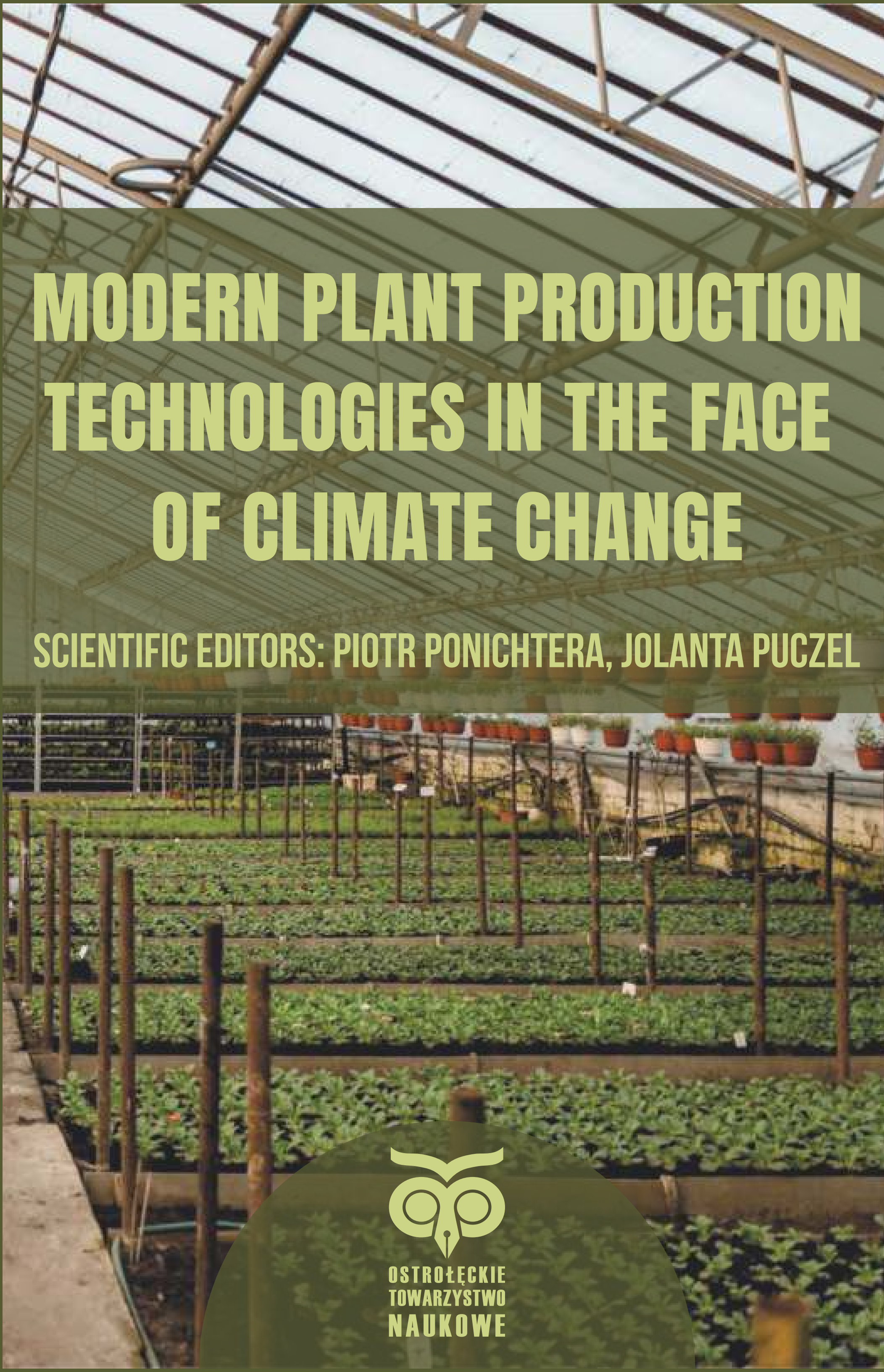

MODERN PLANT PRODUCTION TECHNOLOGIES IN THE FACE OF CLIMATE CHANGE

SCIENTIFIC EDITORS: PIOTR PONICHTERA, JOLANTA PUCZEL

OSTROŁĘCKIE
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MODERN PLANT PRODUCTION TECHNOLOGIES IN THE FACE OF CLIMATE CHANGE

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Publishing house of the Adam Chętnik Scientific Society in Ostrołęka

Ostrołęka 2025

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ISBN 978-83-68680-24-9

DOI: https://doi.org/ 10.62961/ILDH7645

259 publication of the Adam Chętnik Scientific Society in Ostrołęka

Publishing house of the Adam Chętnik Scientific Society in Ostrołęka
07-410 Ostrołęka, ul. Traugutta 9A

tel. 29 764-59-80

www.otn.ostroleka.pl/ct-menu-item-15

e-mail: otn.ostroleka@o2.pl

Cover design: architectural engineer Aleksandra Żuchowska

Typesetting and layout:

Granave Art Ewa K. Czetwertyńska, Łomża

Print:

Drukarnia Hajstra, Grodzisk Mazowiecki

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УДК 631.67:635.25(477.7)

Chapter 4.

STUDY OF THE EFFECT OF SOIL MOISTURE REGIME AND PLANT DENSITY ON THE PRODUCTIVITY OF BULB ONION IN THE SOUTHERN STEPPE OF UKRAINE

Andrii Shepel

4.1. Introduction

The relevance of studying the impact of soil moisture regime and plant density on the productivity of bulb onion in the Southern Steppe of Ukraine is driven by the need to improve the efficiency of onion cultivation under changing climatic conditions. In recent years, there has been an increase in average annual temperatures, a decrease in precipitation, and an uneven distribution of rainfall, creating additional risks for obtaining stable and high agricultural yields, particularly for bulb onions. The Southern Steppe of Ukraine is characterized by insufficient natural moisture, necessitating the use of irrigation to ensure optimal plant growth and development conditions.

Under modern conditions, the use of efficient irrigation methods, such as drip irrigation, has become particularly important, as it promotes the rational use of water resources and maintains the necessary soil moisture levels. At the same time, plant density is a key factor in increasing onion yield, as it affects plant growth, development, product quality, and the efficiency of nutrient uptake from the soil.

Scientific research on the optimal combination of soil moisture regime and plant density for bulb onion cultivation is essential for developing recommendations to enhance its production efficiency in the Southern Steppe of Ukraine. Studies in this field will help optimize soil water balance, reduce the impact of stress factors, and increase crop productivity, which, in turn, will contribute to improving the economic efficiency of farms engaged in onion cultivation. Therefore, conducting comprehensive research aimed at improving onion cultivation technologies, considering moisture regime and plant density, is relevant from both scientific and practical perspectives.

The objective of this study is to examine the effects of different soil moisture regimes and plant densities on the productivity of bulb onion in the conditions of the Southern Steppe of Ukraine. The obtained results will enable the optimization of agronomic practices to increase crop yield and ensure the rational use of water resources.

The main research objectives are defined as follows:

1. Determine the optimal soil moisture regime for maximum water retention and efficient water use by plants.
2. Study the effect of plant density on the yield formation of bulb onion.
3. Establish the relationship between soil water regime and key indicators of crop growth, development, and productivity.
4. Assess the impact of the studied factors on the qualitative characteristics of the yield (mass, marketability, storability).
5. Develop recommendations for optimizing irrigation and planting density to enhance the yield of bulb onion under the conditions of the Southern Steppe of Ukraine.

Scientific Novelty. For the first time, a comprehensive study has been conducted in the Southern Steppe of Ukraine to analyze the relationship between soil moisture levels and bulb onion planting density. The obtained data allow for the formulation of new agronomic approaches to regulating the soil water regime in onion cultivation. Optimal irrigation parameters and plant density levels have been established, contributing to increased yield and improved product quality.

In the context of climate change and water resource scarcity, the issue of rational irrigation use is extremely important. Bulb onion is one of the key vegetable crops grown in the Southern Steppe of Ukraine, and optimizing its cultivation technology will enhance both yield and economic efficiency. The research findings can be applied in practical vegetable farming to optimize irrigation regimes and plant density, leading to higher yields, improved onion quality, and reduced water consumption. Additionally, the obtained data will be valuable for further scientific studies in the field of agricultural technologies.

4.2. The state of research on the effectiveness of irrigation in bulb onion cultivation in Ukraine and worldwide

In the study of the impact of soil moisture regime and plant density on the productivity of bulb onion in the conditions of the Southern Steppe of Ukraine, the following methods were applied: Field method: Establishment of the experiment under natural farm conditions, considering the agro-climatic characteristics of the region. Variation of factors (soil moisture levels and plant density) was used to determine optimal growing conditions. Growth and development of plants were monitored and recorded under different experimental variants. Agronomic method: Assessment of phenological phases of onion development depending on soil moisture levels and planting density. Biometric indicators such as plant height, number of leaves, bulb diameter, and bulb mass were measured. Productivity indicators, including yield, marketability, and the proportion of standard-quality products, were analyzed. Physico-chemical methods: Determination of soil moisture using the drying method to monitor the moisture regime. Analysis of soil agrochemical composition before the experiment and after harvest. Examination of crop quality, including dry matter content, sugar content, and vitamin C concentration.

Statistical methods: Processing of research results using analysis of variance (ANOVA) to assess the impact of the studied factors, calculation of mean values, variation, and reliability of the obtained results, as well as the construction of graphical dependencies and diagrams for data visualization. Meteorological observations: Recording of weather conditions (temperature, air humidity, and precipitation) throughout the growing season, analysis of climatic factors, and their impact on the experiment's results. The integrated use of these methods allows for an objective assessment of the influence of soil moisture and plant density on the productivity of bulb onion and the development of scientifically based recommendations for optimal cultivation conditions in the Southern Steppe of Ukraine.

Vitanov et al (2024) state that bulb onion (*Allium cepa* L.) belongs to the Alliaceae family and the *Allium* genus, which includes approximately 400 species. The high nutritional value of this crop is due to its significant content of carbohydrates and nitrogenous compounds. Onion bulbs contain between 7% and 21% dry matter, while the leaves contain 6.2-7.0%. The primary carbohydrates are sugars (4-14%), including sucrose, glucose, fructose, and maltose. The protein content in bulbs ranges from 2% to 4%, while in leaves, it is 1.3%-1.9%. The amino acid composition includes arginine, valine, histidine, isoleucine, leucine, lysine, methionine, and phenylalanine, with a total concentration reaching 500 mg per 100 g of fresh mass. The characteristic pungent taste of onions is due to the presence of glycosides, which are carbohydrate derivatives.

Thanks to its high vitamin content, onion is considered one of the most valuable foods for year-round consumption. The ascorbic acid (vitamin C) content in green leaves ranges from 20 to 60 mg, while in bulbs, it is 5-10 mg per 100 g. Thiamine (vitamin B1) content is 0.02–0.05 mg in leaves and 0.05-0.1 mg in bulbs, while riboflavin (B2) is found at levels of 0.07–0.1 mg and 0.02-0.04 mg, respectively. Niacin (vitamin PP) is present in concentrations of 0.2-0.3 mg in leaves and 0.4-0.6 mg in bulbs. The pantothenic acid (B3) content in dried onions can reach up to 400 mg per 100 g. Green leaves also contain vitamins B6 (0.1 mg), B9 (10-12 μg), E (1.0-1.5 mg), and A (2.0–3.7 mg per 100 g)[1].

Mohylna et al. (2020) state that bulb onion cultivation is an important sector of vegetable production in Ukraine and worldwide. It is one of the most popular and widely cultivated vegetable crops due to its versatility, nutritional value, and relative ease of cultivation. Bulb onion is among the most well-known vegetables globally and has been grown for thousands of years. The global sown area for onion cultivation is approximately 6 million hectares, with the crop accounting for about 15% of the total vegetable growing area. The leading global producers and exporters of bulb onion are the United States, Japan, Spain, Egypt, and Turkey. China is the world's top onion producer, annually accounting for approximately 19% of the total global output[2].

Vitanov (2020) states that Ukraine is one of the leading producers of bulb onion in Eastern Europe. The primary growing regions include Kherson, Odesa, Mykolaiv, and Dnipropetrovsk oblasts, which lead in production due to favorable climatic conditions. Additionally, Cherkasy, Vinnytsia, and Poltava oblasts allocate significant areas for onion cultivation due to their

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1 Vitanov, O.D., Zelendin, Y.D., & Chefonova, N.V. (2024). *Onion bulb: Effective agrotechniques* (O.D. Vitanov, Ed.). Agrarian Science. https://doi.org/10.31073/978-966-540-617-4

2 Mohylna, O.M., Kuts, O.V., Rud, V.P., Teriokhina, L.A., Kormosh, S.M., Uriupina, L.M., Stovbir, O.P., Dukhin, Ye.O., Datsenko, S.M., Kuzmenko, V.V., Zinchenko, Ye.V., Sidora, V.V., & Yakovchenko, A.V. (2020). *Improving the scientifically based structure of sown areas by region based on effective solutions in vegetable growing*. TVORY. https://ovoch.com/assets/files/library/books-monographs/posivna-ploshhi-povne.pdf

fertile soils. In 2021, the average onion yield in Ukraine was 18.9 tons per hectare, with a sown area of 53.8 thousand hectares, accounting for 10.3% of the total vegetable-growing area. The total onion production amounted to 1,024.4 thousand tons, representing 9.8% of Ukraine's overall vegetable production[3].

