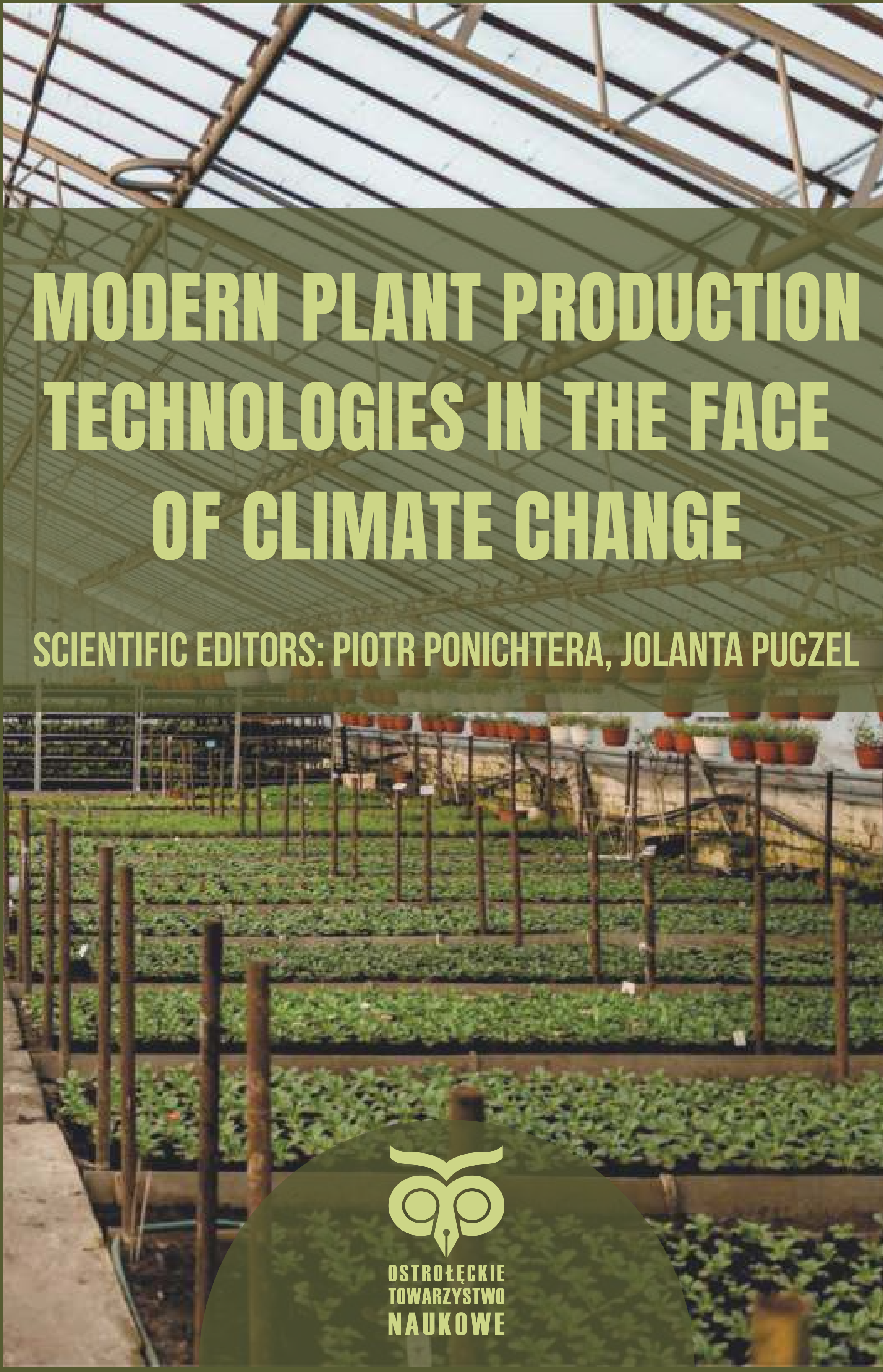

MODERN PLANT PRODUCTION TECHNOLOGIES IN THE FACE OF CLIMATE CHANGE

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Chapter 5. The impact of weed infestation on the initial growth and development of maize grown for grain

Jolanta Puczel

Introduction

Contemporary agriculture in Poland and Ukraine operates in conditions of dynamic climatic, environmental, and economic change, which directly affect the stability of crop production, the efficient use of natural resources, and the country's food security. Progressive global warming, increasingly frequent extreme weather events, and growing anthropogenic pressure necessitate the search for new, integrated technological and agrotechnical solutions adapted to regional natural conditions. This monograph is an attempt to comprehensively address selected issues of contemporary agriculture in Poland and Ukraine, with particular emphasis on the impact of climate change on crop production and the possibilities of increasing its efficiency through rational resource management and the implementation of innovative technologies.

In the context of climate change, the selection of appropriate plant species and cultivation technologies, characterized by high adaptive potential and wide range of uses, is of particular importance. One such plant is oil flax, whose economic importance has grown significantly in recent years. The increase in its cultivation area is primarily due to the growing demand for seeds and linseed oil in the food and pharmaceutical industries and in the production of biologically active additives. At the same time, the untapped potential of oil flax stalks, which in most cases are burned in the fields, remains an unresolved problem. The integrated use of all parts of this plant, including straw as a fiber or energy source, can significantly increase the profitability of production and contribute to solving the raw material and energy problems of many industries.

Another important element of the monograph are issues related to the optimization of oilseed and vegetable cultivation technologies in conditions of limited water availability, characteristic of the southern regions of Ukraine. Research on modern methods of sunflower cultivation has shown that the use of high-yield hybrids, appropriate soil cultivation technologies, and growth regulators can significantly increase yields and improve seed quality, even under water stress conditions. Particular attention was paid to assessing the effectiveness of biostimulants, which increase plant resistance to adverse environmental factors and improve resource efficiency.

An equally important issue is rational water management in vegetable production, as exemplified by research on the impact of soil moisture and planting density on spring onion yields in the southern steppe of Ukraine. The results confirm that precise adjustment of the irrigation system and plant spacing scheme not only increases yield but also improves the commercial quality and storage life of the product.

The considerations contained in the monograph are supplemented by research on the impact of weed infestation on corn yields in the early stages of growth. Significant differences in the response of individual varieties to weed pressure and the timing of herbicide treatments have been demonstrated, which emphasizes the importance of integrated plant protection and the selection of more competitive varieties.

The research results presented in the monograph form a coherent whole, showing the multifaceted impact of climate change and agrotechnical factors on plant production in Poland and Ukraine. The conclusions and practical recommendations contained therein can be a valuable source of knowledge for scientists, agricultural advisors, and agricultural producers, contributing to the sustainable development of agriculture and increasing its resilience to contemporary environmental challenges. The monograph can also be used as teaching material for students of agricultural and natural sciences, supporting the education process in the fields of agronomy, agrometeorology, crop cultivation technology, and natural resource management. The analyses, research methods, and case studies presented will enable students to better understand the relationship between climatic conditions and agricultural practices and to develop the analytical and interpretative skills necessary for future research work.

Piotr Ponichtera
Jolanta Puczel

UDC 551.5+911.2

Chapter 1.

LONG-TERM DYNAMIC OF AIR TEMPERATURE IN CENTRAL UKRAINE

Olha Helevera

1.1. Introduction

The issue of analyzing and predicting changes in weather and climate conditions over certain periods is the most complex in climatology. The interaction of atmospheric and oceanic circulation with polar ice creates not only short-term weather fluctuations but also changes that can last up to 10 thousand years. The least studied are short-term cycles of 11-33 years. Fluctuations of shorter intervals are considered climate variability, and longer ones are considered irreversible fluctuations. A detailed understanding of the temporal and spatial patterns of climate change with high resolution over previous centuries is important for assessing the extent to which the changes of the late 20th – early 21st centuries may be unusual in light of pre-industrial natural climate variability.

Analysis of recent studies and publications. Temperature variability for Europe before 1500 is most extensively examined in the paper "European Seasonal and Annual Temperature Variability, Trends, and Extremes Since 1500". The authors used multiproxy reconstructions of monthly and seasonal surface temperature fields and found that the European climate of the late 20th and early 21st centuries was very likely (>95% confidence level) warmer than at any time during the last 500 years. This is consistent with findings for the entire Northern Hemisphere. Average European winter temperatures between 1500 and 1900 are ~0.5°C lower (0.25°C for annual mean temperatures) compared with the 20th century. Summer temperatures have not experienced systematic cooling on a centennial scale relative to modern conditions. The coldest European winter was 1708-1709; 2003 was the hottest summer on record (Jürg Luterbacher, Daniel Dietrich, Elena Xoplaki, Martin Grosjean, & Heinz Wanner, 2004)[1].

Except for two brief periods around 1530 and 1730, European winters have generally been colder than in the 20th century. The coldest winters occurred in the late 16th century, during the last decades of the 17th century, and in the late 19th century (Jürg Luterbacher et al., 2004). The return period (repeat of the coldest winter of 1708-1709) is 200 to 500 years for winter conditions from 1750 to ~1900. 20th-century warming is increasing in this period.

A strong winter warming trend was observed between 1684 and 1738. The linear trend for this period is +0.32°C per decade. Such a strong increase in winter temperatures in Europe over a comparable period has not been observed elsewhere in the 500-year record. The large-scale warming in Europe during this time could be caused by different processes: increased solar activity and large volcanic eruptions lead to continental warming, however, solar changes have a much stronger effect on continental scales (Jürg Luterbacher et al., 2004).

The linear trend in winter temperatures for the 20th century (1901-2000) is +0.08°C per decade. The winter of 1989-1990 and the decade of 1989-1998 were the warmest since 1500. The period of 1989-1998 was almost twice as warm as the second warmest decade (1733-1742), and thus warmer than any other decade since 1500. On a multi-decadal time scale (30-year averages), the winters between 1973 and 2002 were probably (85% probability) the warmest 30-year period of the last half-millennium. However, the winter of 2002-2003 was 0.4°C colder than the 1901-1995 average. The 19th century (-0.32°C) was the coldest in the last half-millennium (Jürg Luterbacher et al., 2004). The coldest decadal periods occurred in the second half of the 19th century and the end of the 17th century. Decadal continental annual temperature changes during pre-industrial times are likely to have been driven mainly by changes in solar activity (Mann, M.E., E.A. Lloyd, & Oreskes, N., 2017)[2], although long periods of volcanism may also have contributed to the cooling in Europe.

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1 Jürg Luterbacher, Daniel Dietrich, Elena Xoplaki, Martin Grosjean, & Heinz Wanner (2004). European Seasonal and Annual Temperature Variability, Trends, and Extremes Since 1500. Science Vol 303, Issue 5663, pp. 1499-1503. DOI: https://doi.org/10.1126/science. 1093877

2 Mann, M.E., E.A. Lloyd, & Oreskes, N. (2017): Assessing climate change impacts on extreme weather events: the case for an alternative (Bayesian) approach. Climatic

The 20th century (1901-2000) was the warmest since 1500. The 20th century showed a strong warming trend of +0.08°C per decade. The last 30 years (1974-2003) were ~0.45°C warmer than the next warmest 30-year periods (1722-1751 and 1750-1779) of the reconstructions. The nine warmest European years have occurred since 1989. 1989 (+1.3°C) and the decade from 1994 to 2003 (+0.84°C) were probably the warmest in over half a millennium (Jürg Luterbacher et al., 2004).

Each of the last three decades has been warmer than any previous decade since 1850, and the first decade of the 21st century was the warmest. In the Northern Hemisphere, the period from 1983 to 2012 was the warmest 30-year period in the past 1400 years. The average global surface temperature increased by 0.85°C during the period from 1880 to 2012, calculated using a linear trend from several separately developed data series (IPCC, 2022)[3].

According to expected future climate change, the change in the global average surface temperature in the short term for the period 2016-2035 compared to 1986-2005 is likely to be in the range of 0.3-0.7°C. This assessment assumes no major volcanic eruptions or long-term changes in total solar radiation (IPCC, 2023)[4]. However, the eruption of the Hunga Tonga-Hunga Ha'apai (HTHH) volcano in late 2021–early 2022 released a large amount of water vapor into the atmosphere, leading to increased temperatures in the northern hemisphere winter months (Jucker Martin, Lucas Chris, & Dutta Deepashree, 2023)[5]. In the short term (2021-2040), a 20-year average global surface temperature increase of 1.5°C relative to the 1850-1900 average is highly likely (Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., Maycock, A., Mute-

Change, 144(2), 131–142, DOI: https://doi.org/ 10.59327/IPCC/AR6-978929169164 710.1007/s10584-017-2048-3

3 IPCC (2022): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056. DOI: https://doi.org/10.1017/9781009325844

4 IPCC (2023): Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 35-115, DOI: https://doi.org/10.59327/IPCC/AR6-9789291691647

5 Jucker Martin, Lucas Chris, & Dutta Deepashree (2023). Long-term surface impact of Hunga Tonga-Hunga Ha'apai-like stratospheric water vapor injection. ESS Open Archive. August 04. DOI: https://doi.org/10.22541/essoar.169111653.36341315/v1

mi, J., Ndiaye, O., Panickal, S. & Zhou T., 2021)[6]. The frequency of cold spells and frost days will likely continue to decrease during this century, and it is quite likely that frost days will virtually disappear by the end of the century (IPCC, 2023)[7]. In the short term (2021-2040), the average global surface temperature will likely increase by 1.5°C over 20 years compared to the average for the period 1850-1900 (Lee, J.-Y. et al., 2021). The frequency of cold periods and frosty days will likely continue to decline during this century, and, likely, cold periods will virtually disappear by the end of the century (IPCC, 2023).

From 1757, there was a trend towards summer cooling (-0.06°C per decade) until the early 20th century, with 1902 being the coldest summer on record. During the 20th century, instrumental summer data show first a pre-emptive trend until 1947, and then a cooling trend until 1977. This was followed by an extremely strong, unprecedented warming (linear trend of +0.7°C per decade), which was probably marked by the hottest summer decade from 1994 to 2003. European summer temperatures show other multi-decadal periods with comparable, albeit less pronounced, warming trends (1731-1757, +0.42°C per decade; 1923-1947, +0.45°C per decade, respectively). The summer of 2003 exceeded the European summer temperatures from 1901 to 1995 by about +2°C. The summer of 2003 was probably warmer than any other summer before 1500 (Jürg Luterbacher et al., 2004).

The recurrence period of a European-scale summer event exceeding 2°C (relative to the 1901-1995 average) was calculated using the same methodology (change in trend over time) as for the winter of 1708-1709 (IPCC, 2023). The recurrence period is over 5000 years for summer conditions in the mid-18th century. It increases markedly to millions of years at the

6 Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S. & Zhou T. (2021): Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, DOI: https://doi.org/10.1017/9781009157896.006

7 IPCC (2023): Climate Change Information for Regional Impact and for Risk Assessment. In Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1767-1926). Cambridge: Cambridge University Press. DOI: https://doi.org/10.1017/9781009157896.014

turn of the 20th century and decreases to less than 100 years during the last summer (IPCC, 2023).

Studies of the dynamics of climatic indicators for the territory of Ukraine and its regions are ongoing (Helevera Olha, Mostipan Mykola, & Topolnyi Sergii, 2024[8]; Helevera, O.F., 2019[9]; Reshetchenko, S.I., Dmitriiev, S.S., Cherkashyna, N.I., & Goncharova, L.D., 2020[10]), but often they do not cover the entire period of instrumental observations (Osadchyi, V., Skrynyk, O. A., Radchenko, R., & Skrynyk, O. Y., 2018[11]; Pyasetska Svitlana, & Shcheglov Oleksandr, 2023[12]). Researchers note that the average annual temperature has increased by 0.6±0.2°C over 100 years (Borovska, H. & Khokhlov, V., 2023[13]; Boychenko, S., Voloshchuk, V., Movchan, Y., Serdjuchenko, N., Tkachenko V., Tyshchenko, O., & Savchenko S., 2016[14]). There are attempts to predict climate change based on the projection of regional climatic characteristics (using the example of the Odessa region). According to them, shortly (until 2030), changes in the average annual air temperature relative to the current period are +0.44±0.3°C, and its value is 10.9°C. Insignificant changes in the average monthly air temperature

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8 Helevera Olha, Mostipan Mykola, & Topolnyi Sergii (2024). Summer and Autumn Long-term Dynamic of Air Temperature in Central Ukraine. Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology", (61), 144-155. https://doi.org/10.26565/2410-7360-2024-61-12

9 Helevera, O.F. (2019). Long-term dynamics of climatic indicators according to the data of the Kropyvnytskyi weather station. Scientific Bulletin of Kherson State University. Series Geographical Sciences, (10), 107–113. https://doi.org/10.32999/ksu2413-7391/2019-10-15 [in Ukrainian]

10 Reshetchenko, S.I., Dmitriiev, S.S., Cherkashyna, N.I., & Goncharova, L.D. (2020) Climate indicators of changes in hydrological characteristics a case of the Psyol river basin. Visnyk of V.N. Karazin Kharkiv National University, series "Geology. Geography. Ecology", (53), 155-166, DOI: https://doi.org/10.26565/2410-7360-2020-53-12

11 Osadchyi, V., Skrynyk, O. A., Radchenko, R., & Skrynyk, O. Y. (2018). Homogenization of Ukrainian air temperature time series. Int. J. Climatol. (38), 497-505. DOI: https://doi.org/10.1002/joc.5191

12 Pyasetska Svitlana, & Shcheglov Oleksandr (2023). The modern nature of changes in the average monthly air temperature during 2006-2020. Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology", (58), 217-230. DOI: https://doi.org/10.26565/2410-7360-2023-58-17 [in Ukrainian]

13 Borovska, H. & Khokhlov, V. (2023) Climate data for Odesa, Ukraine in 2021-2050 based on EURO-CORDEX simulations. Geoscience Data Journal, 00, 1–12. Available from: https://doi.org/10.1002/gdj3.197

14 Boychenko, S., Voloshchuk, V., Movchan, Y., Serdjuchenko, N., Tkachenko V., Tyshchenko, O., & Savchenko S. (2016). Features of Climate Change on Ukraine: Scenarios, Consequences for Nature and Agroecosystems. Proceedings of the National aviation university, (4), 96–113. DOI: https://doi.org/10.18372/2306-1472.69.11061 [in Ukrainian]

(within ±0.05°C) are expected from January to March, and from April to the end of the year, a progressive increase in average monthly air temperatures is expected. The largest increases are expected in December, September and July (+0.8±0.5°C, +0.79±0.4°C, +0.74±0.4°C respectively). January is the coldest month of the year, the absolute value of the average temperature is predicted to be -1.3°C in this period. July will remain the warmest month with an average temperature of 23.3°C. The smallest confidence intervals were obtained for August ±0.2°C, the largest for January ±0.7°C (Krakovska, S.V., Bilozerova, A.K., & Palamarchuk, L.V., 2015)[15].

Projections of changes in air temperature in Ukraine until the middle of the 21st century indicate clear warming in all months of the year. Changes in the average annual temperature in this period are predicted to be +1.41±0.2°C, and its value is 11.9°C, which is 1.0°C higher than in the previous period. The maximum values of changes are expected, as in the previous period, in December +2.05±0.4°C. Unlike the period of the near future, significant changes will occur in August +1.81±0.4°C and January +1.61±0.6°C, the smallest ones – in spring with a minimum in February +0.79±0.4°C. January, as in the period 2011-2030, is expected to be the coldest place of the year (-0.3°C) (Krakovska, S.V. et al., 2015). Compared to 1961-1990, the smallest changes will be experienced by the average monthly air temperature in spring and autumn (up to 1°C), while the increase in temperature in summer and winter will be 2.5–3.5°C (Zamfirova, M.S., & Khokhlov, V. M., 2020)[16]. In the summer months, warming will occur unevenly: maximum in August, but in July temperature changes are also significant and amount to +1.68±0.3°C. For the entire period, a high homogeneous intermodel agreement was obtained: confidence intervals within ±0.2–0.6°C (Zamfirova, M. S., & Khokhlov, V. M., 2020).