Mohylna et al. (2020) state that approximately 60,000 hectares in Ukraine are allocated for bulb onion cultivation. The largest areas are concentrated in the Steppe zone, which accounts for 48.4% of the total land under this crop, followed by the Forest-Steppe zone with 34.7%, the Polissia zone with 13.3%, and the Carpathian region with 3.6%. The Steppe zone is the main onion-producing region, with an annual production volume reaching 492.7 thousand tons, representing 48.6% of the total national harvest. It is worth noting that the production level in this zone during 2017-2019 was equal to the total onion production in Ukraine in 1990. The Forest-Steppe zone produces 472.7 thousand tons of onions, accounting for 36.7% of the total yield, while the Polissia zone produces 12.9 thousand tons (12.1%), and the Carpathian region produces 26.4 thousand tons (2.6%). The highest yield rates are recorded in the Forest-Steppe (19.6 $t \cdot ha^{-1}$) and Steppe (18.6 $t \cdot ha^{-1}$) zones, whereas in the Polissia zone, the yield is 16.8 $t \cdot ha^{-1}$, and in the Carpathians, it is 13.2 $t \cdot ha^{-1}$[4].

The following cultivation methods are used: Through sets (two-year cycle) – the most common method, Direct seeding – cost-effective for industrial cultivation, Transplanting – used less frequently, mainly for early production. Soil and Climate Requirements: Bulb onion grows best in light, fertile soils with a pH of 6.0-7.0. It responds well to crop rotation and should not be grown after garlic, cabbage, or beet. Good lighting is essential, and the optimal temperature for growth ranges from +15 to +25°C. Irrigation is critical during the bulb formation stage. Fertilization includes nitrogen fertilizers at the beginning of growth and potassium-phosphorus fertilizers during bulb formation. Disease and pest control is essential, with the main threats being downy mildew, powdery mildew, and thrips. The average yield of bulb on-

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3 Vitanov, O.D. (2022). *Modern vegetable production systems*. TVORY. https://ovoch.com/ua/naukovi-vidannya/knigi-monografii1/

4 Mohylna, O.M., Kuts, O.V., Rud, V.P., Vitanov, O.D., Shcherbyna, S.O., Teriokhina, L.A., Serhiienko, O.V., Paramonova, T.V., Zelendin, Y.D., Uriupina, L.M., Stovbir, O.P., Yakovchenko, O.I., Yakovchenko, A.V., & Sidora, V.V. (2020). *Innovative business project for onion production for commercial purposes under organic production conditions*. Institute of Vegetable and Melon Growing NAAS. https://ovoch.com/assets/files/library/methodical/2020/biznes-proekt-cibulya.pdf

ion is 30-50 t·ha^{-1}, with leading farms achieving up to 80 t·ha^{-1}. Storage at a temperature of 0 to +2°C and humidity levels of 65-70% ensures a long shelf life. According to FAO, the world's largest onion producers are: China (~23 million tons), India (~20 million tons), USA (~3 million tons), Egypt (~3 million tons), Turkey (~2 million tons)

Cultivation Characteristics in Different Countries: China and India – primarily export-oriented countries using intensive technologies and drip irrigation, USA – onion production is concentrated in California, Oregon, and Texas, Egypt, Spain, and Italy – leaders in export due to the early maturation of onions. Ukraine has the potential to supply onions to EU and Middle Eastern markets. Gelaye et al. (2024) state that bulb onion (*Allium cepa* L.) is the most important commercial vegetable crop, widely cultivated worldwide. Countries grow onions due to their high nutritional value, medicinal properties, and rich content of minerals, proteins, and carbohydrates. In terms of production volume, onion ranks second after tomatoes globally[5]. Bulb onion remains a strategically important crop, and improving cultivation technologies will contribute to increasing farm profitability.

Researchers from various regions of Ukraine have studied the impact of soil moisture regimes and plant density on the productivity of bulb onions. Fedorchuk M. I. and Svyrydovskyi V. M. investigated the effect of different irrigation regimes and plant protection methods on onion yield in southern Ukraine from 2016 to 2018. In their study, Yarovyi et al. (2023) analyzed the yield, quality characteristics, and storability of different onion hybrids. The authors established the dependence of these indicators on agronomic growing conditions and the genetic traits of the hybrids[6]. Nesterenko (2020) focused his research on the impact of irrigation methods and fertilizer application on the growth, development, and yield of bulb onions[7]. These re-

5 Gelaye, Y., Nakachew, K., & Ali, S. (2024). A review of the prospective effects of spacing and varieties on onion yield and yield components (*Allium cepa* L.) in Ethiopia. *Advances in Agriculture*. https://doi.org/10.1155/2024/2795747

6 Yarovyi, H. I., Hordiienko, I. M., & Kalashnyk, I. M. (2023). Yield, quality, and storability of onion hybrids. Agrarian Innovations, *21*, 132–137. https://doi.org/10.32848/agrar.innov.2023.21.20

7 Nesterenko, A. (2020). Improving elements of resource-saving technologies for growing onions under the conditions of the Dnipro Experimental Station of the Institute of Vegetable and Melon Growing of the NAAS of Ukraine. https://dspace.dsau.dp.ua/bitstream/123456789/4171/1/%D0%9D%D0%B5%D1%81%D1%82%D0%B5%D1%80%D0%B5%D0%BD%D0%BA%D0%BE%20%D0%90.%D0%90.-%D0%BF%D0%B5%D1%80%D0%B5%D1%82%D0%B2%D0%BE%D1%80%D0%B5%D0%BD%D0%BE.pdf

searchers have made a significant contribution to the study of agronomic practices aimed at increasing the productivity of bulb onions in various regions of Ukraine.

According to FAO data for 2023, the largest producers of bulb onions and shallots (dry, excluding dehydrated) are: India – 30,208,000 tons, China (mainland) – 24,860,319.45 tons, Egypt – 3,804,076.72 tons, USA – 3,315,421 tons, and Turkey – 2,600,000 tons. These countries are among the top five global onion producers by volume. India and China lead with a significant margin, which can be attributed to large cultivation areas and favorable climatic conditions. Egypt, the USA, and Turkey follow, ensuring substantial production volumes, particularly for export. Based on the presented Top 20 indicators, we have grouped the production volumes of bulb onions and shallots by continents in Table 2 (FAO, 2023).

Table 1. Top 20 Countries by Production and Gross Output of Bulb Onions and Shallots in 2023

Countries	Production of Bulb Onions and Shallots, tons	Gross Output Value of Bulb Onion and Shallot Production, thousand USD	Country's Share in Global Production (%)
India	30208000	12580144	33.4
China, mainland	24860319.45	10353098	27.5
Egypt	3804076.72	1584211	4.2
USA	3315421	1380709	3.7
Turkey	2600000	1082772	2.9
Bangladesh	2546994	1060698	2.8
Iran	2099865.85	874491	2.3
Indonesia	1985233.34	826752	2.2
Pakistan	1843494	767724	2.0
Algeria	1813467.25	755220	2.0
Mexico	1801137.36	750085	2.0
Russian Federation	1714071.7	713826	1.9
Nigeria	1692279.67	704751	1.9
Brazil	1639970	682967	1.8
Sudan	1627394.95	677730	1.8

Countries	Production of Bulb Onions and Shallots, tons	Gross Output Value of Bulb Onion and Shallot Production, thousand USD	Country's Share in Global Production (%)
Niger	1621936.43	675457	1.8
Netherlands	1605300	668528	1.8
Uzbekistan	1318528.13	549102	1.4
Spain	1205350	501969	1.3
Japan	1204087.39	501443	1.3

Source: FAOSTAT[8]

Table 2. Distribution of Production by Continents

Continent	Production Volume (tons)	Major Producing Countries
Asia	71238435	India, China, Turkey, Bangladesh, Iran, Indonesia, Pakistan, Uzbekistan, Japan.
Africa	10518954	Egypt, Algeria, Nigeria, Sudan, Niger.
North America	5117979	USA, Mexico.
South America	1639970	Brazil
Europe	4531721	Russia, Netherlands, Spain.
Australia and Oceania	Not represented in the top 20.	

Source: Summarized by the author based on[9]

Asia is the absolute leader, producing over 70% of the world's onion and shallot supply. India and China together account for more than 55 million tons, which is more than all other continents combined. High yields and strong domestic demand contribute to the dominance of Asian countries. Africa is the second-largest producing continent, with Egypt as the main producer, exporting a significant portion of its harvest. Algeria, Nigeria,

8 FAOSTAT. (2023.). Food and Agriculture Organization of the United Nations statistics database. https://www.fao.org/faostat/en/#rankings/countries_by_commodity

9 FAOSTAT. (2023.). Food and Agriculture Organization of the United Nations statistics database. https://www.fao.org/faostat/en/#rankings/countries_by_commodity

Sudan, and Niger also have substantial production, primarily for domestic consumption. North America is an important but less productive region, with the USA and Mexico as the main producers. Despite relatively lower volumes, these countries export a significant share of their harvest, especially to neighboring countries. Europe has a moderate level of production. The Netherlands is a key exporter, while Russia and Spain produce mainly for domestic consumption. Production levels are significantly lower than in Asia and Africa. South America and Oceania are minor producers. Brazil is the only country in the region that ranks in the global top 20. Australia and Oceania are not represented among the major producers at all.

Asia is the global hub for onion production due to its favorable climate, vast cultivated areas, and high domestic demand. Africa and North America are important producers, primarily serving regional markets. Europe and South America produce less, with the Netherlands and Spain focusing on quality and exports. Oceania plays an insignificant role in global onion production. Onion cultivation is mainly concentrated in countries with warm climates and intensive farming, while the leading exporters remain Egypt, India, China, and the Netherlands. India and China together account for nearly 54% of the total global value of onion and shallot production. India is the absolute leader ($12.58 billion), driven by both high production volumes and relatively high profitability. China ranks second ($10.35 billion), falling behind India in both quantity and market value. Egypt is the dominant player in Africa. With a production value of $1.58 billion, Egypt is the largest producer on the continent and a key exporter. Other African countries, such as Algeria, Nigeria, Sudan, and Niger, demonstrate high production levels, though their output is mainly used for domestic consumption.

The USA and Turkey are key producers outside of Asia. The USA ($1.38 billion) has lower production volumes but a higher product value due to superior quality and higher market prices. Turkey ($1.08 billion) also holds a strong position in the global market, benefiting from its strategic geographic location and strong domestic demand. Asian countries have stable demand and low production costs. Bangladesh, Iran, Indonesia, and Pakistan are among the nations with low production costs and consistent domestic demand. The gross production value in these countries ranges from $1.06 billion to $0.77 billion. European countries are smaller producers but focus on high-quality products. The Netherlands ($668 million), Spain ($502 million), and Russia ($714 million) are the leading European producers. Although their production volumes are not as large, high quality and efficient logistics ensure strong market prices. Key Trends: Asia dominates onion production and market value. Egypt leads in Africa and has strong export potential. The USA and Turkey achieve high product value despite relatively lower production volumes. European countries prioritize quality and exports. The global onion and shallot market remain highly concentrated, with Asia maintaining a dominant position and influencing global prices.

Improving the efficiency of crop rotations largely depends on selecting optimal predecessors for vegetable crops. Experimental research by Vitanov (2023) confirms the feasibility of including perennial leguminous grasses and winter wheat in crop rotations. It has been established that vegetable crops exhibit different responses when planted after alfalfa and winter wheat. Specifically, the yield of bulb onions (grown from seeds), cucumbers, and tomatoes remains at the same level after alfalfa as it does after winter wheat[10]. The optimal predecessors for growing onions are early potatoes, cucumbers, legumes (excluding perennial grasses), early tomatoes, and annual grasses. Pumpkins, zucchini, and watermelons are also considered acceptable. It is recommended to plant onions near carrots, as their scent repels one of the main pests-the onion fly. Onions should not be replanted in the same area for at least 3-4 years[11].

Modern agriculture largely depends on the effective regulation of soil regimes, including hydrological, thermal, and biological factors. Land reclamation measures, such as irrigation and drainage, play a crucial role in this process by reducing the impact of natural moisture on agricultural production. In Ukraine, the primary irrigation methods remain sprinkler, drip, and surface irrigation. Among them, sprinkler irrigation covers the largest area, although it is gradually being replaced by drip irrigation due to its increasing popularity. Research on the efficiency of domestic drip irrigation systems began in 1970 at Formerly, the Ukrainian Research Institute of Irrigated Agriculture (now the Institute of Climate-Oriented Agriculture, Kherson) and the Ukrainian Research Institute of Hydrotechnics and Reclamation (now the Institute of Water Problems and Land Reclamation, Kyiv).

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10 Vitanov, O. D. (2023). Specialized vegetable crop rotations (2nd ed., revised and expanded). TVORY. https://ovoch.com/assets/files/library/books-monographs/sivozminu-povne.pdf

11 Vitanov, O. D. (2023). *Home vegetable gardening: Scientific-practical guide* (2nd ed.). Vinichenko Publishing House. https://ovoch.com/assets/files/library/books-monographs/vitanov-prisadibne-povne.pdf

For the southern regions of Ukraine, it is recommended to apply 8-12 drip irrigations for onions with rates of 100-110 or 170-180 $m \cdot ha^{-3}$, depending on the planting scheme. On medium-loamy soils, the optimal moisture levels are considered to be 85%, 75%, and 70% of field capacity, corresponding to different growth stages of the crop[12].

Mohylna et al. (2020) conducted a field experiment using the Veselka onion variety, developed by specialists from the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine. The authors of this variety are V.M. Tymchuk, H.H. Yashchuk, L.M. Haidukova, and O.M. Piddubna. Veselka belongs to the semi-sharp onion group and is recommended for salad use. It is cultivated as an annual crop from seeds, with a vegetation period of 92-115 days. The variety is resistant to downy mildew (Peronospora) and well-adapted to industrial cultivation technologies. It exhibits a high ripening rate by harvest time, allowing for storage of up to six months. The yield of the Veselka variety ranges from 30 to 40 $t \cdot ha^{-1}$. The bulbs are predominantly round or slightly flattened (90%), have a single– or double-bud structure, and weigh 100-150 g. The outer scales (2–3 layers) are violet-red, with a thickness of 1.1-1.2 mm. The inner juicy scales are light violet, with a purple-tinged epidermis. The dry matter content is 10-12%, while total sugar content ranges from 8.7% to 9.5%. This variety is recommended for cultivation in all agro-climatic zones of Ukraine[13].

Aku (2023) found that drip irrigation was the most favoured technique amongst bulb onion farmers because it made it possible to maintain a steady soil moisture level and reduce water wastage. Drip irrigation is also well-suited with automation, particularly in comparison to surface or sprinkler irrigation techniques. In addition, drip irrigation with fertigation of NPK nutrients improves plant growth (delivering up to twice the yield of surface irrigation), carbohydrate accumulation and photosynthesis levels, and reduc-

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12 Vitanov, O.D. (2023). *Specialized vegetable crop rotations* (2nd ed., revised and expanded). TVORY. https://ovoch.com/assets/files/library/books-monographs/sivozminu-povne.pdf

13 Mohylna, O.M., Onyshchenko, O.I., Shcherbyna, S.O., Datsenko, S. M., Bilenka, O.M., & Ivanin, D.V. (2021). *Comprehensive system of measures to protect onions and garlic from pests, diseases, and weeds: Scientific-practical recommendations*. Agrarian Science. ISBN 978-966-540-517-7 https://ovoch.com/assets/files/library/ methodical/2021/verstka_mogylna_topress.pdf

ing bolting[14]. Belo (2022) in climates where rainfall is uncommon during the 23 growing season such as most of the western U.S., irrigation methods that avoid wetting the foliage (e.g., drip or furrow) can decrease onion bacterial disease pressure, but any reductions in the volume of irrigation to limit bacterial disease development must be managed carefully to avoid reducing marketable yield[15]. Blanco et al. (2021) studied two irrigation regimes: normal (with daily watering) and water deficit (WD) with a three-day irrigation interval. The yield was 36 t·ha-^{1}, which was similar under both irrigation regimes. However, irrigation every three days (WD) resulted in a 35% water savings and an increase in water use efficiency (WUE)[16]. Mandal et al. (2022) state that their study found low-cost drip irrigation to be the farmers' priority choice[17]. Sansan et al. (2024) state that onions are a crop that requires an adequate water supply for cultivation. This indicates that optimal soil moisture is essential for achieving high yields[18] .

Yield formation occurs as plants absorb nutrients from the surrounding environment, transform them through internal metabolism, and subsequently grow and develop. The majority of the crop's dry mass (90-95%) is formed as a result of photosynthesis, which takes place in the leaves under the influence of solar energy. Any agronomic practice aimed at increasing yield is effective if it: promotes rapid leaf area expansion in crops and ensures its maximum value; enhances the efficiency of photosynthetic activity per square meter of leaf surface and prolongs its active state; ensures the rational

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14 Aku, R., Kristiansen, P., & Coleman, M. (2023). Water management and irrigation for bulb onion (*Allium cepa* L.) growth and development in the Papua New Guinea Highlands: A review. *Asia Pacific Journal of Sustainable Agriculture, Food and Energy (APJSAFE), 11*(2), 47-58. https://ojs.bakrie.ac.id/index.php/APJSAFE/about

15 Belo, T. R. D. (2022). *Reducing the risk of onion bacterial diseases through irrigation and nitrogen fertility management* (Master's thesis). Washington State University. https://rex.libraries.wsu.edu/esploro/ outputs/graduate/Reducing-the-risk-of-onion-bacterial/99900898640801842

16 Blanco, E.L., Rada, F., Paolini, J., & Guerrero, J.A. (2021). Effects of induced water deficit and biofertilization on growth dynamics and bulb yield of onion (*Allium cepa* L.) in a neotropical semi-arid environment. *Canadian Journal of Soil Science, 101*(3), 494-506. https://doi.org/10.1139/cjss-2021-0011

17 Mandal, U.K., Burman, D., Digar, S., Sharma, P.C., & Maji, B. (2022). Cropping system intensification for smallholder farmers in coastal zone of West Bengal, India: A socio-economic evaluation. *Frontiers in Sustainable Food Systems, 6.* https://doi.org/10.3389 /fsufs.2022.1001367

18 Sansan, O.C., Ezin, V., Ayenan, M.A.T., Chabi, I. B., Adoukonou-Sagbadja, H., Saïdou, A., & Ahanchede, A. (2024). Onion (*Allium cepa* L.) and drought: Current situation and perspectives. *Advances in Agriculture.* https://doi.org/10.1155/2024/6853932

use of photosynthesis products-initially to stimulate plant growth and later to accumulate nutrients in economically valuable plant organs.

The leaf surface area of agricultural crops can range from 5,000-7,000 $m \cdot ha^{-2}$ to 40,000-50,000 $m \cdot ha^{-2}$. However, excessive leaf mass development can have negative effects: it reduces light penetration to the lower layers, decreasing photosynthesis intensity, causing lower leaves to wither, stems to elongate, and plants to lodge, all of which negatively impact yield and product quality. For achieving high bulb onion yields, it is crucial that the leaf surface area rapidly reaches 35,000-40,000 $m \cdot ha^{-2}$ and remains at this level for as long as possible. The dynamics of leaf surface area development change throughout the growing season. From the second ten-day period of May to the second ten-day period of July, there is an active increase in leaf surface area, with an average growth rate of 696 $m \cdot ha^{-2}$ per day. From the second ten-day period of July to the first ten-day period of August, the growth rate slows down by 2.3 times, reaching approximately 300 $m \cdot ha^{-2}$ per day. Starting from the second ten-day period of August, the leaf surface area gradually decreases due to leaf senescence, occurring at an average rate of 1,000 $m \cdot ha^{-2}$ per day. Table 3 presents data on the dynamics of bulb onion leaf surface area depending on pre-irrigation soil moisture (%) and plant density (thousand $plants \cdot ha^{-1}$) throughout the growing season.

Table. Dynamics of bulb onion leaf surface area depending on the drip irrigation regime and plant density, average for 2024, $m \cdot ha^{-2}$.

1*	2*	Sampling dates									
Factor A	Factor B	15.05	25.05	04.06	14.06	24.06	04.07	14.07	24.07	03.08	13.08
60-65	550	270	1641	6441	13797	21867	29699	33551	34419	28110	17347
	750	315	1872	7313	15832	25168	34234	38681	39659	32266	19668
	950	415	2530	9919	21334	33859	46016	51949	53258	43365	26572

1*	2*	Sampling dates									
Factor A	**Factor B**	**15.05**	**25.05**	**04.06**	**14.06**	**24.06**	**04.07**	**14.07**	**24.07**	**03.08**	**13.08**
70-75	550	255	1582	6207	13247	20972	28478	32126	32939	26859	16579
	750	341	2054	8130	17333	27437	37239	42127	43259	35526	22157
	950	393	2570	10099	21426	33858	45954	51724	52998	43138	26679
80-85	550	242	1581	6216	13209	20888	28352	31916	32698	26618	16435
	750	336	2070	8097	17382	27563	37453	42269	43329	35267	21632
	950	477	2815	11147	23916	37944	51540	58318	59867	49066	30370

1 – Antecedent soil water,% of minimum moisture-holding capacity (MMHC)
2 – Plant density, thousand plants·ha^{-1}.

Source: results of own scientific research.

1) Effect of Pre-Irrigation Soil Moisture on Leaf Area. At 60-65% MMHC: The lowest leaf area values among all irrigation regimes were observed, with a maximum of 53,258 m·ha^{-2} at a plant density of 950,000 plants·ha^{-1} (August 13). The smaller leaf area under lower moisture levels indicates limited water availability, which slows down the plant's photosynthetic activity. At 70-75% MMHC: An increase in leaf area was recorded compared to the 60-65% regime, with the highest value reaching 52,998 m·ha^{-2} at a density of 950,000 plants·ha^{-1} (August 13). At 80-85% MMHC: The maximum leaf area was 59,867 m·ha^{-2} at a density of 950,000 plants·ha^{-1} **(**August 13). Higher moisture levels promoted better leaf mass development, leading to more efficient absorption of solar energy and nutrients. The optimal soil moisture level

for leaf area development is 80-85% MMHC**,** ensuring maximum photosynthetic productivity.

2) Effect of Plant Density on Leaf Area. At all moisture levels, the largest leaf area was formed by plants at a density of 950,000 plants·ha^{-1}. At lower densities (550,000-750,000 plants·ha^{-1}), leaf mass developed more slowly, as fewer plants resulted in a smaller overall leaf area. The highest recorded value (59,867 m·ha^{-2}) was achieved with a combination of 80-85% MMHC and a 950,000 plants·ha^{-1} density. The higher the plant density, the greater the leaf area formation, which contributes to increased productivity.

3) Dynamics of Leaf Area Changes During the Growing Season. The most intensive increase in leaf area was observed from May 15 to July 14, with an average daily growth rate of ≈ 696 m·ha^{-2}. From July 14 to August 3, the growth rate slowed down by approximately 2.3 times, reaching ≈ 300 m·ha^{-2} per day. After August 3, leaf area began to decrease due to leaf senescence, with an average reduction of ≈ 1,000 m·ha^{-2} per day. The main accumulation of leaf mass occurs until mid-July, after which a decline in growth rates is observed, followed by leaf senescence in the second half of August.

The optimal conditions for leaf area growth are 80-85% MMHC soil moisture and a plant density of 950,000 plants·ha^{-1}. The most intensive leaf area expansion is observed from May to mid-July. After the second half of July, the growth rate slows down, and from the second decade of August, leaf senescence begins. Low moisture levels (60-65% MMHC) restrict leaf area growth, which may lead to reduced yield. Recommendation: To achieve maximum development of bulb onions, it is necessary to maintain 80-85% MMHC soil moisture and a plant density of 950,000 plants·ha^{-1}. The effect of increasing plant density is as follows: Increasing density from 550,000 to 750,000 plants·ha^{-1} significantly enhances leaf area, allowing plants to utilize soil space more efficiently. This boosts photosynthetic activity and improves light interception, leading to higher crop productivity. The leaf area increase remains stable and positive during this period. Optimized space utilization promotes better leaf mass development and higher yield. Increasing plant density from 750,000 to 950,000 plants·ha^{-1} leads to: Further expansion of leaf area, although its growth dynamics change. Excessive plant density (950,000 plants·ha^{-1}) results in: Increased competition for light, water, and nutrients, Shading of lower leaf layers, potentially reducing photosynthetic efficiency, Higher risk of lodging, especially under excess moisture conditions, A potential decline in crop quality if density becomes too high. Increasing plant density to 950,000 plants·ha^{-1} promotes maximum possible leaf area development but may also cause negative effects due to overcrowding. Maintaining an optimal balance between plant density and moisture levels is crucial to achieving high yields without compromising quality. Experimental data indicate that net photosynthetic productivity (NPP) varies throughout the growing season and depends on the factors studied, as presented in Table 4.

The data from Table 4 demonstrate how the net photosynthetic productivity (NPP) of bulb onions varies under different preirrigation soil moisture levels (60-65%, 70-75%, 80-85% MMHC) and plant densities (550, 750, 950 thousand plants·ha^{-1}) during different vegetation periods. The main trends are as follows:

1) High values at the beginning of the growing season (May 15-May 25). In all experimental variants, the highest NPP is observed on the first sampling date (May 15). For example, at a soil moisture level of 60-65% MMHC and a plant density of 950 thousand plants·ha^{-1}, the NPP value reaches 20.84 g·m·day^{-2}, which is the maximum among all variants. A subsequent decrease in NPP is observed by May 25 in all conditions, but the values remain relatively high.

2) Gradual decline in NPP from June to July. During the period from June 4 to July 4, NPP decreases, which may be associated with the biological characteristics of plant development, changing weather conditions, or accumulated stress due to plant density. The lowest values during this period are recorded at a soil moisture level of 80-85% MMHC and a plant density of 550 thousand plants·ha^{-1}.

3) Critical decrease in NPP at the end of the growing season (July 24 – August 3). After July 14, NPP values in most variants approach zero, and by August 3, they even become egative. This indicates the completion of the active growth phase and the aging of plants. For example, at a soil moisture level of 60-65% MMHC and a plant density of 950 thousand plants·ha^{-1}, the NPP value on August 3 is -3.21 g·m·day^{-2}, which is the lowest recorded value.

Table 4. Dynamics of net photosynthetic productivity of bulb onion depending on drip irrigation regime and plant density, 2024, g·m^{-2} per day

1* Factor A	2* Factor B	Sampling dates 15.05	25.05	04.06	14.06	24.06	04.07	14.07	24.07	03.08
60-65	550	14.13	8.43	5.29	5.85	6.93	7.92	3.81	0.18	-2.32
	750	16.56	9.87	6.17	6.85	8.14	9.25	4.45	0.21	-2.72
	950	20.84	11.67	7.30	8.14	9.55	11.01	5.22	0.28	-3.21
70-75	550	12.63	7.54	4.71	5.21	6.21	7.06	3.38	0.14	-2.07
	750	16.33	9.74	6.11	6.74	8.01	9.13	4.37	0.21	-2.68
	950	18.94	10.61	6.63	7.40	8.71	10.01	4.74	0.25	-2.91
80-85	550	11.97	7.15	4.47	4.94	5.88	6.70	3.21	0.14	-1.96
	750	16.11	9.61	6.00	6.64	7.90	9.00	4.31	0.21	-2.64
	950	18.91	10.60	6.63	7.41	8.68	10.00	4.74	0.25	-2.91

1 – Antecedent soil water,% of minimum moisture-holding capacity (MMHC)
2 – Plant density, thousand plants·ha^{-1}.