In January, the temperature rose everywhere. The largest increase (3.0°C) occurred in the northeast and east, in a significant part of the country it was 2.0°C, in the south and the Transcarpathian lowland 1.0-1.4°C

[15] Krakovska, S.V., Bilozerova, A.K., & Palamarchuk, L.V. (2015). Projections of regional climatic characteristics in the XXI century based on modeling data (on the example of Odesa region). Physical geography and geomorphology. Vol. 2(78) ~132. ISSN 0868-6939 [in Ukrainian]

[16] Zamfirova, M. S., & Khokhlov, V. M. (2020). Air temperature and precipitation regime in Ukraine in 2021-2050 by CORDEX model ensemble. Ukrainian Hydrometeorological Journal. (25), 17-27. DOI: https://doi.org/ 10.31481/uhmj.25.2020.02 [in Ukrainian]

(Osadchyi, V.I., & Babichenko, V.M., 2013)[17]. In February, the temperature warmed up by 1.5-2.0°C in most of the territory, in the southeast the air temperature increased by 1.0°C, in Crimea and Transcarpathia – by 0.5°C. In March, an increase of 1.0-1.5°C was observed in most of the territory, and the Transcarpathian lowland – by only 0.3°C. In April, the air temperature for 1991-2010 in most of the territory became higher by 1.0°C, and only in the south and Transcarpathia it increased by 0.4°C. In May, there was a slight increase in air temperature in the west (by 0.4-0.7°C), in the rest of the territory the temperature almost did not change. In December, there was a decrease in air temperature by 0.1-0.5°C throughout the territory. In general, the air temperature increased by almost 1.0°C throughout the year (Osadchyi, V.I., & Babichenko, V.M., 2013). It is important to identify the dynamics of modern changes in air temperature against the background of the age-related temperature trend for the entire observation period (1881-2010), where its long-term increases and decreases are traced. Two periods can be conditionally distinguished: 1881-1946 and 1947-2010. A comparison of these periods showed that in the winter months, the air temperature for 1947-2010 is higher than for 1881-1946, and in the summer it is almost the same for these same periods. In the winter months, a steady trend towards increasing air temperature, which has been observed not only in recent years (1991-2010), but over a long period, has affected the period 1947-2010.

The average annual air temperature in the last almost twenty years has a general upward trend, even though two periods are clearly distinguished in the time distribution: 2000-2006 and 2007-2018. Moreover, in the first case, a slight decrease is observed, and in the second – an increase in the values of this characteristic. In the northern and north-eastern regions of Ukraine, the annual temperature increased by 1.0±0.2°C /100 years; in the southern and south-western regions – only by 0.5±0.1°C /100 years; there is a decrease in the amplitude of the seasonal temperature change by ~0.4-0.5°C: significant warming in the cold period of the year (1.0-2.0°C /100 years), for spring (1.5-2.0°C /100 years); warming was insignificant in the summer months (Boychenko, S. et al., 2016).

Other researchers argue that from 2000 to 2020, the air temperature in Ukraine increased significantly, especially during the warm season, when

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[17] Osadchyi, V.I., & Babichenko, V.M. (2013) Air temperature on the territory of Ukraine in modern climate conditions. Ukrainian Geographical Journal, (4), 32-39. DOI: https://doi.org/10.15407/ugz2013.04.032 [in Ukrainian]

extreme temperatures became more frequent both in the country and worldwide (Pyasetska Svitlana, & Shcheglov Oleksandr, 2023). The changes in the temperature regime observed now are confirmed by changes in atmospheric circulation in Europe, which has led to an increase in the duration of sunshine (Osadchyi, V. et al., 2018) and changes in the characteristics of the radiation balance, including in most regions of Ukraine. (Semenova, I., & Vicente-Serrano, S. M., 2024)[18]. The temperature increase in Europe and Ukraine has been stronger than the global average in recent decades (Rybchenko, L.S., Savchuk, S.V., Timofeev, V.E., & Shcheglov, A.A., 2022)[19]. There has been an increase in the duration and severity of droughts in most regions, especially in the central part of Ukraine, which negatively affects agriculture (Zamfirova, M.S., & Khokhlov, V.M., 2020).

Highlighting previously unresolved parts of the general problem to which the article is devoted. Climate changes with a resolution from seasonal to annual over the past centuries have been highlighted in several studies, which included climate modeling experiments with estimates of natural and anthropogenic radiative changes and empirical reconstructions (IPCC, 2022; Jones, P. D., Briffa, K. R., & Osborn, T. J., 2003[20]; Kundzewicz, Z.W., & Parry, M.L., 2001[21]). Reconstructions of hemispheric and global temperature do not provide information about regional-scale variations, such as the characteristic seasonal patterns of climate change that occurred, in particular, in central Ukraine over the past centuries. Currently, much attention is paid to the study of local (regional) climates, because the trends in air temperature changes are ambiguous in different regions. Therefore, the issue of processing instrumental studies of the climate of central Ukraine over as long a time as possible remains relevant.

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18 Semenova, I., & Vicente-Serrano, S. M. (2024). Long-termvariability and trends of meteorological droughts inUkraine. International Journal of Climatology, 44(6), 1849–1866. DOI: https://doi.org/10.1002/joc.8416

19 Rybchenko, L.S., Savchuk, S.V., Timofeev, V.E., & Shcheglov, A.A. (2022) Dynamics of photosynthetic solar active radiation in Ukraine over 1986-2015. Ukraïns'kij Gìdrometeorologìčnij Žurnal, 30, 12-23 DOI: https://doi.org/10.31481/uhmj.30.2022.02 [in Ukrainian]

20 Jones, P.D., Briffa, K.R., & Osborn, T.J. (2003). Changes in the Northern Hemisphere annual cycle: Implications for paleoclimatology? J. Geophys. Res., 108(D18), 4588, DOI: https://doi.org/10.1029/2003JD003695

21 Kundzewicz, Z. W., & Parry, M. L. (2001). In Climate Change 2001: Impacts. Adaptation, and Vulnerability, J. J. McCarthy et a., Eds. (Cambridge Univ. Press, New York, 2001), 641-692.

The purpose of this study is to analyze data from weather stations in central Ukraine that have the longest continuous or almost continuous observation period (Uman, Kropyvnytskyi, Poltava). This publication is a continuation and generalization of our research on climate change in central Ukraine, which was published in scientific articles (Helevera Olha, Mostipan Mykola, & Topolnyi Sergii, 2023[22]; Helevera Olha, et al., 2024; Helevera, O.F., 2019). The task of the study is to determine: – changes in average annual air temperatures; – changes in average monthly air temperatures in the winter, spring, summer, and autumn seasons; – periods of increase and decrease in temperature indicators throughout the entire period of instrumental observations (139-200 years) in central Ukraine.

Presentation of the main material of the study. To characterize the climate of Central Ukraine, meteorological data from weather stations with the longest continuous or almost continuous observation period were taken. In particular, temperature indicators were analyzed:

1. The weather station in Uman (Cherkasy region), which has coordinates: latitude 48.77 and longitude 30.23, is located at an altitude of 216 m above sea level. The weather station has been operating since 1885 and continuous data for 139 years are available.
2. The weather station in Kropyvnytskyi (Kirovohrad region), has coordinates: latitude 48.52 and longitude 32.20, located at an altitude of 171 m above sea level. The weather station has been operating since 1874, however, meteorological data for 1941-1944 are partially or completely missing. Meteorological data for 150 years were analyzed.
3. The meteorological station in Poltava has coordinates: latitude 49.60 longitude 34.55, located at an altitude of 160 m above sea level. The meteorological station has been operating since 1824, however, meteorological data for 1832-1835, 1858, 1865-1885, and 1941-1943 are partially or completely missing. Meteorological data for 200 years were analyzed.

Several scientists have identified periodic components of climate change, the main one being the eleven-year solar activity cycle (the Schwabe

[22] Helevera Olha, Mostipan Mykola, & Topolnyi Sergii (2023). Winter and spring long – term dynamic of air temperature in Central Ukraine. Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology", (59), 83-94. DOI: https://doi.org/10.26565/2410-7360-2023-59-07 [in Ukrainian]

cycle) (Borovska, H. & Khokhlov, V., 2023). Therefore, in addition to the empirical data, we added eleven-year rolling periods to the graphs.

1.2. Dynamics of average annual air temperatures

Analysis of data from the meteorological station in Uman over 139 years showed the following: the average annual air temperature is +7.68°C. The lowest was recorded in 1942 at +4.8°C. The highest was in 2020 and 2023 at +10.7°C and in 2024 at +11.5°C. According to the linear trend graph, the average annual temperatures for the entire observation period increased from +6.7°C to +8.8°C, i.e. by 2.1 degrees. During the period from 1885 to 1987, there was almost no increase in the average annual temperature. However, from 1989 to 2024, there was a fairly significant increase in temperature, according to the graph of the eleven-year smoothed trend (Fig. 1). The average annual temperatures for the period 1886-1899. were +7.21°C (base period); for the period 1900-1924 they were +7.15°C (-0.060 relative to the base period); from 1925 to 1949 they were +7.15°C (-0.06°C relative to the base period); for the period 1950-1974 they were +7.44°C (+0.24°C relative to the base period); from 1975 to 1999 they were +7.60°C (+0.390 relative to the base period); for the period 2000-2024 they were +9.34°C (+2.13°C relative to the base period).

In Uman, the coldest month for the entire observation period was February 1929 (-16.6°C). The warmest month for the entire observation period was July 2024 (+24.3°C). That is, the amplitude of absolute extremes was 40.9°C.

The last decade is characterized by exceptionally high temperatures compared to the entire observation period: the average annual temperature for the decade (2015-2024): is +9.95°C, which is 2.27°C higher than the average for the entire observation period. 5 out of 10 years of this period are among the 10 warmest years for the entire observation period. 2024 is the warmest year in the entire history of observations with an average annual temperature of +11.5°C. 2020 and 2023 are the next warmest with an average annual temperature of +10.7°C.

Analysis of data from the meteorological station in Kropyvnytskyi for 150 years showed the following: the average annual air temperature is +8.22°C. The lowest was recorded in 1987 at +5.9°C. The highest is +11.0°C in 2020, +11.2°C in 2023, and +12.3°C in 2024. According to the linear trend graph, the average annual temperatures for the entire observation period increased from +7.4°C to +9.2°C, i.e. by 1.8 degrees. During the period from 1874 to 1987, there was almost no increase in the average annual temperature. However, from 1989 to 2024 there was also a fairly significant increase in temperature, according to the graph of the eleven-year smoothed trend (Fig. 1). The average annual temperatures for the period 1875-1899 were +7.64°C (base period); for the period 1900-1924 they were +7.93°C (+0.29°C relative to the base period); from 1925 to 1949 +8.1°C (+0.46°C relative to the base period); for the period 1950-1974 it was +7.96°C (+0.32°C relative to the base period); from 1975 to 1999 it was +8.0°C (+0.360 relative to the base period); for the period 2000-2024 it was +9.65°C (+2.01°C relative to the base period).

In Kropyvnytskyi, the coldest month for the entire observation period was also in February 1929 (-15.2°C). The warmest month for the entire observation period was also in July 2024 (+26.2°C). That is, the amplitude of absolute extremes was 41.4°C.

The last decade is characterized by very high temperatures compared to the entire observation period: the average annual temperature for the decade (2015-2024): is +10.33°C, which is 2.11°C higher than the average for the entire observation period. 5 out of 10 years of this period are among the 10 warmest years for the entire observation period. 2024 is the warmest in the entire history of observations with an average annual temperature of +12.3°C. 2023 is the next warmest year with an average annual temperature of +11.2°C, and 2020 is the next warmest year with an average annual temperature of +11.0°C.

Fig. 1. Average annual temperatures in °C in central Ukraine (Uman, Kropyvnytskyi, Poltava): 1 – empirical data; 2 – eleven-year moving averages; 3 – linear trend.

Source: results of own scientific research.

Analysis of data from the meteorological station in Poltava for 200 years showed the following: the average annual air temperature is +7.35°C. The lowest was recorded in 1840 at +4.6°C. The highest was in 2020 at +10.6°C and in 2024 at +11.4°C. According to the linear trend graph, the average annual temperatures for the entire observation period increased from +5.8°C to +8.8°C, i.e. by 3.0 degrees (from 1886 – from +6.4°C to +8.8°C, i.e. by 2.4 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1824 to 1863 – an increase in temperature; from 1887 to 1933 – slight temperature fluctuations; from 1934 to 1975 – a slight increase in temperature; from 1976 to 1987 – a slight decrease in temperature; from 1989 to 2024 – a rather significant increase in temperature (Fig. 1). The average annual temperatures for the period 1825-1849 were +5.64°C (base period); 1850-1874 +7.2°C (+1.56°C relative to the base period); for the period 1875-1899 they were +6.81°C (+1.17°C relative to the base period); for the period 1900-1924 they were +6.96°C (+1.32°C relative to the base period); from 1925 to 1949 +7.13°C (+1.49°C relative to the base period); for the period 1950-1974 they were +7.45°C (+1.81°C relative to the base period); from 1975 to 1999 +7.64°C (+2.0°C relative to the base period); for the period 2000-2024 it was +9.31°C (+3.67°C relative to the base period).

In Poltava, the coldest month for the entire observation period was also in February 1929 (-17.0°C). The warmest month for the entire observation period was in August 2010 (+25.6°C). That is, the amplitude of absolute extremes was 42.6°C. The last decade is characterized by exceptionally high temperatures compared to the entire observation period: the average annual temperature for the decade (2015-2024): is +9.87°C, which is 2.52°C higher than the average for the entire observation period. 5 out of 10 years of this period are among the 10 warmest years for the entire observation period. 2024 is the warmest in the entire history of observations with an average annual temperature of +11.4°C. 2020 is the next warmest year with an average annual temperature of +10.6°C, and 2023 is the next warmest year with an average annual temperature of +10.2°C. Warming in Poltava (~3°C over 200 years) is occurring faster than the global average (~1°C over the same period), which is consistent with the known fact that continental regions in mid-latitudes exhibit more pronounced climate change than the global average.

Thus, 2024 became the warmest year in the history of meteorological observations at all three weather stations studied. Analysis of the frequency of average monthly extreme temperatures at all three weather stations studied shows the following: there is a significant decrease in the number of months with an average temperature below -10°C (from 2-3 cases per decade in the first half of the 20th century to the almost complete absence of such cases after 2000). At the same time, there is an increase in the number of months with an average temperature above +20°C (from 1-2 cases per decade in the first half of the 20th century to 5-7 cases per decade in the 21st century). The rate of warming has significantly accelerated in recent decades, showing an average increase of +0.4°C per decade in 2000-2020, compared to +0.1°C per decade in the period 1900-1950.

1.3. Characteristics of the winter season

December: The average monthly long-term temperature in December in Uman is -2.64°C. The lowest was recorded in 1890 at -11.3°C. The highest was in 1960 at +3.2°C. According to the linear trend graph, the average monthly temperatures in December for the entire observation period increased from -4.0°C to -1.0°C, i.e. by 3.0 degrees. Analyzing the graph of eleven-year sliding scales, the following periods can be distinguished: from 1885 to 1919 – an increase in temperature; from 1920 to 1934 – a slight decrease in temperature; from 1935 to 1960 – a slight increase in temperature; from 1961 to 2003 – slight temperature fluctuations; from 2004 to 2024 – a slight increase in temperature (Fig. 2). The average December temperatures for the period 1885-1899 were -4.29°C (base period); for the period 1900-1924 they were -2.53°C (+1.76°C relative to the base period); from 1925 to 1949 they were -3.82°C (+0.47°C relative to the base period); for the period 1950-1974 they were -2.15°C (+2.14°C relative to the base period); from 1975 to 1999 they were -2.70°C (+1.59°C relative to the base period); for the period 2000-2024 they were -1.01°C (+3.28°C relative to the base period).

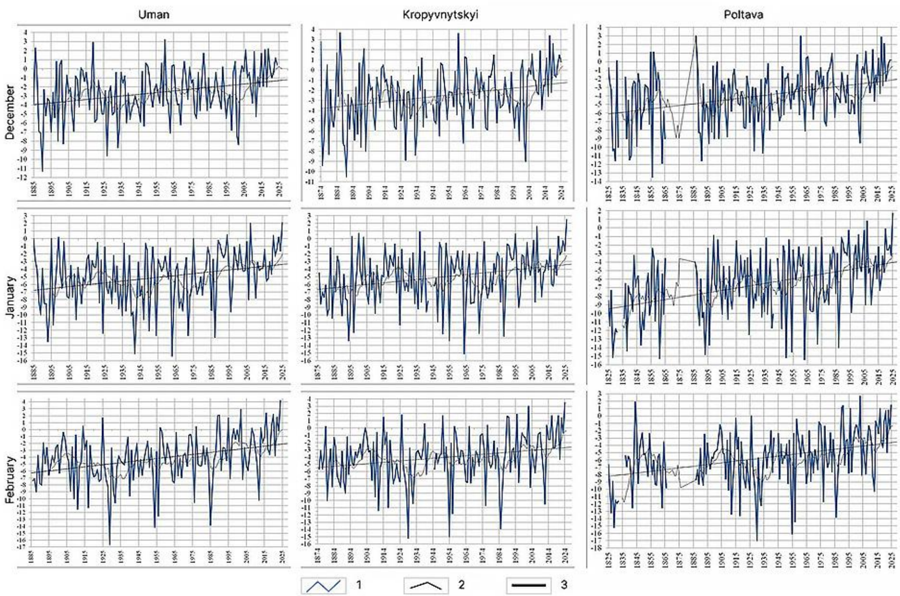

Fig. 2. Average temperatures in °C in the winter months (December, January, February) in central Ukraine (Uman, Kropyvnytskyi, Poltava): 1 – empirical data; 2 – eleven-year moving averages; 3 – linear trend.

Source: results of own scientific research.

In Kropyvnytskyi, the average monthly long-term temperature in December is the highest among the studied weather stations -2.53°C. The lowest was also recorded in 1890 -10.5°C. The highest – in 1886 +3.7°C. According to the linear trend graph, the average monthly temperatures in December for the entire observation period increased from -3.7°C to -1.3°C, i.e. by 2.4°C. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1899 – slight temperature fluctuations; from 1900 to 1918 – slight temperature increase; from 1919 to 1934 – slight temperature decrease; from 1935 to 1960 – slight temperature increase; from 1961 to 2003 – slight temperature fluctuations; from 2004 to 2024 – a slight increase in temperature (Fig. 2). Average December temperatures for the period 1874-1899 were -3.79°C (base period); for the period 1900-1924 they were -2.37°C (+1.42°C relative to the base period); from 1925 to 1949 -3.44°C (+0.35°C relative to the base period); for the period 1950-1974 they were -2.06°C (+1.73°C relative to the base period); from 1975 to 1999 -2.71°C (+1.08°C relative to the base period); for the period 2000-2024 they were -0.87°C (+2.92°C relative to the base period).

In Poltava, the average monthly long-term temperature is the lowest among the studied weather stations -3.98°C. The lowest in 1855 was -13.5°C. The highest was observed in 1960, the same as in Uman, +3.0°C. According to the linear trend graph, the average monthly temperatures in December for the entire observation period increased significantly from -6.0°C to -2.1°C, i.e. by 3.9 degrees (from 1886 – from -4.9°C to -2.1°C, i.e. by 2.8°C). Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1825 to 1860 – an increase in temperature; from 1888 to 1934 – slight temperature fluctuations; from 1936 to 1983 – a slight increase in temperature; from 1985 to 2003 – a slight decrease in temperature; from 2004 to 2024 – an increase in temperature (Fig. 2). The average December temperatures for the period 1824-1849 were -5.81°C (base period); 1850-1874 -4.53°C (+1.280 relative to the base period); for the period 1875-1899 -5.5°C (+0.31°C relative to the base period); for the period 1900-1924 -4.2°C (+1.61°C relative to the base period); from 1925 to 1949 -4.83°C (+0.98°C relative to the base period); for the period 1950-1974 -2.97°C (+2.84°C relative to the base period); from 1975 to 1999 -3.54°C (+2.27°C relative to the base period); for the period 2000-2024 it was -1.61°C (+4.2°C relative to the base period).

At the weather stations of Uman and Kropyvnytskyi for the entire observation period, the lowest average monthly temperatures in December were recorded in 1890, and the highest at the weather stations of Uman and Poltava in 1960. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in average monthly temperatures in December occurred from 2004 to 2024.