Source: results of own scientific research.

The highest values of NPP were recorded at 60-65% MMHC in the early stages of development (especially at a density of 950 thousand plants·ha^{-1}). At 70-75% MMHC, NPP is slightly lower but more stable in the mid-development phase. Soil moisture of 80-85% MMHC does not contribute to an increase in NPP, especially at later stages. NPP increases with plant density from 550 to 950 thousand plants·ha^{-1} during the initial growth stages. At later phases, high density may lead to faster resource depletion and a decline in NPP. The optimal pre-irrigation soil moisture for maximum NPP is 60-65% MMHC in the early stages and 70-75% MMHC in the mid-development phase.

The optimal plant density is 750-950 thousand plants·ha^{-1}, as it provides high NPP values, although a decline is observed at the end of the growing season. By the end of the growing season (July-August), NPP becomes zero or negative, indicating the physiological aging of plants. During vegetation, the accumulation of biological and economically valuable yield occurs. These indicators depend on the plant's development phase and the studied factors (Table 5).

Table 5. Dynamics of the economic efficiency coefficient (EEC) of bulb onion depending on the drip irrigation regime and plant density, 2024

1*	2*	Sampling dates									
Factor A	Factor B	15.05	25.05	04.06	14.06	24.06	04.07	14.07	24.07	03.08	13.08
60-65	550	0.30	0.35	0.35	0.32	0.36	0.44	0.52	0.55	0.59	0.63
	750	0.36	0.42	0.42	0.37	0.42	0.52	0.61	0.63	0.68	0.73
	950	0.47	0.56	0.56	0.49	0.56	0.69	0.82	0.85	0.91	0.98
70-75	550	0.29	0.34	0.33	0.30	0.34	0.42	0.49	0.52	0.55	0.60
	750	0.38	0.45	0.45	0.40	0.45	0.54	0.66	0.69	0.73	0.79
	950	0.46	0.54	0.54	0.48	0.54	0.65	0.78	0.82	0.88	0.95

1*	2*	Sampling dates									
Factor A	Factor B	15.05	25.05	04.06	14.06	24.06	04.07	14.07	24.07	03.08	13.08
80-85	550	0.28	0.33	0.33	0.29	0.33	0.40	0.47	0.50	0.53	0.60
	750	0.38	0.45	0.45	0.40	0.45	0.54	0.66	0.68	0.73	0.80
	950	0.54	0.63	0.63	0.56	0.63	0.77	0.91	0.95	1.01	1.10

1 – Antecedent soil water,% of minimum moisture-holding capacity (MMHC)
2 – Plant density, thousand plants·ha^{-1}.

Source: results of own scientific research.

The economic efficiency coefficient (EEC) is an important indicator that reflects the ratio between the total and economically valuable yield of bulb onions. Main trends: Increase in EEC during the growing season – in all experimental variants, a gradual increase in the economic efficiency coefficient was observed from May 15 to August 13. Lowest values at the beginning of the growing season (0.28-0.54 in May), which can be explained by the early development stages when the formation of economically valuable yield is not yet intensive. Maximum EEC values were recorded at the end of the experiment (August 13), reaching 1.10 in the variant with a pre-irrigation soil moisture of 80-85% MMHC and a plant density of 950 thousand plants·ha^{-1}.

2) Effect of Soil Moisture: The lowest values of the Economic Efficiency Coefficient (EEC) are observed at a moisture level of 60-65% MMHC. At 70-75% MMHC, the EEC values are slightly higher, indicating the positive effect of increased moisture. The highest EEC values are achieved at 80-85% MMHC, which suggests favorable conditions for the formation of commercially valuable yields under high moisture conditions.

3) Effect of Plant Density: A density of 550,000 plants.ha-1 results in the lowest EEC values, especially during the early stages of development

(e.g., 15.05 – 0.28-0.30). A density of 750,000 plants.ha-1 provides average EEC values and is more stable over time. A density of 950,000 plants·ha^{-1} demonstrates the highest EEC values, especially during the later stages of development (13.08 – 0.98-1.10), indicating optimal land use and more effective accumulation of commercially valuable yields. The optimal pre-irrigation soil moisture is 80-85% MMHC, which provides the highest EEC values. The optimal plant density is 950,000 plants·ha^{-1}, as this variant achieved the maximum economic efficiency coefficient (1.10). The gradual increase in EEC during the growing season indicates effective accumulation of commercially valuable yields, especially in the later stages of development.

The Coefficient of Photosynthetically Active Radiation Use (CPARU) is one of the key indicators of the efficiency of photosynthesis in agricultural crops. Its analysis allows to: assess the productivity of crops (determining how effectively plants use solar energy to form a yield), optimize agronomic practices (helping to justify planting density, fertilizer rates, irrigation regimes, and other factors affecting photosynthesis), increase yield (determining CPARU allows to identify reserves for increasing plant productivity), and develop effective agribusiness strategies (enabling the implementation of more energy-efficient technologies and improving production process management).

Methods of determining the CPARU efficiency coefficient (PAR): the direct method (involves field measurements of the amount of absorbed photosynthetically active radiation using quantum sensors and determining biomass growth), the calculation method (uses radiation balance models that take into account crop parameters (leaf index, light reflectance coefficient, etc.)), and spectral analysis (remote methods, including the use of satellite or drone images to assess the efficiency of photosynthetically active radiation use). Optimization of CPARU involves: selecting crops with high photosynthetic productivity potential, using growth regulators, adjusting planting dates, and controlling plant density. Thus, monitoring CPARU helps improve production efficiency and implement innovative management methods for agricultural systems. We analyzed the photosynthetically active radiation utilization coefficient of onion crops in 2024 in Table 6.

Table 6. Photosynthetically active radiation utilization coefficient of onion crops, 2024.

1*	2*	Dry matter, t·ha^{-1}		Energy input with yield, GJ·ha^{-1}	Incoming PAR, GJ·ha^{-1}	CPARU,%
Faktor A	Factor B	leaves	onions.			
60-65	550	2.51	8.95	106.10	17393	0.61
	750	2.94	10.35	123.38	17393	0.71
	950	3.95	13.92	165.34	17393	0.95
70-75	550	2.41	8.43	101.45	17393	0.57
	750	3.05	11.00	131.44	17393	0.75
	950	3.86	13.36	159.83	17393	0.91
80-85	550	2.34	8.12	96.81	17393	0.55
	750	3.07	10.91	130.05	17393	0.75
	950	4.15	15.05	180.13	17393	1.03

1 – Antecedent soil water,% of minimum moisture-holding capacity (MMHC)
2 – Plant density, thousand plants·ha^{-1}.

Source: results of own scientific research.

At all levels of soil moisture, increasing plant density from 550 to 950 thousand plants per hectare leads to an increase in the radiation use efficiency (CPARU). At the minimum density (550 thousand plants·ha^{-1}), the CPARU value ranges from 0.55 to 0.61, while at the maximum density (950 thousand plants·ha^{-1}) it ranges from 0.91 to 1.03. This is explained by the fact that a higher number of plants per unit area contributes to a more complete absorption of photosynthetically active radiation. At 60-65% MMHC, the RUE ranges from 0.61 to 0.95. At 70-75% MMHC, the CPARU is slightly lower, ranging from 0.57 to 0.91, which may be due to excessive moisture that impairs soil aeration and the photosynthetic activity of plants. The maximum CPARU value (1.03) is observed at 80-85% field capacity and a density of 950 thousand plants·ha^{-1}, indicating an optimal combination of moisture and density. The highest productivity (dry matter 4.15 t·ha^{-1}) and the greatest energy input from the harvest (15.05 GJ·ha^{-1}) are also observed at 80-85% MMHC and a density of 950 thousand plants·ha^{-1}. This confirms that under optimal water conditions and planting density, plants use solar energy more effectively.

The optimal conditions for maximum Radiation Use Efficiency (CPARU) are soil moisture of 80-85% MMHC and a density of 950 thousand plants per hectare. Low plant density (550 thousand plants·ha^{-1}) significantly reduces the efficiency of photosynthetically active radiation (PAR) use.

Exceeding the optimal moisture level (over 75%) can negatively affect photosynthesis if the planting density is insufficient. Therefore, to improve the efficiency of photosynthetically active radiation use in onion crops, it is necessary to optimize planting density and maintain an appropriate level of soil moisture. The yield of bulb onions has a strong correlation with the use of photosynthetically active radiation (r=0,97). This relationship has a logarithmic nature and can be described by the following equation:

$$Y = 50{,}721 \cdot \ln(x) + 71{,}709 \text{, t·ha}^{-1}\text{:} \quad (1)$$

$$R^2=0{,}93 \; r=0{,}96$$

where, Y – Onion yield, t·ha^{-1};
x – coefficient of utilization of photosynthetically active radiation,%;

We have grouped proposals for improving the coefficient of utilization of photosynthetically active radiation (PAR) in onion crops:

1. Optimization of planting density – increasing plant density to 950 thousand plants·ha^{-1} will promote more complete absorption of solar radiation, regulating seed uniformity to reduce competition between plants.
2. Rational irrigation: maintaining pre-irrigation soil moisture at 80-85% MMHC, which ensures maximum utilization of PAR, and using drip irrigation for optimal water distribution.
3. Improvement of the plant's photosynthetic apparatus: application of nitrogen fertilizers during the active growth phase to stimulate leaf development, and the use of micronutrients (Mg, Fe, Mn) that promote intense photosynthesis.
4. Selection of high-yielding varieties: growing varieties and hybrids with high assimilation leaf surface area, and using stress-resistant varieties that effectively utilize solar energy.

5. Optimization of agronomic practices: black fallow or mulching to reduce moisture loss and enhance photosynthetic efficiency, and timely removal of weeds that can shade the main crops.
6. Use of bio stimulants and growth regulators: treating seeds and plants with bioproducts that stimulate root system and photosynthetic apparatus development, and using anti-stress agents during unfavorable weather conditions.

The implementation of these measures will increase the efficiency of PAR utilization and, accordingly, the productivity of onion crops.

4.3. Yield and quality of onions

To achieve high vegetable yields, it is necessary to take environmental conditions into account, as without this, it is impossible to properly plan agronomic practices. Although all factors affecting plant growth are indispensable and interconnected, it is usually possible to identify the one that is limiting at a particular stage of development. In natural conditions, the level of influence of these factors constantly changes, and the change of one parameter usually leads to the adjustment of others. For example, an increase in temperature can lead to a decrease in air and soil moisture, which in turn affects the composition of soil air and the concentration of nutrients in the soil solution.

The reaction of plants to external factors is determined not only by their heredity but also by their age-related characteristics. Moreover, different crops and even varieties may respond differently to the same factor. Yield, photosynthetic productivity, as well as the distribution and accumulation of its products, depend both on the genetic traits of the crop and on the ability of humans to adapt the growing conditions to the plants' needs through agronomic technologies. In the case of water shortage, the size of root crops and other vegetables decreases, and their structure becomes coarser. Additionally, soil, air, or irrigation water pollution with toxic substances, radionuclides, or pesticides can render vegetable products unsuitable for consumption, and growing crops in such areas may become impossible. The research by Kiura et al. (2021) suggests that onions should be harvested when 75% of the foliage has lodged and dried for at least one week before removing the foliage to improve the visual and storage quality of the harvested onions[19]. The Kherson region is located in an area with insufficient moisture, where the distribution of rainfall throughout the year is uneven. Most of the precipitation occurs during the cold period, while in the summer season, when onions actively grow, rainfall is rare and mostly of a torrential nature. As a result, artificial irrigation is necessary to ensure a stable harvest. To determine the optimal drip irrigation regime, a study was conducted that considered soil moisture levels of 65%, 75%, and 85% of the minimum moisture capacity (MWC). Table 7 provides information on the yield and marketability of onion crops depending on pre-irrigation soil moisture and plant density, 2024.

Table 7. Yield and marketability of onions depending on pre-irrigation soil moisture and plant density, 2024

1*	2*	Yield, t·ha^{-1}		Marke-tability, %	Average bulb diameter, mm.
Factor A	Factor B	total,	marketable		
60-65	550	43.50	29.67	68.20	58.6
	750	54.81	36.26	66.15	55.1
	950	64.96	42.73	65.77	52.4
70-75	550	44.83	33.39	74.48	59.3
	750	58.25	43.26	74.27	55.8
	950	69.71	52.59	75.44	54.6
80-85	550	45.55	35.14	77.14	59.5
	750	60.81	45.67	75.10	58.3
	950	75.27	57.73	76.70	57.6
LSD $_{05}$ by factor A		2.20	2.05	1.65	1.66
LSD $_{05}$ by factor B		1.58	1.03	0.88	0.89

1 – Antecedent soil water,% of minimum moisture-holding capacity (MMHC)
2 – Plant density, thousand plants·ha^{-1}.

Source: results of own scientific research.