January: in Uman, the average monthly long-term temperature is -5.10°C. The lowest was recorded in 1963 at -15.4°C. The highest was in 2007 at +2.0°C and in 2025 at +2.1°C. According to the linear trend graph, the average monthly temperatures in January for the entire observation period increased from -6.5°C to -3.3°C, i.e. by 3.2 degrees. Analyzing the graph of eleven-year sliding scales, the following periods can be distinguished: from 1885 to 1923 – a slight increase in temperature; from 1924 to 1947 – a slight decrease in temperature; from 1948 to 1962 – a slight increase in temperature; from 1963 to 1972 – a slight decrease in temperature; from 1975 to 2025 – a slight increase in temperature (Fig. 2).

The average January temperatures for the period 1886-1899 were -6.41°C (base period); for the period 1900-1924 they were -5.33°C (+1.08°C relative to the base period); from 1925 to 1949 they were -6.36°C (+0.05°C relative to the base period); for the period 1950-1974 they were -6.15°C (+0.26°C relative to the base period); from 1975 to 1999 they were -4.14°C (+2.27°C relative to the base period); for the period 2000-2025 they were -2.88°C (+3.53°C relative to the base period). In Kropyvnytskyi, the average monthly long-term temperature among the studied weather stations is the highest -5.02°C. The lowest was also in 1963 -15.1°C. The highest was also in 2007 at + 1.6°C and in 2025 at +2.5°C. According to the linear trend graph, the average monthly temperatures in January for the entire observation period increased from -6.5°C to -3.50, i.e. by 3.0°C. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1923 – a slight increase in temperature; from 1924 to 1947 – a slight decrease in temperature; from 1948 to 1962 – a slight increase in temperature; from 1963 to 1972 – a slight decrease in temperature; from 1975 to 2025 – a slight increase in temperature (Fig. 2). The average temperatures in January for the period 1875-1899 were -6.56°C (base period); for the period 1900-1924 it was -4.85°C (+1.71°C relative to the base period); from 1925 to 1949 it was -5.4°C (+1.16°C relative to the base period); for the period 1950-1974 it was -5.99°C (+0.57°C relative to the base period); from 1975 to 1999 it was -4.32°C (+2.24°C relative to the base period); for the period 2000-2024 it was -3.08°C (+3.48°C relative to the base period).

In Poltava, the average monthly long-term temperature in January is the lowest among the studied weather stations -6.56°C. The lowest was also observed in 1963 -15.4°C. The highest – also in 2007 + 0.8°C and in 2025 +1.7°C. According to the linear trend graph, the average monthly temperatures in January for the entire observation period increased significantly from -9.3°C to -4.0°C, i.e. by 5.3 degrees (from 1886 – from -7.8°C to -4.0°C, i.e. by 3.8°C). Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1825 to 1860 – an increase in temperature; from 1887 to 1962 – slight temperature fluctuations; from 1963 to 1987 – a slight decrease in temperature; from 1989 to 2025 – a fairly significant increase in temperature (Fig. 2). The average January temperatures for the period 1825-1849 were -9.44°C (base period); 1850-1874 -7.72°C (+1.72°C relative to the base period); for the period 1875-1899 -8.01°C (+1.43°C relative to the base period); for the period 1900-1924 -6.4°C (+3.04°C relative to the base period); from 1925 to 1949 -6.68°C (+2.76°C relative to the base period); for the period 1950-1974 -7.05°C (+2.39°C relative to the base period); from 1975 to 1999 -5.0°C (+4.44°C relative to the base period); for the period 2000-2024 it was -3.81°C (+5.63°C relative to the base period).

At all studied weather stations for the entire observation period, the lowest average monthly temperatures in January were recorded in 1963, and the highest – in 2007 and 2025. For all three weather stations, there are common periods of increases and decreases in temperature, in particular, a decrease in average monthly temperatures in January occurred from 1963 to 1972-1987, and from 1989 to 2025 there was an increase in air temperature.

February: in Uman, the average monthly long-term temperature is -4.19°C. The lowest was recorded in 1929 at -16.6°C. The highest was in 2002 at +2.9°C and in 2024 at +4.2°C. According to the linear trend graph, the average monthly temperatures in February for the entire observation period increased significantly from -6.0°C to -2.2°C, i.e. by 3.8 degrees. Analyzing the graph of eleven-year sliding scales, the following periods can be distinguished: from 1885 to 1904 – a slight increase in temperature; from 1905 to 1932 – a slight decrease in temperature; from 1933 to 1944 – a slight increase in temperature; from 1945 to 1985 – slight temperature fluctuations; from 1987 to 2024 – a slight increase in temperature (Fig. 2). The average February temperatures for the period 1886-1899 were -5.39°C (base period); for the period 1900-1924 they were -4.88°C (+0.51°C relative to the base period); from 1925 to 1949 they were -5.46°C (-0.07°C relative to the base period); for the period 1950-1974 they were -4.47°C (+0.92°C relative to the base period); from 1975 to 1999 they were -3.75°C (+1.59°C relative to the base period); for the period 2000-2024 they were -1.75°C (+3.64°C relative to the base period). In Kropyvnytskyi, the average monthly long-term temperature among the studied weather stations is the highest and is -4.07°C. The lowest was also in 1929 -15.2°C. The highest was also observed in 2002 +3.0°C and in 2024 +3.5°C. According to the linear trend graph, the average monthly temperatures in February for the entire observation period increased from -5.3°C to -2.8°C, i.e. by 2.5°C. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1904 – a slight increase in temperature; from 1905 to 1932 – a slight decrease in temperature; from 1933 to 1946 – a slight increase in temperature; from 1948 to 1985 – slight temperature fluctuations; from 1987 to 2024 – a slight increase in temperature (Fig. 2). Average February temperatures for the period 1875-1899. were -4.84°C (base period); for the period 1900-1924 they were -4.33°C (+0.51°C relative to the base period); from 1925 to 1949 -4.9°C (-0.06°C relative to the base period); for the period 1950-1974 they were -4.34°C (+0.5°C relative to the base period); from 1975 to 1999 -4.01°C (+0.83°C relative to the base period); for the period 2000-2024, they were -2.08°C (+2.76°C relative to the base period).

In Poltava, the average monthly long-term temperature in February is the lowest among the studied weather stations -5.77°C. The lowest was also observed in 1929 -17.0°C. The highest was also in 2002 +2.7°C. According to the linear trend graph, the average monthly temperatures in February for the entire observation period increased significantly from -8.1°C to -3.8°C, i.e. by 4.3 degrees (from 1886 – from -7.0°C to -3.8°C, i.e. by 3.2°C). Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1825 to 1854 – an increase in temperature; from 1904 to 1933 – a decrease in temperature; from 1934 to 1986 – slight fluctuations in temperature; from 1989 to 2024 – a slight increase in temperature (Fig. 2). The average February temperatures for the period 1824-1849 were -7.46°C (base period); 1850-1874 -7.03°C (+0.43°C relative to the base period); for the period 1875-1899 -6.52°C (+0.94°C relative to the base period); for the period 1900-1924 -6.13°C (+1.33°C relative to the base period); from 1925 to 1949 -6.58°C (+0.88°C relative to the base period); for the period 1950-1974 -5.73°C (+1.73°C relative to the base period); from 1975 to 1999 -4.88°C (+2.58°C relative to the base period); for the period 2000-2024 amounted to -2.89°C (+4.57°C relative to the base period).

At all studied weather stations for the entire observation period, the lowest average monthly temperatures in February were recorded in 1929, and the highest in 2002. For all three weather stations, there are common periods of increases and decreases in temperature, in particular, a decrease in average monthly temperatures in February occurred from 1904-1905 to 1932-1933, and from 1987-1989 to 2024 there was a slight increase in air temperature.

In general, the winter season (December-February) for Uman is characterized by the following features:

- Average temperature of winter months: -3.98°C.
- Coldest month: January (-5.10°C).
- Extremely cold winters: 1929 (February: -16.6°C), 1942 (January: -15.1°C), 1963 (January: -15.4°C).

- Extremely warm winters: 2024 (February: +4.2°C), 2020 (January: +0.4°C, February: +2.2°C), 2025 (January: +2.1°C).

The winter season for Kropyvnytskyi is characterized by the following features:

- Average temperature of winter months: -3.87°C.
- Coldest month: January (-5.02°C).
- Extremely cold winters: 1929 (February: -15.2°C), 1954 (February: -15.0°C), 1963 (January: -15.4°C).
- Extremely warm winters: 2024 (February: +3.5°C), 2020 (January: +0.3°C, February: +1.7°C), 2025 (January: +2.5°C).
- The winter season for Poltava is characterized by the following features:
- Average temperature of winter months: -5.43°C.
- Coldest month: January (-6.56°C).
- Extremely cold winters: 1929 (February: -17.0°C), 1954 (February: -16.1°C), 1963 (January: -15.4°C).
- Extremely warm winters: 2024 (February: +1.5°C), 2020 (January: -0.1°C, February: +0.7°C), 2025 (January: +1.7°C).

Thus, the winter season is the warmest in Kropyvnytskyi, and the coldest in Poltava, which is explained by the increase in the continentality of the climate. The duration of winter has decreased by ~20-25 days compared to the beginning of observations. The number of very cold months with average temperatures below -10°C has decreased. The frequency of warm winters with positive average monthly temperatures has increased. The winter season has shown the most pronounced warming, especially in recent decades. The number of "warm winters" (with average temperatures above -2°C) has increased significantly in the 21st century.

1.4. Characteristics of the spring season

March: in Uman, the average monthly long-term temperature is +0.54°C. The lowest was recorded in 1952 at -7.3°C. The highest in 1990 at +6.7°C and in 2014 at +6.6°C. According to the linear trend graph, the average monthly temperatures in March for the entire observation period increased from -1.1°C to +2.2°C, i.e. by 3.3 degrees. Analyzing the graph of eleven-year sliding scales, the following periods can be distinguished: from 1885 to 1921 – a slight increase in temperature; from 1922 to 1932 – a slight decrease in temperature; from 1933 to 1987 – slight fluctuations in temperature; from 1988 to 2024 – a slight increase in temperature (Fig. 3). The average temperatures in March for the period 1886-1899 were -0.49°C (base period); for the period 1900-1924 they were +0.39°C (+0.88°C relative to the base period); from 1925 to 1949 they were -0.65°C (-0.16°C relative to the base period); for the period 1950-1974 they were -0.53°C (-0.04°C relative to the base period); from 1975 to 1999 they were +1.14°C (+1.63°C relative to the base period); for the period 2000-2024 they were +2.95°C (+3.44°C relative to the base period).