[19] Kiura, I. N., Gichimu, B. M., & Rotich, F. (2021). Visual and keeping quality of stored bulb onions as affected by harvest and postharvest treatments. *Advances in Agriculture.* https://doi.org/10.1155/2021/9969571

The pre-irrigation soil moisture significantly influenced the yield and marketability of onions. There was a tendency for both total and marketable yields to increase with higher moisture levels: 60-65% MMHC: total yield 43.50-64.96 $t \cdot ha^{-1}$, marketable yield – 29.67-42.73 $t \cdot ha^{-1}$; 70-75% MMHC: total yield 44.83-69.71 $t \cdot ha^{-1}$, marketable yield – 33.39-52.59 $t \cdot ha^{-1}$; 80-85% MMHC: total yield 45.55-75.27 $t \cdot ha^{-1}$, marketable yield – 35.14-57.73 $t \cdot ha^{-1}$. Thus, increasing moisture promotes higher yields and better marketability of the product.

An increase in onion planting density (550 → 750 → 950 thousand plants $\cdot ha^{-1}$) results in higher yields, but marketability and the average diameter of the bulbs slightly decrease: 550 thousand plants $\cdot ha^{-1}$: yield 43.50-45.55 $t \cdot ha^{-1}$ at 60-65% WHC, marketability 68.20-77.14%; 750 thousand plants $\cdot ha^{-1}$: yield 54.81-60.81 $t \cdot ha^{-1}$, marketability 66.15-75.10%; 950 thousand plants $\cdot ha^{-1}$: yield 64.96-75.27 $t \cdot ha^{-1}$, marketability 65.77-76.70%. When the density increases to 950 thousand plants $\cdot ha^{-1}$, the highest yield (75.27 $t \cdot ha^{-1}$) is observed, but marketability is slightly lower (76.70%) compared to lower densities. The optimal pre-irrigation moisture content is 80-85% MMHC, which ensures the highest yield and marketability. The optimal density is 750-950 thousand plants $\cdot ha^{-1}$: 950 thousand plants $\cdot ha^{-1}$ provides the maximum yield, but 750 thousand plants $\cdot ha^{-1}$ ensures higher marketability. The recommended combination is 80-85% MMHC with a density of 750 thousand plants $\cdot ha^{-1}$, which gives high yield (60.81 $t \cdot ha^{-1}$) and marketability (75.10%) without significant reduction in bulb size. These data can be useful for optimizing onion growing technology to increase economic efficiency.

Based on the analysis of the data in the table, the following measures can be suggested to improve the yield and marketability of bulb onions: the highest yield and marketability were observed at a moisture level of 80-85% MMHC. It is recommended to maintain soil moisture at 80-85% MMHC throughout all stages of vegetation, especially during the active growth and bulb formation period. The use of drip irrigation will allow for more efficient water use and ensure uniform moisture distribution. A density of 950 thousand plants $\cdot ha^{-1}$ provides the maximum yield (75.27 $t \cdot ha^{-1}$), but marketability slightly decreases. To maintain an optimal balance between bulb size and total yield, it is recommended to use a density of 750-900 thousand plants $\cdot ha^{-1}$ for better quality produce. On light soils, the density can be increased to 950 thousand plants $\cdot ha^{-1}$ to achieve maximum yield.

To improve marketability and the average diameter of the bulbs, the following measures should be taken: use sorting by size before planting seeds, provide balanced nutrition (especially potassium fertilizers for forming large bulbs), and maintain optimal lighting conditions – in dense plantings, it is important to control the level of sunlight. The best effect on yield and marketability is achieved with balanced nutrition: nitrogen (N) – for green mass growth (not excessively, to avoid reducing bulb storage), phosphorus (P) – for root system development, potassium (K) – to enhance marketability and storage of bulbs, micronutrients (B, Zn, Mn) – to improve product quality. Optimal harvesting and storage technology: use mechanized harvesting when the tops begin to dry (to reduce bulb damage), ensure proper drying after harvesting to preserve marketable qualities, and store at a temperature of 0-3°C and relative humidity of 65-75%. Suggestions for improving research and further experiments may include: conducting trials with different onion varieties to determine the most productive ones under specific conditions, evaluating the economic efficiency of different density and irrigation levels, studying the impact of biopreparations and organic fertilizers on product marketability, and expanding research to various soil types to adapt the technology to different agro-climatic conditions. Based on the analysis of experimental data, a multiple regression equation was obtained that reflects the impact of the studied factors on the yield of bulb onions:

$$У = 0,408 \cdot x_1 + 0,048 \cdot x_2 - 11,034 \quad (2)$$

$$R^2=0,94 \; r=0,96$$

where, $У$ – yield of bulb onions, t·ha^{-1};
x_1 – pre-irrigation soil moisture.,% MMHC;
x_2 – onion plant density, thousand plants·ha^{-1};

Based on the results of the comparative analysis of actual and theoretical yields, it can be concluded that the multiple regression equation obtained from the experimental data has high adaptability and reflects the impact of the studied factors on the productivity of bulb onions. Table 8 presents information regarding the results of the calculations of the theoretical yield of bulb onions depending on the studied factors.

Table 8. Results of calculations of the theoretical yield of bulb onions depending on the studied factors.

Variant number	Antecedent soil water,% of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Yield, t·ha^{-1}		V %
	x_1	x_2	theoretical	actual	
1	65	550	41.89	43.50	3.6
2	65	750	51.49	54.81	1.2
3	65	950	61.09	64.96	1.7
4	75	550	45.94	44.83	0.1
5	75	750	55.57	58.25	1.0
6	75	950	65.17	69.71	0.2
7	85	550	50.05	45.55	4.2
8	85	750	59.65	60.81	1.1
9	85	950	69.25	75.27	2.0

Source: results of own scientific research.

The analysis of the data shows that the actual yield in most variants exceeds the theoretically calculated yield. The relative deviation (V,%) ranges from 0.1% to 4.2%, indicating sufficient prediction accuracy. The smallest discrepancy between the theoretical and actual results is observed at 70-75% MMHC and a density of 550 thousand plants·ha^{-1} (0.1%). The largest deviation (4.2%) is observed at 80-85% MMHC and a density of 550 thousand plants·ha^{-1}, which may indicate the influence of additional factors (agricultural techniques, seed quality, etc.). The impact of pre-irrigation moisture: at 65% MMHC: the calculated yield is lower than the actual yield by 1.2-3.6%, which confirms the positive effect of higher moisture; at 75% MMHC: there is almost perfect alignment with the theoretical yield (deviation 0.1-1.0%); at 85% MMHC: the deviation is more significant (1.1-4.2%), which may indicate the impact of high moisture on the quality of bulb maturation. Increasing planting density from 550 to 950 thousand plants·ha^{-1} contributes to higher yield, with the relative deviation of actual values from theoretical ones not exceeding 4.2%, confirming the adequacy of the calculated model. The most accurate yield prediction was obtained at 70-75%

MMHC – this moisture level is optimal. At 80-85% MMHC, there may be an oversaturation of the soil with moisture, which can affect the actual yield. The optimal plant density for balanced yield and marketability is 750-950 thousand plants·ha^{-1}.

Suggestions for improving the accuracy of forecasting and yield: expand the forecasting model – consider additional factors (weather conditions, seed quality, agronomic practices); optimize the irrigation regime – maintain 70-75% MMHC for maximum efficiency; control planting density – for a balanced yield, use 750-900 thousand plants·ha^{-1}; improve the nutrition system – soil analysis will help adjust fertilizer application and improve the alignment of actual indicators with forecasted ones. Implementing these measures will not only improve forecasting accuracy but also optimize onion cultivation for stable yields. Table 9 presents the results of calculations for the theoretical average bulb diameter depending on the studied factors.

Table 9. Results of calculations for the theoretical average bulb diameter depending on the studied factors

Variant number	Antecedent soil water,% of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Average diameter, mm		V %
	x_1	x_2	theoretical	actual	
1	65	550	56.3	58.6	1.4
2	65	750	53.4	55.1	0.3
3	65	950	50.6	52.4	0.3
4	75	550	58.4	59.3	0.3
5	75	750	55.6	55.8	0.3
6	75	950	53.5	54.6	0.5
7	85	550	56.2	59.5	1.4
8	85	750	57.7	58.3	0.2
9	85	950	54.9	57.6	1.1

Source: results of own scientific research.

Analysis of the results of theoretical average bulb diameter calculations

1) Comparison of theoretical and actual values: the analysis shows that the actual average bulb diameter in most cases exceeds the theoretically calculated one, with the relative deviation (V,%) being insignificant and ranging from 0.2% to 1.4%, indicating a high accuracy of prediction. The smallest deviation (0.2%-0.3%) is observed at a planting density of 750,000-950,000 plants·ha^{-1}, regardless of soil moisture. The largest deviation (1.4%) is recorded at 550,000 plants·ha^{-1} and soil moisture levels of 65% and 85% of field capacity MMHC), which may be due to the influence of microclimatic conditions or cultivation technology.
2) Impact of pre-irrigation moisture: At 65% MMHC: The average bulb diameter decreases with increasing planting density (from 58.6 mm at 550,000 plants·ha^{-1} to 52.4 mm at 950,000 plants·ha^{-1}). At 75% MMHC: The largest average diameter (59.3 mm) is obtained at a density of 550,000 plants·ha^{-1}, indicating an optimal balance of the water regime. At 85% MMHC: The actual values exceed the theoretical ones (e.g., at 550,000 plants·ha^{-1}– 59.5 mm compared to the theoretical 56.2 mm), which may be associated with more favorable conditions for bulb formation.
3) Impact of plant density. As plant density increases from 550,000 to 950,000 plants·ha^{-1}, the average bulb diameter decreases due to competition for resources. The minimal deviation between theoretical and actual values at 750,000–950,000 plants·ha^{-1} indicates the stability of the calculation model for these density levels. At 550,000 plants·ha^{-1}, actual values significantly exceed theoretical ones, which may be attributed to specific varietal characteristics or more efficient nutrient uptake and irrigation.

The best correlation between predicted and actual data was obtained at a density of 750,000–950,000 plants·ha^{-1} and 75% MMHC. The maximum average bulb diameter (59.5 mm) was observed at 550,000 plants·ha^{-1} and 85% MMHC; however, under these conditions, the overall yield is lower. The minimal deviation confirms that the prediction model is quite accurate, though at 550,000 plants·ha^{-1}, actual values often exceed the calculated ones.

Recommendations for improvement, optimization of planting density: A density of 750,000–950,000 plants·ha^{-1} ensures stable bulb diameter with minimal deviations, optimization of irrigation regime: Maintaining soil moisture at 70-75% MMHC provides the most accurate results and promotes balanced growth. Fertilizer impact research: Analyzing the application of potassium and phosphorus fertilizers may help optimize bulb diameter. Refinement of the calculation model: Incorporating factors such as temperature, light intensity, and soil agrochemical conditions could improve forecasting accuracy. Implementing these recommendations will not only enhance crop quality but also allow for more precise predictions of bulb size, optimizing the production process.

The water consumption coefficient is an important indicator of the effectiveness of agrotechnical measures, as it reflects the amount of water required to produce a unit of yield. It is largely determined by the meteorological conditions of the growing season, the irrigation scheme, and plant density. The water consumption coefficient of onion has a strong correlation (r = 0.97) with plant density and can be described by the following equation:

$$У = 0,0001 \cdot x^2 - 0,2189 \cdot x + 166,92 \quad (3)$$

$$R^2=0,94 \; r=0,97$$

where, $У$ – Water consumption coefficient of onion, m^3/t.;
x – Plant density, thousand plants·ha^{-1}.

The analysis of this indicator makes it possible to determine the optimal combination of factors that ensure minimal water consumption while maximizing productivity. Research has confirmed that the water consumption coefficient depends on the technological elements of onion cultivation and weather conditions during the growing season (Table 10). At 65% MMHC, the water consumption coefficient ranges from 81.5 m·t^{-3} (550,000 plants·ha^{-1}) to 60.5 m·t^{-3} (950,000 plants·ha^{-1}). At 75% MMHC, water consumption decreases to 80.5-52.7 m^3/t, indicating more efficient water use under this moisture level. At 85% MMHC, the coefficient slightly increases compared to 75% MMHC (81.9-52.2 m·t^{-3}), which may be due to excessive soil moisture saturation and less efficient water utilization.

Table 10. Water consumption coefficient of onion depending on the studied factors

Antecedent soil water,% of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Water consumption coefficient, m·t^{-3}, average.
65% MMHC	550	81.5
	750	68.2
	950	60.5
75% MMHC	550	80.5
	750	61.8
	950	52.7
85% MMHC	550	81.9
	750	62.7
	950	52.2

Source: results of own scientific research.

Increasing plant density from 550,000 to 950,000 plants·ha^{-1} significantly reduces the water consumption coefficient. The highest coefficient at 550,000 plants·ha^{-1} (81.5-81.9 m·t^{-3}) indicates inefficient water use due to an insufficient number of plants per unit area. The lowest coefficient at 950,000 plants·ha^{-1} (60.5-52.2 m·t^{-3}) suggests more efficient water utilization at higher planting densities. The optimal pre-irrigation moisture level is 75% MMHC, as it results in the lowest water consumption coefficient (80.5-52.7 m·t^{-3}). The optimal plant density is 950,000 plants·ha^{-1}, since under these conditions, plants utilize water most efficiently (showing the lowest water consumption values across all moisture levels). Excessively low or high soil moisture levels (65% or 85% MMHC) reduce water use efficiency, confirming the importance of maintaining a balanced moisture level.