In Kropyvnytskyi, the average monthly long-term temperature is the highest among the studied weather stations +0.79°C. The lowest was in 1987 -7.7°C. The highest was observed in 2020 at +6.7°C and in 1990 and 2014 at +6.5°C. According to the linear trend graph, the average monthly temperatures of March for the entire observation period increased from -0.5°C to +2.2°C, i.e. by 2.7 degrees. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1922 – a slight increase in temperature; from 1923 to 1932 – a slight decrease in temperature; from 1933 to 1987 – slight temperature fluctuations; from 1988 to 2024 – a slight increase in temperature (Fig. 3). The average temperatures of March for the period 1875-1899 were -0.26°C (base period); for the period 1900-1924 amounted to +1.07°C (+1.33°C relative to the base period); from 1925 to 1949 to +0.16°C (+0.42°C relative to the base period); for the period 1950-1974 to -0.25°C (+0.010 relative to the base period); from 1975 to 1999 to +1.0°C (+1.26°C relative to the base period); for the period 2000-2024 to +2.96°C (+3.22°C relative to the base period).

In Poltava, the average monthly long-term temperature in March among the studied weather stations is the lowest at -0.55°C. The lowest was observed in 1825 -8.6°C. The highest was also in 2020 at +6.8°C and in 1990 and 2014 at +5.7°C. According to the linear trend graph, the average monthly temperatures in March for the entire observation period increased significantly from -2.5°C to +1.3°C, i.e. by 3.8 degrees (from 1886 – from -1.5°C to +1.30, i.e. by 2.8°C). Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1825 to 1865 – a slight increase in temperature; from 1888 to 1989 – slight temperature fluctuations; from 1990 to 2024 – a slight increase in temperature (Fig. 3). The average temperatures in March for the period 1824-1849 were -2.06°C (base period); 1850-

1874 -1.41°C (+0.65°C relative to the base period); for the period 1875-1899 -1.54°C (+0.52°C relative to the base period); for the period 1900-1924 -0.62°C (+1.44°C relative to the base period); from 1925 to 1949 -1.4°C (+0.66°C relative to the base period); for the period 1950-1974 -1.17°C (+0.89°C relative to the base period); from 1975 to 1999 +0.54°C (+2.6°C relative to the base period); for the period 2000-2024 amounted to +2.28°C (+4.34°C relative to the base period).

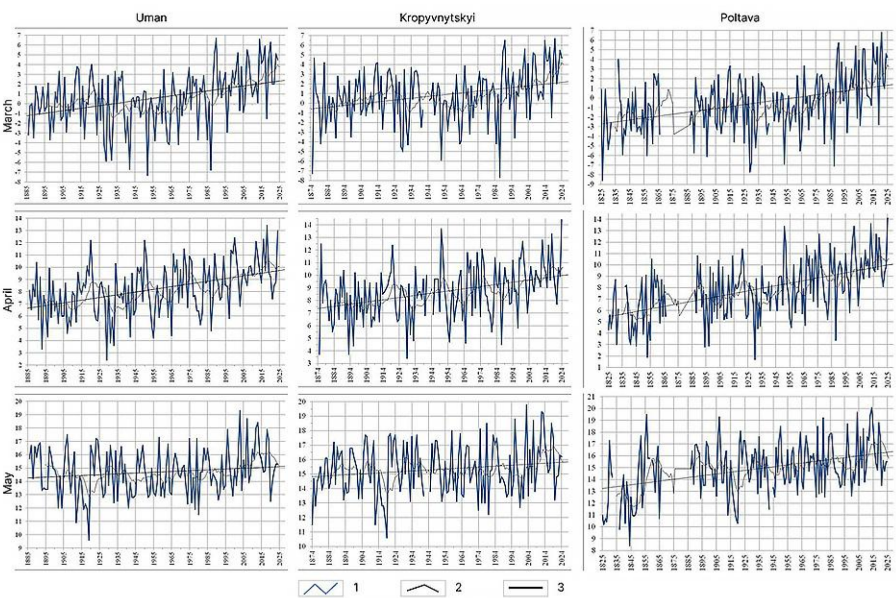

Fig. 3. Average temperatures in °C in the spring months (March, April, May) in central Ukraine (Uman, Kropyvnytskyi, Poltava): 1 – empirical data; 2 – eleven-year moving averages; 3 – linear trend.

Source: results of own scientific research.

At all studied weather stations for the entire observation period, the highest average monthly temperatures in March were recorded in 1990 and 2014. For all three weather stations, there are common periods of temperature increases and decreases, in particular, a slight increase in average monthly temperatures in March occurred from 1988-1990 to 2024.

April: in Uman, the average monthly long-term temperature is +8.19°C. The lowest was recorded in 1929 at +2.4°C. The highest in 2018 was +13.4°C and in 2024 at +13.0°C. According to the linear trend graph, the average monthly temperatures in April for the entire observation period increased from +6.9°C to +9.6°C, i.e. by 2.7°C. Analyzing the graph of eleven-year sliding scales, the following periods can be distinguished: from 1885 to 1912 – slight temperature fluctuations; from 1913 to 1920 – slight temperature increase; from 1921 to 1932 – slight temperature decrease; from 1934 to 1951 – slight temperature increase; from 1952 to 1965 – slight temperature decrease; from 1966 to 1976 – a slight increase in temperature; from 1977 to 1987 – a slight decrease in temperature; from 1988 to 2024 – an increase in temperature (Fig. 3). The average March temperatures for the period 1886-1899 were +7.35°C (base period); for the period 1900-1924 they were +7.44°C (+0.09°C relative to the base period); from 1925 to 1949 +7.35°C; for the period 1950-1974 they were +8.26°C (-0.91°C relative to the base period); from 1975 to 1999 +8.46°C (+1.11°C relative to the base period); for the period 2000-2024 were +9.9°C °C (+2.55°C relative to the base period).

In Kropyvnytskyi, the average monthly long-term temperature among the studied weather stations is the highest at +8.68°C. The lowest was also in 1929 +3.4°C. The highest was observed in 1950 +13.7°C and in 2024 +14.4°C. According to the linear trend graph, the average monthly temperatures in April for the entire observation period increased from +7.4°C to +10.0°C, i.e. by 2.6 degrees. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1912 – slight temperature fluctuations; from 1913 to 1920 – slight temperature increase; from 1921 to 1933 – slight temperature decrease; from 1934 to 1950 – slight temperature increase; from 1952 to 1965 – a slight decrease in temperature; from 1966 to 1976 – a slight increase in temperature; from 1977 to 1987 – a slight decrease in temperature; from 1988 to 2024 – an increase in temperature (Fig. 3). The average April temperatures for the period 1875-1899 were +7.77°C (base period); for the period 1900-1924 they were +8.2°C (+0.43°C relative to the base period); from 1925 to 1949 they were +8.2°C (+0.43°C relative to the base period); for the period 1950-1974 they were +8.7°C (+0.93°C relative to the base period); from 1975 to 1999 they were +8.88°C (+1.11°C relative to the base period); for the period 2000-2024 amounted to +10.27°C (+2.5°C relative to the base period).

In Poltava, the average monthly long-term temperature is the lowest +7.89°C. The lowest was also in 1929 +1.7°C. The highest in 2012 at +13.6°C and in 2024 at +14.1°C. According to the linear trend graph, the average monthly temperatures in April for the entire observation period increased significantly from +5.6°C to +9.9°C, i.e. by 4.3 degrees (from 1886 – from +6.7°C to +9.9°C, i.e. by 3.2°C). Analyzing the graph of eleven-year sliding, we can distinguish five small periods of increase and decrease in temperature with a general tendency to increase in temperature: from 1845 to 1865 – increase in temperature; from 1889 to 1903 – decrease in temperature; from 1904 to 1921 – increase in temperature; from 1924 to 1934 – decrease in temperature; from 1935 to 1951 – increase in temperature; from 1953 to 1966 – decrease in temperature; from 1967 to 1977 – increase in temperature; from 1978 to 1988 – decrease in temperature; from 1990 to 2024 – increase in temperature (Fig. 3). Average April temperatures for the period 1824-1849 were +5.64°C (base period); 1850-1874 were +6.86°C (+1.22°C relative to the base period); for the period 1875-1899 were +7.1°C (+1.46°C relative to the base period); for the period 1900-1924 were +7.6°C (+1.96°C relative to the base period); from 1925 to 1949 +7.19°C (+1.55°C relative to the base period); for the period 1950-1974 it was +8.47°C (+2.83°C relative to the base period); from 1975 to 1999 +8.89°C (+3.25°C relative to the base period); for the period 2000-2024 it was +10.32°C (+4.68°C relative to the base period).

At all studied weather stations for the entire observation period, the lowest average monthly temperatures in April were recorded in 1929, and the highest in 2024. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in average monthly temperatures in April occurred from 1904-1913 to 1920-1921; from 1921-1924 to 1933-1934 there was a decrease in temperature; from 1934-1935 to 1950-1951 – a slight increase in temperature; from 1952-1953 to 1965-1966 – a slight decrease in temperature; from 1966-1967 to 1976-1977 – a slight increase in temperature; from 1977-1988 to 1987-1988 – a slight decrease in temperature; from 1988-1990 to 2024 – an increase in air temperature.

May: in Uman, the average monthly long-term temperature is the lowest among the studied weather stations +14.68°C. The lowest was recorded in 1919 at +9.6°C. The highest was in 2003 +19.3°C and in 2007 +18.7°C. According to the linear trend graph, the average monthly temperatures in May for the entire observation period increased slightly from +14.4°C to

+15.0°C, i.e. by 0.6°C. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1885 to 1919 – a slight decrease in temperature; from 1920 to 1931 – a slight increase in temperature; from 1932 to 1999 – slight temperature fluctuations; from 2000 to 2024 – a slight increase in temperature (Fig. 3). The average temperatures in May for the period 1886-1899 were +15.26°C (base period); for the period 1900-1924 they were +14.16°C (-1.1°C relative to the base period); from 1925 to 1949 they were +14.45°C (-0.81°C relative to the base period); for the period 1950-1974 they were +14.27°C (-0.99°C relative to the base period); from 1975 to 1999 they were +14.55°C (-0.71°C relative to the base period); for the period 2000-2024 they were +15.63°C (+0.37°C relative to the base period).

In Kropyvnytskyi, the average monthly long-term temperature is the highest +15.31°C. The lowest was also in 1919 +10.6°C. The highest was observed in 2003 +19.8°C and 2012 +19.3°C. According to the linear trend graph, the average monthly temperatures in May for the entire observation period increased slightly from +14.8°C to +15.7°C, i.e. by 0.9°C. Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1874 to 1919 – a slight decrease in temperature; from 1920 to 1931 – a slight increase in temperature; from 1932 to 1999 – slight temperature fluctuations; from 2000 to 2024 – a slight increase in temperature (Fig. 3). The average temperatures in May for the period 1874-1899 were +15.03°C (base period); for the period 1900-1924 it was +15.0°C (-0.03°C relative to the base period); from 1925 to 1949 it was +15.48°C (+0.45°C relative to the base period); for the period 1950-1974 it was +15.02°C (-0.01°C relative to the base period); from 1975 to 1999 it was +15.19°C (+0.16°C relative to the base period); for the period 2000-2024 it was +16.14°C (+1.11°C relative to the base period).

In Poltava, the average monthly long-term temperature is +14.89°C. The lowest was in 1843 +8.4°C. The highest was observed in 2013 +20.1°C and in 2003 +19.7°C. According to the linear trend graph, the average monthly temperatures in May for the entire observation period increased from +13.1°C to +16.2°C, i.e. by 3.1 degrees (from 1886 – from +14.2°C to +16.2°C, i.e. by 2.0°C). Analyzing the graph of eleven-year sliding, the following periods can be distinguished: from 1827 to 1866 – an increase in temperature; from 1892 to 1923 – a decrease in temperature; from 1924 to 1987 – slight temperature fluctuations; from 1988 to 2003 – a slight decrease in temperature; from 2004 to 2024 – an increase in temperature

(Fig. 3). The average temperatures in May for the period 1824-1849 were +12.11°C (base period); 1850-1874 +15.25°C (+3.14°C relative to the base period); for the period 1875-1899 they were +15.38°C (+3.27°C relative to the base period); for the period 1900-1924 they were +14.6°C (+2.49°C relative to the base period); from 1925 to 1949 +15.08°C (+2.97°C relative to the base period); for the period 1950-1974 they were +15.14°C (+3.03°C relative to the base period); from 1975 to 1999 +15.33°C (+3.22°C relative to the base period); for the period 2000-2024 it was +16.3°C (+4.19°C relative to the base period).

At all studied weather stations for the entire observation period, the highest average monthly temperatures in May were recorded in 2003. For all three weather stations, there are common periods of increases and decreases in temperature, in particular, a decrease in average monthly temperatures in May occurred until 1919-1923; from 2000-2004 to 2024 – an increase in air temperature.

In general, the spring season (March-May) for Uman is characterized by the following features:

- Average temperature of spring months: +7.8°C.
- Extremely cold springs: 1919 (May: +9.6°C), 1929 (March: -5.9°C, April: +2.4), 1952 (March: -7.3°C).
- Extremely warm springs: 1990 (March: +6.7°C), 2018 (April: +13.4°C), 2003 (May: +19.3°C).

The spring season for Kropyvnytskyi is characterized by the following features:

- Average temperature of spring months: +8.26°C.
- Extremely cold springs: 1919 (May: +10.6°C), 1929 (March: -5.0°C, April: +3.4), 1987 (March: -7.7°C).
- Extremely warm springs: 2020 (March: +6.7°C), 2024 (April: +14.4°C), 2003 (May: +19.8°C).
- The spring season for Poltava is characterized by the following features:
- Average temperature of spring months: +7.41°C.

- Extremely cold springs: 1825 (March: -8.6°C), 1843 (May: +8.4°C), 1852 (April: +1.9°C), 1928 (March: -7.7°C).
- Extremely warm springs: 2020 (March: +6.8°C), 2024 (April: +14.1°C), 2013 (May: +20.1°C).

Thus, the spring season is the warmest in Kropyvnytskyi, and the coldest (except for May) in Poltava, which is explained by the increase in the continentality of the climate. The spring season also shows a warming trend, although less pronounced compared to the winter season. Warming is especially noticeable in March and April.

1.5. Characteristics of the summer season

June: in Uman, the average monthly temperatures among the studied weather stations are the lowest at +17.97°C. The lowest was recorded in 1925 at +14.6°C. The highest was observed in 2019 at +22.4°C. According to the linear trend graph, the average monthly temperatures in June for the entire observation period increased from +17.0°C to +19.1°C, i.e. by 2.1 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1885 to 1921 – a slight decrease in temperature; from 1922 to 1964 – a slight increase in temperature; from 1965 to 1994 – a slight decrease in temperature; from 1995 to 2024 – an increase in temperature (Fig. 4). The average June temperatures for the period 1886-1899 were +17.37°C (base period); for the period 1900-1924 they were +17.34°C (-0.030 relative to the base period); from 1925 to 1949 they were +17.46°C (+0.09°C relative to the base period); for the period 1950-1974 they were +18.07°C (+0.7°C relative to the base period); from 1975 to 1999 they were +17.86°C (+0.49°C relative to the base period); for the period 2000-2024 they were +19.44°C (+2.070 relative to the base period).

In Kropyvnytskyi, the average monthly temperatures are the highest among the studied weather stations +18.96°C. The lowest was observed in 1887 and 1894 +15.4°C. The highest was in 1875 +23.4°C and 2019 +23.0°C. According to the linear trend graph, the average monthly temperatures in June for the entire observation period increased slightly from +18.4°C to +19.5°C, i.e. by 1.1 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1874 to 1921 – a slight decrease in temperature; from 1922 to 1947 – a slight increase in temperature; from 1948 to 1994 – a slight decrease in temperature; from 1995 to 2024 – an increase in temperature (Fig. 4). The average June temperatures for the period 1874-1899 were +18.62°C (base period); for the period 1900-1924 they were +18.62°C; from 1925 to 1949 they were +18.83°C (+0.21°C relative to the base period); for the period 1950-1974 they were +18.91°C (+0.29°C relative to the base period); from 1975 to 1999 they were +18.72°C (+0.10 relative to the base period); for the period 2000-2024 they were +20.01°C (+1.39°C relative to the base period).

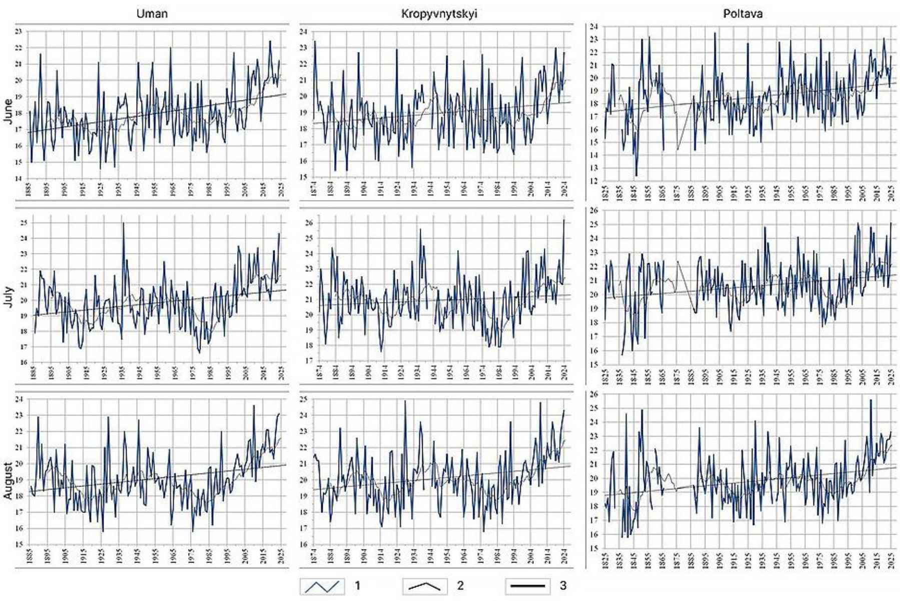

Fig. 4. Average temperatures in °C in the summer months (June, July, August) in central Ukraine (Uman, Kropyvnytskyi, Poltava):
1 – empirical data; 2 – eleven-year moving averages; 3 – linear trend.

Source: results of own scientific research.

In Poltava, the average monthly temperature is +18.56°C. The lowest in 1846 is +12.4°C. The highest in 1901 is +23.5°C and in 2019 is +23.1°C. According to the linear trend graph, the average monthly temperatures in June for the entire observation period increased from +17.1°C to +19.5°C, i.e. by 2.1 degrees (from 1886 – from +18.0°C to +19.5°C, i.e. by 1.5 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1825 to 1934 – temperature fluctuations;

from 1935 to 1957 – a slight increase in temperature; from 1958 to 1995 – a slight decrease in temperature; from 1996 to 2024 – an increase in temperature (Fig. 4). The average June temperatures for the period 1824-1849 were +17.11°C (base period); 1850-1874 +19.35°C (+2.24°C relative to the base period); for the period 1875-1899 they were +17.59°C (+0.48°C relative to the base period); for the period 1900-1924 they were +18.22°C (+1.11°C relative to the base period); from 1925 to 1949 +18.07°C (+0.96°C relative to the base period); for the period 1950-1974 they were +19.03°C (+1.92°C relative to the base period); from 1975 to 1999 +18.83°C (+1.72°C relative to the base period); for the period 2000-2024 amounted to +19.96°C (+2.85°C relative to the base period).

At all studied weather stations for the entire observation period, the highest average monthly temperatures in June were recorded in 2019. For all three weather stations, there are common periods of increases and decreases in temperature, in particular, an increase in average monthly temperatures in June occurred from 1922-1934 to 1947-1957; from 1948-1965 to 1994-1995 there was a decrease in temperature; from 1995-1996 to 2024 – an increase in air temperature.