Recommendations for Improving the Water Consumption Coefficient: optimize the irrigation system: Maintain soil moisture at 75% MMHC to achieve minimal water consumption, increase planting density: Use 950,000 plants·ha^{-1} for more efficient water utilization. Implement drip irrigation: this will enable precise water delivery to the root zone, reducing unproductive water losses. Optimize fertilizer application: A balanced supply of macro– and micronutrients will improve water absorption and enhance its efficient use. Improve soil structure: Applying mulching or organic amendments will help retain moisture and reduce evaporation. Implementing these measures will reduce the water consumption coefficient and increase the economic efficiency of onion cultivation. Table 11 presents the calculation results of the theoretical water consumption coefficient of onion in 2024. In most cases, the actual values of the water consumption coefficient slightly exceed the theoretically calculated ones, with deviations (V,%) ranging from 0.9% to 7.1%. The smallest deviation (0.9%-1.2%) is observed at 550,000 plants·ha^{-1}, regardless of the pre-irrigation moisture level. The largest deviation (7.1%) is recorded at 750,000 plants·ha^{-1} and 70-75% MMHC, which may be due to the influence of additional factors such as climatic conditions or soil characteristics. For a density of 950,000 plants·ha^{-1}, deviations within 2.5-5.3% indicate a relatively stable level of water consumption.

Table 11. Calculation results of the theoretical water consumption coefficient of onion

Variant number	Antecedent soil water,% of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Water consumption coefficient, m·t^{-3}		V %
	x_1	x_2	Theoretical	Actual	
1	60-65	550	80.5	81.5	0.9
2	60-65	750	66.3	68.2	1.1
3	60-65	950	57.1	60.5	5.3
4	70-75	550	79.5	80.5	0.9
5	70-75	750	58.3	61.8	7.1
6	70-75	950	53.1	52.7	3.1
7	80-85	550	80.5	81.9	1.2
8	80-85	750	60.3	62.7	5.0
9	80-85	950	53.1	52.2	2.5

Source: results of own scientific research.

Effect of Pre-Irrigation Soil Moisture: At 60-65% MMHC: the theoretical coefficient decreases from 80.5 m·t^{-3} (550,000 plants·ha^{-1}) to 57.1 m³/t

(950,000 plants·ha^{-1}), with actual values being slightly higher. At 70-75% MMHC: A similar trend is observed, with the lowest coefficient recorded at 950,000 plants·ha^{-1} (53.1 m·t^{-3} theoretical, 52.7 m·t^{-3} actual). At 80-85% MMHC: The largest discrepancies between actual and theoretical values occur at 750,000 plants·ha^{-1} (60.3 m·t^{-3} theoretical, 62.7 m·t^{-3} actual, deviation 5.0%). An increase in plant density from 550,000 to 950,000 plants·ha^{-1} leads to a reduction in the water consumption coefficient, indicating more efficient water use at higher planting densities. The lowest coefficient (52.2-52.7 m·t^{-3}) was recorded at 950,000 plants·ha^{-1} and 70-85% MMHC, demonstrating the optimal balance of moisture and density for efficient water utilization. The optimal pre-irrigation moisture level is 70-75% MMHC, as it results in the lowest water consumption coefficient (53.1-80.5 m·t^{-3}). The optimal plant density is 950,000 plants·ha^{-1}, as it ensures the lowest water consumption across all moisture levels. The prediction model is fairly accurate, but the largest deviation is observed at 750,000 plants·ha^{-1} and 70-85% MMHC, suggesting the potential influence of additional factors. Recommendations for Improving the Water Consumption Coefficient: optimize the irrigation regime: Maintain soil moisture at 70-75% MMHC, as this level ensures the best balance between water consumption and yield. Optimize planting density: Use a density of 950,000 plants·ha^{-1} to enhance the efficiency of water resource utilization. Implement drip irrigation to minimize unproductive water losses and improve plant water absorption. Investigate additional factors that may have influenced the discrepancies between theoretical and actual values (e.g., soil structure, evaporation rate, air temperature). Introduce a soil moisture monitoring system to ensure uniform irrigation and prevent excessive water losses. Implementing these measures will help reduce water consumption, improve water use efficiency, and enhance the profitability of onion cultivation.

4.4. Economic efficiency of cultivation technology elements

Irrigation is one of the key factors in increasing the economic efficiency of agricultural production, as it enables the intensive use of soils with high fertility potential. Without additional moisture, such soils are either left unused or utilized in extensive farming. As a rent-generating factor, irrigation plays a crucial role in stabilizing and increasing yields, reducing dependence on weather conditions. Alongside land, water is one of the primary resources in irrigated agriculture. Creating optimal conditions for securing high yields contributes to improved economic performance in agricultural production. The analysis of the economic efficiency of onion cultivation was based on actual production costs over an average four-year period. The cost price included expenses for land lease, insurance contributions, fuel and lubricants, seed material, fertilizers, plant protection products, equipment depreciation and maintenance, irrigation costs (water costs, electricity, drip irrigation systems), labor wages, and organizational and management expenses. The assessment of economic efficiency was conducted based on the following criteria: labor costs (man-hours) per hectare and per ton of production, total production costs (UAH) per hectare and per ton, profitability, and the level of cost-effectiveness (Table 12). The calculations were based on current rates for manual and mechanized operations, wages of machine operators, market prices for seeds, fuel, mineral fertilizers, plant protection products, irrigation water, etc. The output rates for manual and mechanized operations were determined according to generally accepted methodologies.

Table 12. Economic efficiency of onion cultivation depending on irrigation regime and plant density, 2024

Antecedent soil water, % of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Yield, t·ha^{-1}	Labor costs, person-hours		Cost price, UAH		Gross product value, UAH	Conditionally net profit, UAH·ha^{-1}	Profitability, %
			1 ha	1 t	1 ha	1 t			
60-65% MMHC	550	43.50	578.0	13.3	269421	6194	435000	165579	61
	750	54.81	709.6	12.9	286452	5226	548100	261648	91
	950	64.96	816.9	12.7	302086	4650	649600	347514	115

Antecedent soil water, % of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Yield, t·ha^{-1}	Labor costs, person-hours		Cost price, UAH		Gross product value, UAH	Conditionally net profit, UAH·ha^{-1}	Profitability, %
			1 ha	1 t	1 ha	1 t			
70-75% MMHC	550	44.83	593.2	13.2	270503	6034	448300	177797	66
	750	58.25	742.5	12.7	288519	4953	582500	293981	102
	950	69.71	870.7	12.5	305325	4380	697100	391775	128
80-85% MMHC	550	45.55	600.8	13.2	271443	5959	455500	184057	67
	750	60.81	782.3	12.7	291264	4790	608100	316836	108
	950	75.27	935.0	12.4	309453	4111	752700	443247	143

Source: results of own scientific research.

The impact of pre-irrigation soil moisture on economic indicators: At 60-65% MMHC (yield: 43.50-64.96 t·ha^{-1}, profitability: 61-115%, net profit: 165,579-347,514 UAH·ha^{-1}). The highest efficiency was observed at 950 thousand plants·ha^{-1} (64.96 t·ha^{-1}, 115% profitability). At 70-75% MMHC (yield: 44.83-69.71 t·ha^{-1}, profitability: 66-128%, net profit: 177,797-391,775 UAH·ha^{-1}), the best indicators were also recorded at 950 thousand plants·ha^{-1} (69.71 t·ha^{-1}, 128% profitability). At 80-85% MMHC (yield: 45.55-75.27 t·ha^{-1}, profitability: 67-143%, net profit: 184,057-443,247 UAH·ha^{-1}), the optimal option was 950 thousand plants·ha^{-1} (75.27 t·ha^{-1}, 143% profitability).

An increase in planting density from 550 to 950 thousand plants·ha^{-1} contributes to higher yield, net profit, and profitability. The lowest labor costs per ton of production were recorded at 950 thousand plants·ha^{-1} (12.4 person-hours). The lowest production cost per ton (4111 UAH) was also observed at 950 thousand plants·ha^{-1} and 80-85% MMHC. The most effective pre-irrigation moisture level is 80-85% MMHC, as it ensures the highest yield (75.27 t·ha^{-1}), maximum net profit (443,247 UAH·ha^{-1}), and profitability (143%). The optimal planting density is 950 thousand plants·ha^{-1}, which allows reducing labor costs and production costs while achieving maximum economic benefits. The lowest efficiency was observed at 550 thousand plants·ha^{-1} and 60-65% MMHC, confirming the feasibility of higher moisture levels and increased planting density. Proposals for improving economic indicators: apply the optimal irrigation regime (80-85% MMHC) to ensure maximum productivity, use a plant density of 950 thousand plants·ha^{-1}, which helps reduce production costs and increase profitability, implement precise water resource management using soil moisture sensors for efficient irrigation regulation, optimize fertilizer use by applying balanced nutrition to reduce the cost of producing 1 ton of product, automate cultivation processes to reduce labor costs and increase productivity. Implementing these measures will increase the profitability of onion cultivation, reduce costs, and enhance the efficiency of agricultural production.

The total labor costs per hectare gradually increase with higher plant density, which is explained by the need to manage a larger number of plants. However, labor costs per ton of production decrease with increasing planting density and irrigation levels, indicating improved production efficiency. At 60-65% MMHC (labor costs per hectare: 578.0-816.9 labor-hours, labor costs per ton: 13.3-12.7 labor-hours), an increase in plant density led to higher per-hectare costs but reduced costs per ton of production. At 70-75% MMHC (labor costs per hectare: 593.2-870.7 labor-hours, labor costs per ton: 13.2-12.5 labor-hours), a similar trend is observed-the higher the density, the lower the labor costs per unit of production. At 80-85% MMHC (labor costs per hectare: 600.8-935.0 labor-hours, labor costs per ton: 13.2-12.4 labor-hours), the maximum labor costs per hectare were recorded, but the lowest labor costs per ton of production were observed at 950 thousand plants·ha^{-1}. With an increase in plant density from 550 to 950 thousand plants·ha^{-1}, labor costs per hectare rose by 35-55%, while labor costs per ton of production decreased by 6-8%. The lowest labor costs per ton of production (12.4 labor-hours) were recorded at 950 thousand plants·ha^{-1} and 80-85% MMHC, indicating the most efficient combination of factors.

Increasing planting density from 550 to 950 thousand plants·ha^{-1} leads to higher labor costs per hectare but a significant reduction in labor costs per ton of production. The optimal pre-irrigation soil moisture level is 80-85% of field capacity, as it ensures the lowest labor costs per unit of production. Maximum production efficiency is achieved at 950 thousand plants·ha^{-1} and 80-85% field capacity, confirming the feasibility of intensive farming practices. Proposals for optimizing labor costs: mechanization of technological processes, especially at a density of 950 thousand plants·ha^{-1}, to reduce the labor burden; optimization of the irrigation regime to reduce the need for manual moisture control and plant care; use of automated irrigation management systems to reduce manual labor; introduction of high-performance equipment for planting and harvesting, which will reduce labor costs. Implementing these measures will reduce labor costs, increase production efficiency, and enhance the economic profitability of growing onion crops.

The cost of production depends on the production expenses, irrigation regime, and yield level. Overall, there is a trend of decreasing cost per ton of production as planting density and pre-irrigation moisture level increase. At 60-65% field capacity (cost per hectare: 269,421 – 302,086 UAH, cost per ton: 6,194-4,650 UAH), as plant density increases, the cost per ton decreases by 25%, indicating more efficient resource use. At 70-75% field capacity (cost per hectare: 270,503 – 305,325 UAH, cost per ton: 6,034-4,380 UAH), the lowest cost per ton occurs at 950 thousand plants·ha^{-1} (4,380 UAH), confirming the effectiveness of increasing planting density. At 80-85% field capacity (cost per hectare: 271,443-309,453 UAH, cost per ton: 5,959-4,111 UAH), the lowest cost per ton of onion is 4,111 UAH at 950 thousand plants·ha^{-1}, which is the most efficient option.

Increasing the planting density from 550 to 950 thousand plants·ha^{-1} leads to a 12-14% increase in total costs per hectare but reduces the cost per ton of production by 27-33%. The maximum reduction in cost per ton is observed at 80-85% field capacity and a planting density of 950 thousand plants·ha^{-1}, indicating the most rational use of water resources and area.

The lowest cost per ton of production (4,111 UAH) is observed at 80-85% MMHC and a planting density of 950 thousand plants·ha^{-1}. Increasing the planting density leads to an increase in total costs per hectare but a significant reduction in the cost per ton of production, making production more profitable. The irrigation regime of 80-85% field capacity is optimal, as it ensures the lowest cost with the maximum yield.

Proposals for reducing production costs: optimize planting density (950 thousand plants·ha^{-1}) to achieve the lowest cost per ton; maintain pre-irrigation soil moisture at 80-85% field capacity to reduce costs per unit of production; use precise fertilization and irrigation techniques to reduce water and fertilizer costs; automate production processes to reduce labor costs and minimize manual operations; implement the latest irrigation technologies (drip irrigation, moisture sensors) to reduce water and electricity consumption. The implementation of these measures will minimize production costs and increase the profitability of growing onions.

The total value of gross production depends on yield and market price. The table shows that increasing pre-irrigation moisture and plant density leads to an increase in the value of gross production. At 60-65% field capacity (MMHC), the gross production value is 435,000-649,600 UAH·ha^{-1}, with the maximum value recorded at 950,000 plants·ha^{-1} (649,600 UAH·ha^{-1}). At 70-75% MMHC (gross production value: 448,300-697,100 UAH·ha^{-1}), higher moisture levels contribute to a 5-7% increase in product value compared to 60-65% MMHC. At 80-85% MMHC (gross production value: 455,500 – 752,700 UAH·ha^{-1}), the largest increase occurred at 950,000 plants·ha^{-1} (752,700 UAH·ha^{-1}), which is the highest value among all options.

Increasing the plant density from 550,000 to 950,000 plants·ha^{-1} results in a 49-65% increase in the value of the product, indicating a significant improvement in productivity with denser plantings. The maximum production value (752,700 UAH·ha^{-1}) was achieved at 80-85% MMHC and 950,000 plants·ha^{-1}, confirming the effectiveness of this combination. Increasing the planting density from 550,000 to 950,000 plants·ha^{-1} contributes to a 50-65% increase in the value of gross production. The optimal pre-irrigation moisture is 80-85% MMHC, as this combination achieves the maximum production value. The maximum gross production value (752,700 UAH·ha^{-1}) was recorded at 80-85% MMHC and a density of 950,000 plants·ha^{-1}.

To achieve the highest product value, it is recommended to optimize planting density at 950,000 plants·ha^{-1}. The most productive irrigation regime is 80-85% of field capacity (MMHC). Using high-quality seed material enhances the average bulb weight and product marketability. Implementing modern fertilization and plant protection technologies helps reduce yield losses. Optimizing harvesting and storage periods prevents losses and improves product quality. The implementation of these measures will maximize economic benefits and increase the efficiency of onion production. Net profit is a key indicator of economic efficiency. It is calculated as the difference between the value of gross production and total production costs. The table shows that increasing pre-irrigation moisture and plant density contributes to higher net profit. At 60-65% MMHC, the net profit ranges from 165,579 to 347,514 UAH·ha^{-1}, with a maximum profit of 347,514 UAH·ha^{-1} at a density of 950,000 plants·ha^{-1}. At 70-75% MMHC, the net profit varies from 177,797 to 391,775 UAH·ha^{-1}, increasing by an average of 12% compared to 60-65% MMHC. At 80-85% MMHC, the net profit ranges from 184,057 to 443,247 UAH·ha^{-1}, with the highest profit (443,247 UAH·ha^{-1}) achieved at 950,000 plants·ha^{-1}, which is the best result.

Increasing the planting density from 550,000 to 950,000 plants·ha^{-1} leads to a 110-140% increase in profit, confirming the effectiveness of higher planting density. The maximum profit (443,247 UAH·ha^{-1}) was achieved at 80-85% field capacity (MMHC) and 950,000 plants·ha^{-1}, proving the optimality of this combination. The optimal pre-irrigation moisture level is 80-85% MMHC, as it ensures the highest net profit. The optimal planting density is 950,000 plants·ha^{-1}, as it provides the greatest economic benefit. The maximum net profit (443,247 UAH·ha^{-1}) was recorded at 80-85% MMHC and a density of 950,000 plants·ha^{-1}, making this the most effective technological combination.

Proposals for increasing net profit: optimize planting density (950,000 plants·ha^{-1}) to achieve the highest profit, use an irrigation regime of 80-85% MMHC, as it provides the best balance between yield and costs. Optimize production costs by implementing precision fertilization and irrigation to minimize resource expenditures. Use high-quality onion varieties with better marketability and higher profitability. Reduce losses during storage and sale by optimizing logistics processes. Implementing these measures will maximize net profit, improve production efficiency, and make onion cultivation more profitable. Profitability is a key indicator of production efficiency. It is calculated as the ratio of profit to costs and demonstrates how profitable crop cultivation is under different technological conditions. The table shows that increasing soil moisture enhances profitability by ensuring higher yields and greater gross product value. At 60-65% field capacity (MMHC)**,** profitability ranges from 61% to 115%**,** with a maximum profitability of 115% at 950,000 plants·ha^{-1}**.** At 70-75% MMHC, profitability varies from 66% to 128%, with an average increase of 10-12% compared to 60-65% MMHC. At 80-85% MMHC, profitability fluctuates between

67% and 143%**,** with the maximum profitability (143%) achieved at 950,000 plants·ha^{-1}**,** which is the best result. Increasing planting density from 550,000 to 950,000 plants·ha^{-1} boosts profitability by 80-135%, confirming the effectiveness of higher density planting**.** The maximum profitability (143%) was achieved at 80-85% MMHC and 950,000 plants·ha^{-1}, making this the optimal combination for maximum profit.

The most optimal pre-irrigation moisture level is 80-85% MMHC, as it ensures the highest profitability (143%). The optimal planting density is 950,000 plants·ha^{-1}, providing the greatest economic efficiency. The maximum profitability (143%) was recorded at 80-85% MMHC and 950,000 plants·ha^{-1}, which is the best combination for profitable cultivation.

Proposals for increasing profitability: optimize planting density (950,000 plants·ha^{-1}) to achieve the highest economic efficiency, use an irrigation regime of 80-85% field capacity (MMHC) to maximize profitability. Minimize production costs by implementing modern irrigation technologies, automation, and optimized fertilization. Improve product quality to sell the harvest at higher prices. Optimize post-harvest processing and storage to reduce losses and enhance product competitiveness. Implementing these measures will maximize profit and profitability in onion production, increasing the efficiency of resource utilization. In addition to traditional methods of evaluating agricultural production efficiency, which are based on economic and labor indicators, energy analysis is gaining increasing importance in modern global practice. One of its key indicators is the coefficient of energy and bioenergy efficiency, which helps assess the rational use of resources. Agriculture relies on two types of energy: non-renewable and renewable. Non-renewable energy sources include oil, natural gas, coal, and nuclear fuel. The primary renewable energy source is solar energy, which is stored in plant biomass through photosynthesis. The main objective of energy analysis is to identify optimal production methods that promote the efficient use of both natural and artificial energy resources while reducing environmental impact. This analysis allows for the evaluation of fertilizer application efficiency, plant protection measures, irrigation effectiveness, and the impact of soil and climatic conditions on crop productivity. Energy analysis of crop cultivation technologies concludes with the calculation of the energy cost of the yield. A high energy efficiency coefficient indicates a resource-saving and energy-efficient nature of the technology. This indicator depends on the structure of sown areas, crop rotation types, and natural conditions. Vitanov (2023) stated, "…in vegetable production, a significant amount of energy is consumed for fuel and lubricants. Under the basic technology, plowing and pesticide application were factors contributing to high energy expenditures ”[20]. When assessing the bioenergy efficiency of vegetable production, it is essential to consider not only caloric content but also the presence of valuable chemical compounds that determine its nutritional, medicinal, and dietary value. Since the energy content of vegetables is relatively low, their energy efficiency coefficient often does not exceed one. Therefore, for a comprehensive evaluation of vegetable products, in addition to caloric content, consumer value coefficients are used, which take into account their biological activity and health benefits.

Table 13. Energy efficiency of onion cultivation depending on irrigation regime and plant density

Antecedent soil water,% of minimum moisture-holding capacity	Plant density, thousand plants·ha^{-1}	Energy input from yield, GJ·ha^{-1}	Energy costs for production, GJ·ha^{-1}	Energy efficiency coefficient	Bioenergy efficiency coefficient
60-65% MMHC	550	60.43	84.53	0.71	6.22
	750	76.32	90.18	0.84	7.31
	950	90.33	95.09	0.94	8.16
70-75% MMHC	550	62.41	85.66	0.73	6.33
	750	81.08	92.30	0.88	7.65
	950	97.13	97.88	0.99	8.60
80-85% MMHC	550	63.36	87.12	0.73	6.33
	750	86.21	95.05	0.90	7.86
	950	105.24	101.78	1.03	8.95

Source: results of own scientific research.

[20] Vitanov, O. D. (2023). *Specialized vegetable crop rotations* (2nd ed., revised and expanded). TVORY. https://ovoch.com/assets/files/library/books-monographs/sivozminupovne.pdf

At 60-65% field capacity (MMHC): energy input from yield: 60.43-90.33 GJ·ha^{-1}, energy consumption for production: 84.53-95.09 GJ·ha^{-1}, energy efficiency coefficient: 0.71-0.94, bioenergy efficiency coefficient: 6.22-8.16. Maximum values were achieved at 950,000 plants·ha^{-1} (0.94; 8.16). At 70-75% MMHC: energy input from yield: 62.41-97.13 GJ·ha^{-1}, energy consumption for production: 85.66-97.88 GJ·ha^{-1}, energy efficiency coefficient: 0.73-0.99, bioenergy efficiency coefficient: 6.33-8.60, optimal balance between energy expenditure and output. At 80-85% MMHC: energy input from yield: 63.36105.24 GJ·ha^{-1}, energy consumption for production: 87.12-101.78 GJ·ha^{-1}, energy efficiency coefficient: 0.73-1.03, bioenergy efficiency coefficient: 6.33-8.95, maximum coefficient values (1.03; 8.95) were recorded at 950,000 plants·ha^{-1}, indicating the most efficient resource utilization (Table 13). With an increase in planting density from 550,000 to 950,000 plants·ha^{-1}, energy input from yield increased by 40-50%, confirming higher productivity. The energy efficiency coefficient rose from 0.71-0.73 to 0.94-1.03, proving the advantage of higher planting density, while the bioenergy efficiency coefficient increased by 30-40%. The optimal irrigation regime is 80-85% MMHC, as it ensures the highest energy efficiency (1.03) and bioenergy efficiency (8.95). The optimal planting density is 950,000 plants·ha^{-1} , promoting rational energy and resource use. Increasing both planting density and soil moisture enhances energy efficiency, supporting the validity of intensive technologies.

Proposals for improving energy efficiency: optimize planting density (950,000 plants·ha^{-1}) to ensure the best balance between energy input and output, use an irrigation regime of 80-85% MMHC, as it provides the highest energy efficiency coefficient, apply resource-saving technologies to reduce energy consumption for soil cultivation and irrigation, implement drip irrigation to decrease energy and water use, introduce modern fertilizers and growth stimulators to lower energy costs per unit of production. Implementing these measures will enhance energy efficiency, reduce energy consumption, and make onion cultivation more environmentally and economically sustainable. Energy input from yield: At 60-65% MMHC, energy input ranges from 60.43 to 90.33 GJ·ha^{-1}. Increasing plant density from 550,000 to 950,000 plants·ha^{-1} results in a 49.5% increase in energy input, due to higher yields. At 70-75% MMHC, energy input ranges from 62.41 to 97.13 GJ·ha^{-1}, with a 55.6% increase in energy input as density increases, indicating more efficient resource use. At 80-85% MMHC, energy input ranges from 63.36 to 105.24 GJ·ha^{-1}. The highest value (105.24 GJ·ha^{-1}) was recorded at 950,000 plants·ha^{-1}, proving the optimal combination of density and soil moisture. With an increase in plant density from 550,000 to 950,000 plants·ha^{-1}, energy input increased by an average of 50-60%, demonstrating higher yield potential. The highest level (105.24 GJ·ha^{-1}) was achieved at 950,000 plants·ha^{-1} and 80-85% MMHC. Optimal pre-irrigation soil moisture: 80-85% MMHC, ensuring the highest energy input (105.24 GJ·ha^{-1}). Optimal planting density: 950,000 plants·ha^{-1}, maximizing energy accumulation in biomass. Increasing planting density and soil moisture significantly boosts energy output, confirming the effectiveness of these technological solutions.

Proposals for increasing energy input: to maximize energy accumulation in biomass, the following measures are recommended, optimize planting density (950 thousand plants·ha^{-1}) to ensure maximum energy accumulation in biomass, maintain soil moisture at 80-85% MMHC, as this regime promotes the highest productivity. Implement effective fertilization systems, particularly nitrogen and potassium fertilizers, which enhance the photosynthesis process. Optimize harvesting time to avoid yield losses and maximize energy accumulation. Use high-yield onion varieties with higher dry matter content and energy value. The application of these measures will allow maximizing energy input from the yield, increasing production efficiency, and enhancing the profitability of onion cultivation.

At 60-65% MMHC, energy consumption ranges from 84.53 to 95.09 GJ·ha^{-1}, with an increase in plant density leading to a 12.5% rise in energy costs. At 70-75% MMHC, energy consumption is 85.66 to 97.88 GJ·ha^{-1}, and increasing density results in a 14.2% rise in energy expenditure, indicating intensified production. At 80-85% MMHC, energy consumption varies from 87.12 to 101.78 GJ·ha^{-1}. The highest energy expenditure (101.78 GJ·ha^{-1}) is recorded at 950 thousand plants·ha^{-1}, due to increased irrigation, maintenance, and harvesting costs. As planting density increases from 550 to 950 thousand plants·ha^{-1}, energy costs rise on average by 15-20%, due to higher expenses for maintenance, nutrition, and irrigation. The highest energy expenditure is observed at 950 thousand plants·ha^{-1} and 80-85% MMHC (101.78 GJ·ha^{-1}). The lowest energy consumption (84.53 GJ·ha^{-1}) occurs at 60-65% MMHC and 550 thousand plants·ha^{-1}, but under these conditions, yield is the lowest. The maximum energy expenditure (101.78 GJ·ha^{-1}) is recorded at 80-85% MMHC and 950 thousand plants·ha^{-1}, indicating the high energy intensity of intensive production. The optimal irrigation regime is

70-75% MMHC, as it provides a balance between energy costs and yield levels.

Proposals for reducing energy costs: to optimize energy consumption and improve production efficiency, the following measures are recommended, optimize planting density (750-950 thousand plants·ha^{-1}) to reduce maintenance costs without significantly decreasing yield, implement energy-saving technologies, including automated irrigation systems and precision fertilizer application. Optimize irrigation by minimizing unproductive water losses, especially at 80-85% MMHC. Reduce mechanized work costs by using modern machinery and energy-efficient equipment. Adopt agronomic practices that enhance natural soil fertility, reducing the need for additional fertilization and tillage. The implementation of these measures will help optimize energy consumption, increase production efficiency, and improve profitability. The energy efficiency coefficient is determined as the ratio of the energy obtained from the yield to the energy costs of production. The higher this indicator, the more efficient the use of energy resources.

At 60-65% MMHC, the energy efficiency coefficient ranged from 0.71 to 0.94, with the highest value (0.94) recorded at 950 thousand plants·ha^{-1}, indicating more efficient energy use with increased planting density. At 70-75% MMHC, the coefficient ranged from 0.73 to 0.99, with the maximum value (0.99) observed at 950 thousand plants·ha^{-1}, demonstrating more efficient energy utilization at higher irrigation levels. At 80-85% MMHC, the energy efficiency coefficient ranged from 0.73 to 1.03, with the highest value (1.03) achieved at 950 thousand plants·ha^{-1}, indicating the most efficient combination of planting density and moisture level. With an increase in planting density from 550 to 950 thousand plants·ha^{-1}, the energy efficiency coefficient grows by an average of 30-40%, highlighting the more rational use of energy resources at higher densities. The maximum energy efficiency (1.03) was recorded at 80-85% MMHC and 950 thousand plants·ha^{-1}, confirming the effectiveness of intensive cultivation technologies.

The optimal irrigation regime is 80-85% MMHC, as it achieves an energy efficiency coefficient of 1.03, the highest recorded value. The most efficient planting density is 950 thousand plants·ha^{-1}, allowing for the most effective use of energy resources. Increasing both planting density and soil moisture contributes to higher energy efficiency, confirming the feasibility of implementing intensive cultivation technologies. Proposals for increasing the energy efficiency coefficient: optimize planting density (950 thousand plants·ha^{-1}) to ensure maximum productivity with minimal energy costs, maintain irrigation levels within 80-85% MMHC, as this provides the best balance between energy input and output. Implement energy-saving technologies, such as drip irrigation, precision fertilization, and efficient soil tillage methods**.** Optimize mechanized processes by using energy-efficient machinery for sowing, maintenance, and harvesting. Improve soil fertility through the application of organic fertilizers and crop rotation, enhancing natural productivity without additional energy expenses. The implementation of these measures will optimize energy use, reduce costs, and make onion cultivation more efficient and economically viable.

The bioenergy efficiency coefficient reflects the efficiency of energy resource utilization, considering the nutritional value of the obtained product. Higher values of this coefficient indicate a more rational use of energy for producing valuable output. At 60-65% MMHC**,** the coefficient values range from 6.22 to 8.16**,** with the highest value (8.16**)** recorded at 950 thousand plants·ha^{-1}**,** indicating more efficient energy use with increased planting density. At 70-75% MMHC, the coefficient ranges from 6.33 to 8.60**,** with the maximum value (8.60) at 950 thousand plants·ha^{-1}**,** demonstrating more effective utilization of bioenergy resources. At 80-85% MMHC**,** the coefficient values range from 6.33 to 8.95**,** with the highest coefficient **(**8.95**)** achieved at 950 thousand plants·ha^{-1}**,** indicating the best balance between energy input and the nutritional value of the product. With an increase in planting density from 550 to 950 thousand plants·ha^{-1}**,** the bioenergy efficiency coefficient increases by an average of 30-40%**,** highlighting the more rational use of energy with higher planting density. The maximum bioenergy efficiency (8.95) was recorded at 80-85% MMHC and 950 thousand plants·ha^{-1}**,** confirming the effectiveness of intensive cultivation technologies. The optimal irrigation regime is 80-85% MMHC, as it achieves a bioenergy efficiency coefficient of 8.95, the highest recorded value. The most efficient planting density is 950 thousand plants·ha^{-1}**,** allowing for the most effective use of energy resources. Increasing both planting density and soil moisture contributes to higher bioenergy efficiency, confirming the feasibility of implementing intensive cultivation technologies.

The bioenergy efficiency coefficient reflects the effectiveness of energy resource utilization, considering the nutritional value of the obtained product. Higher values of this coefficient indicate a more rational use of energy for producing valuable output. At 60-65% MMHC, the coefficient values range from 6.22 to 8.16, with the highest value (8.16) recorded at 950 thousand plants·ha^{-1}, indicating more efficient energy use with increased planting density. At 70-75% MMHC, the coefficient ranges from 6.33 to 8.60, with the maximum value (8.60) at 950 thousand plants·ha^{-1}, demonstrating more effective utilization of bioenergy resources. At 80-85% MMHC, the coefficient values range from 6.33 to 8.95**,** with the highest coefficient **(**8.95**)** achieved at 950 thousand plants·ha^{-1}, indicating the best balance between energy input and the nutritional value of the product. With an increase in planting density from 550 to 950 thousand plants·ha^{-1}, the bioenergy efficiency coefficient increases by an average of 30-40%**,** highlighting the more rational use of energy with higher planting density. The maximum bioenergy efficiency (8.95) was recorded at 80-85% MMHC and 950 thousand plants·ha^{-1}, confirming the effectiveness of intensive cultivation technologies. The optimal irrigation regime is 80-85% MMHC, as it achieves a bioenergy efficiency coefficient of 8.95, the highest recorded value. The most efficient planting density is 950 thousand plants·ha^{-1}, allowing for the most effective use of energy resources. Increasing both planting density and soil moisture contributes to higher bioenergy efficiency, confirming the feasibility of implementing intensive cultivation technologies.

Proposals for increasing the bioenergy efficiency coefficient: optimize planting density (950 thousand plants·ha^{-1}) to ensure maximum productivity with minimal energy consumption, maintain irrigation levels within 80-85% MMHC, as this provides the best balance between energy input and output, use energy-saving technologies, such as drip irrigation, precision fertilization, and efficient soil treatment methods. Optimize mechanized processes by utilizing energy-efficient equipment for sowing, crop management, and harvesting. Improve soil fertility by applying organic fertilizers and crop rotation, which will enhance natural productivity without additional energy costs. Implementing these measures will optimize energy use, reduce costs, and make onion cultivation more efficient and economically viable.

Conclusions. The study of the impact of soil moisture regime and plant density on the productivity of bulb onions in the conditions of the Southern Steppe of Ukraine has made it possible to determine the most effective technological parameters for crop cultivation. The irrigation regime has a decisive influence on yield and product quality. The optimal pre-irrigation moisture level is 80-85% of field capacity (MMHC), ensuring the highest yield (75.27 t·ha^{-1}), maximum net profit (443,247 UAH·ha^{-1}), and profitability (143%). Plant density directly affects crop productivity, bulb marketability, and water use efficiency. The best results were obtained at 950,000 plants·ha^{-}

^{1}, which contributed to increased yield, improved commercial quality of bulbs, and an optimal water consumption coefficient (52.2 m·t^{-3}). The optimal combination of factors (80-85% MMHC and 950,000 plants·ha^{-1}) provided the highest energy efficiency (1.03) and bioenergy efficiency (8.95), confirming the feasibility of using intensive technologies in onion cultivation.

Analysis of economic efficiency and future research prospects: the analysis of economic efficiency showed that applying the optimal irrigation level and increased planting density significantly reduces the production cost (down to 4111 UAH·t^{-1}), increases profitability, and improves the cost-effectiveness of production. The optimized irrigation system not only enhances yield but also ensures the rational use of water resources, which is critically important for the Southern Steppe of Ukraine, characterized by an arid climate.

Future research prospects include: expanding studies to other onion varieties to determine their adaptation to changing climatic conditions, implementing advanced irrigation systems, including soil moisture sensor monitoring and automated irrigation control, investigating the impact of biostimulants and growth regulators on yield and product quality. Analyzing the use of organic fertilizers and their effects on water use efficiency and bulb quality. Optimizing post-harvest processing and storage to minimize product losses and improve marketable quality.

Proposals for Improving the Technology of Growing Bulb Onions in Southern Ukraine: optimization of irrigation regime – implementation of drip and subsoil irrigation to reduce water losses and increase water use efficiency, use of adapted varieties and hybrids – selection of drought-resistant varieties to ensure stable yields even in dry years, balanced fertilization – improving the efficiency of using macro– and microelements to enhance harvest quality. Application of precision agriculture technologies – automated monitoring of crop condition, soil analysis, and real-time irrigation regulation.

In global practice, the implementation of sustainable agro-technologies involves minimizing the negative impact on the environment, using energy-saving and eco-friendly production methods; applying alternative energy sources in agriculture – solar power plants to supply energy for irrigation systems; researching the impact of climate change on onion production and developing adaptation strategies for increased temperatures and changing rainfall patterns; optimizing logistics and storage of products – introducing energy-efficient storage methods, refrigeration systems, and modern packaging technologies. The implementation of these measures will increase the productivity of bulb onions, optimize resource usage, reduce costs, and improve the profitability of growing the crop both in the Southern Steppe of Ukraine and globally.

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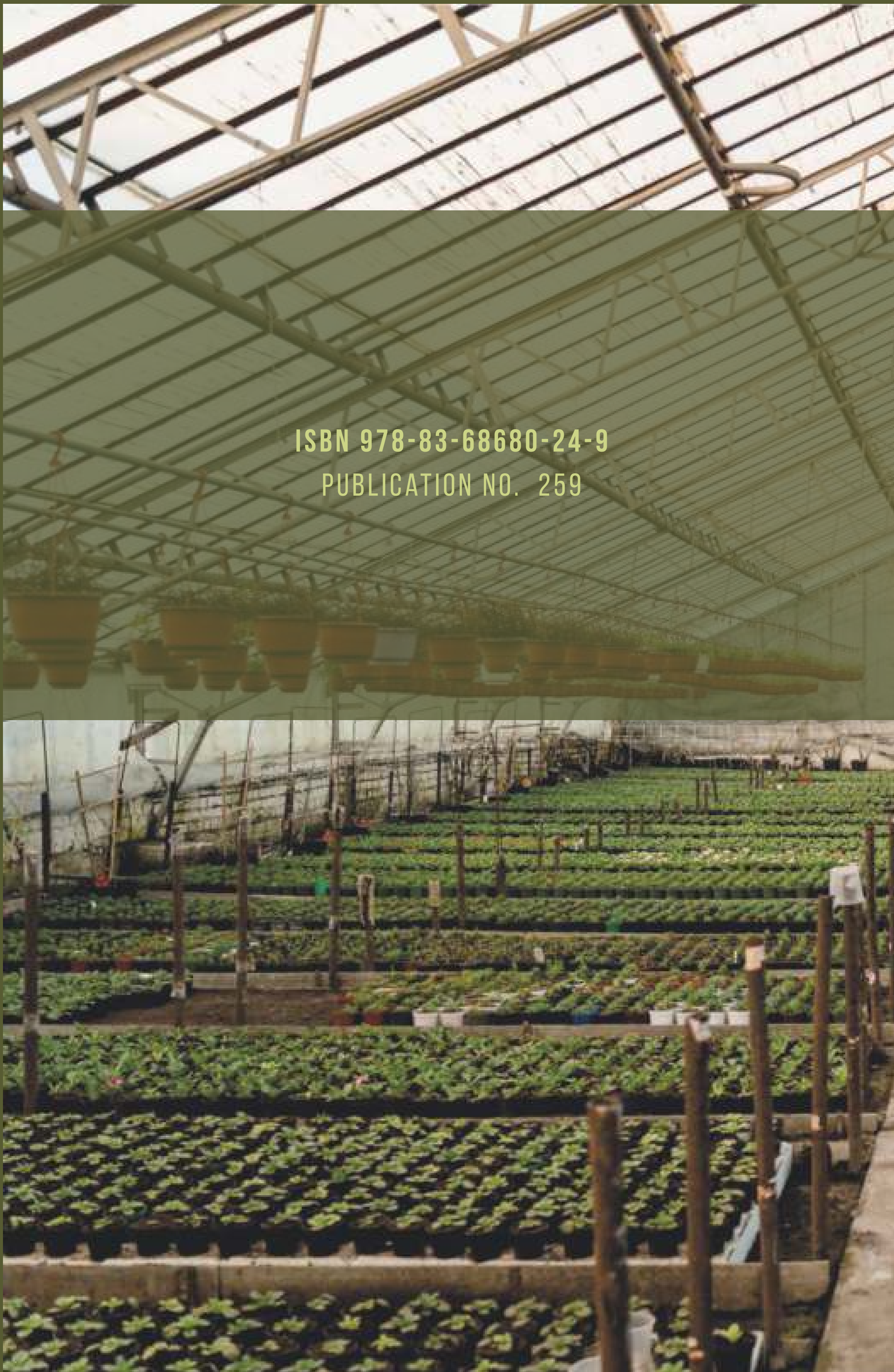
Abstract

This study examines the impact of soil moisture regime and plant density on the productivity of bulb onion under the conditions of the Southern Steppe of Ukraine. The effects of different soil moisture levels and plant spacing options on the growth, development, and yield formation of the crop were analyzed. Optimal soil moisture levels ensuring the highest onion productivity were identified, along with effective plant placement schemes for the rational use of land area and water resources. The research results demonstrated that reducing moisture deficiency during critical growth phases enhances yield and improves the qualitative characteristics of the produce. Practical recommendations were proposed for optimizing onion cultivation technology, considering the climatic conditions of the Southern Steppe. It was established that the proper selection of an irrigation regime can significantly improve the storability of the harvested onions. The study also confirmed the substantial influence of plant density on commercial quality indicators, particularly bulb size and uniformity. The obtained results can be utilized by farmers to increase the efficiency of bulb onion production.

Keywords: bulb onion, soil moisture, plant density, yield, product quality, Southern Steppe of Ukraine.



ISBN 978-83-68680-24-9
PUBLICATION NO. 259