July: in Uman, the average monthly temperatures are the lowest among the studied weather stations +19.84°C. The lowest was recorded in 1979 at +16.6°C. The highest – in 1936 +25.0°C and in 2024 +24.3°C. According to the linear trend graph, the average monthly temperatures in July for the entire observation period increased from +19.3°C to +20.6°C, i.e. by 1. degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1885 to 1918 – a slight decrease in temperature; from 1920 to 1946 – a slight increase in temperature; from 1947 to 1986 – a slight decrease in temperature; from 1987 to 2024 – an increase in temperature. Average July temperatures for the period 1886-1899. were +20.17°C (base period); for the period 1900-1924 they were +18.92°C (-1.25°C relative to the base period); from 1925 to 1949 they were +19.80°C (-0.37°C relative to the base period); for the period 1950-1974 they were +19.74°C (-0.43°C relative to the base period); from 1975 to 1999 they were +19.03°C (-1.14°C relative to the base period); for the period 2000-2024 they were +21.52°C (+1.35°C relative to the base period).

In Kropyvnytskyi, the average monthly temperatures among the studied weather stations are the highest at +20.95°C. The lowest was observed 1912 at +17.6°C. The highest was also in 1936 at +25.6°C and in 2024 at +26.2°C. According to the linear trend graph, the average monthly temperatures in July for the entire observation period have almost not changed – it was +20.7°C and became +21.4°C, i.e. they increased by 0.7 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1874 to 1918 – a slight decrease in temperature; from 1920 to 1940 – a slight increase in temperature; from 1947 to 1986 – a slight decrease in temperature; from 1987 to 2024 – an increase in temperature. Average July temperatures for the period 1874-1899 were +21.13°C (base period); for the period 1900-1924, they were +20.46°C (-0.67°C relative to the base period); from 1925 to 1949 they were +21.13°C; for the period 1950-1974 they were +20.79°C (-0.34°C relative to the base period); from 1975 to 1999 they were +20.03°C (-1.10 relative to the base period); for the period 2000-2024 they were +22.18°C (+1.05°C relative to the base period).

In Poltava, the average monthly temperature is +20.62°C. The lowest was observed in 1836 at +15.7°C. The highest were in 2001 and 2024 at +25.1°C. According to the linear trend graph, the average monthly temperatures in July for the entire observation period increased from +19.6°C to +21.3°C, i.e. by 1.7 degrees (from 1886 – from +20.1°C to +21.3°C, i.e. by 1.2 degrees). Analyzing the graph of the eleventh smoothed trend, the following periods can be distinguished: from 1825 to 1919 – temperature fluctuations; from 1920 to 1942 – a slight increase in temperature; from 1945 to 1967 – slight temperature fluctuations; from 1969 to 1986 – a decrease in temperature; from 1988 to 2024 – an increase in temperature (Fig. 4). The average July temperatures for the period 1824-1849 were +19.53°C (base period); 1850-1874 +20.98°C (+1.45°C relative to the base period); for the period 1875-1899 they were +20.64°C (+1.11°C relative to the base period); for the period 1900-1924 they were +20.0°C (+0.47°C relative to the base period); from 1925 to 1949 +20.79°C (+1.26°C relative to the base period); for the period 1950-1974 they were +20.87°C (+1.34°C of the base period); from 1975 to 1999 +20.06°C (+0.53°C relative to the base period); for the period 2000-2024 it was +22.14°C (+2.61°C of the base period).

At all studied weather stations for the entire observation period, the highest average monthly temperatures in July were recorded in 2024. For all three weather stations, there are common periods of increase and increase in temperature, in particular, an increase in average monthly temperatures in July occurred from 1920 to 1940-1946; from 1947-1969 to 1986, a decrease in temperature was observed; from 1987-1988 to 2024 – an increase in air temperature.

August: in Uman, the average monthly temperatures among the studied weather stations are the lowest at +19.08°C. The lowest was recorded in 1926 and 1976 at +16.8°C. The highest was in 2010 at +23.6°C and in 2024 at +23.1°C. According to the linear trend graph, the average monthly temperatures in August for the entire observation period increased from +18.4°C to +19.7°C, i.e. by 1.3 degrees. Analyzing the graph of the eleventh smoothed trend, the following periods can be distinguished: from 1885 to 1917 – a slight decrease in temperature; from 1920 to 1946 – a slight increase in temperature; from 1947 to 1985 – a slight decrease in temperature; from 1986 to 2024 – an increase in temperature. The average August temperatures for the period 1886-1899 were +19.41°C (base period); for the period 1900-1924 they were +18.31°C (-1.10 relative to the base period); from 1925 to 1949 they were +19.0°C (-0.41°C relative to the base period); for the period 1950-1974 they were +18.76°C (-0.65°C different base periods); from 1975 to 1999 they were +18.32°C (-1.090 relative to the base period); for the period 2000-2024, they were +20.86°C (+1.45°C base period). In Kropyvnytskyi, the average monthly temperature is the highest among the studied weather stations +20.10°C. The lowest was also observed in 1976 at +16.8°C. The highest was in 1929 at +24.9°C, in 2010 at +24.8°C, and 2024 at +24.3°C. According to the linear trend graph, the average monthly temperatures in August for the entire observation period increased slightly from +19.4°C to +20.6°C, i.e. by 1.2 degrees. Analyzing the graph of the eleventh smoothed trend, the following periods can be distinguished: from 1874 to 1916 – a slight decrease in temperature; from 1917 to 1946 – a slight increase in temperature; from 1947 to 1985 – a slight decrease in temperature; from 1986 to 2024 – an increase in temperature. The average temperatures in August for the period 1874-1899 were +19.92°C (base period); for the period 1900-1924 it was +19.5°C (-0.42°C relative to the base period); from 1925 to 1949 it was +20.26°C (+0.34°C relative to the base period); for the period 1950-1974 it was +19.81°C (-0.11°C relative to the base period); from 1975 to 1999 it was +19.43°C (-0.49°C relative to the base period); for the period 2000-2024 it was +21.71°C (+1.79°C relative to the base period).

In Poltava, the average monthly temperature is +19.83°C. The lowest in 1836 and 1840 is +15.8°C. The highest in 2010 is +25.6°C and in 1929 is +24.9°C. According to the linear trend graph, the average monthly temperatures in August for the entire observation period slightly increased from +18.9°C to +20.8°C, i.e. by 1.9 degrees (from 1886 – from +19.1°C to +20.8°C, i.e. by 1.7 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1825 to 1901 – temperature fluctuations; from 1902 to 1920 – a slight decrease in temperature; from 1920 to 1939 – a slight increase in temperature; from 1940 to 1964 – slight temperature fluctuations; from 1968 to 1985 – temperature decrease; from 1990 to 2024 – temperature increase (Fig. 4). Average August temperatures for the period 1824-1849 were +18.62°C (base period); 1850-1874 +20.31°C (+1.69°C relative to the base period); for the period 1875-1899 they were +19.83°C (+1.21°C relative to the base period); for the period 1900-1924 they were +19.12°C (+0.50 relative to the base period); from 1925 to 1949 +19.83°C (+1.21°C relative to the base period); for the period 1950-1974 were +19.9°C (+1.28°C relative to the base period); from 1975 to 1999 +19.33°C (+0.71°C relative to the base period); for the period 2000-2024 they were +21.75°C (+3.13°C relative to the base period).

For all three weather stations, there are common periods of temperature increases and decreases, in particular, a decrease in the average monthly temperatures of August occurred in 1916-1920; from 1917-1920 to 1939-1946 – a slight increase in temperature; from 1947-1968 to 1985 – a slight decrease in temperature; from 1986-1990 to 2024 – an increase in air temperature.

In general, the summer season (June-August) for Uman is characterized by the following features:

- Average temperature of summer months: +18.96°C.
- Warmest month: July (+19.84°C).
- Extremely warm summers: 1936 (July: +25.0°C), 2010 (August: +23.6°C), 2024 (July: +24.3°C).
- Extremely cold summers: 1925 (June: +14.6°C), 1926 and 1976 (August: +15.8°C), 1979 (July: +16.6°C).

The summer season for Kropyvnytskyi is characterized by the following features:

- Average temperature of summer months: +20.0°C.
- Warmest month: July (+20.95°C).
- Extremely warm summers: 1875 (June: +23.4°C), 1929 (August: +24.9°C), 2010 (August: +24.8°C), 2024 (July: +26.2°C).

- Extremely cold summers: 1887 and 1894 (June: +15.4°C), 1912 (July: +17.6°C), 1915 (August: +17.1°C), 1933 (June: +15.6°C).

The summer season for Poltava is characterized by the following features:

- Average temperature of the summer months: +19.67°C.
- The warmest month: July (+20.62°C).
- Extremely warm summers: 1855 (June: +23.2°C), 1936 (July: +24.8°C), 2010 (August: +25.6°C), 2001 and 2024 (July: +25.1°C).
- Extremely cold summers: 1844 (June: +14.1°C), 1836 (July: +15.7°C, August: +15.8°C), 1840 (August: +15.8°C).

Thus, the summer season is the warmest in Kropyvnytskyi and the coldest in Uman. The summer season shows a steady warming trend, especially after 2000. The increase in maximum temperatures in July and August is especially noticeable. There is a lengthening of the summer season with average daily temperatures above 20°C.

1.6. Characteristics of the autumn season

September: in Uman, the average monthly temperatures are the lowest among the studied weather stations +14.04°C. The lowest was recorded in 1959 at +10.8°C. The highest – in 1909 +18.3°C, in 2023 +18.4°C and 2024 +19.4°C. According to the linear trend graph, the average monthly temperatures in September for the entire observation period have almost not changed – it was +13.6°C, and now +14.4°C, that is, they have increased by 0.8 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished; from 1885 to 1954 – slight temperature fluctuations; from 1956 to 1966 – slight temperature decrease; from 1967 to 2000 – slight temperature fluctuations; from 2001 to 2024 – a increase in temperature (Fig. 5). The average September temperatures for the period 1885-1899 were +14.26°C (base period); for the period 1900-1924 they were +13.72°C (-0.54°C relative to the base period); from 1925 to 1949 they were +14.03°C (-0.37°C relative to the base period); for the period 1950-1974 they were +13.56°C (-0.70 relative to the base period); from 1975 to 1999 they were +13.58°C (-0.68°C relative to the base period); for the period 2000-2024 they were +15.17°C (+0.91°C relative to the base period).

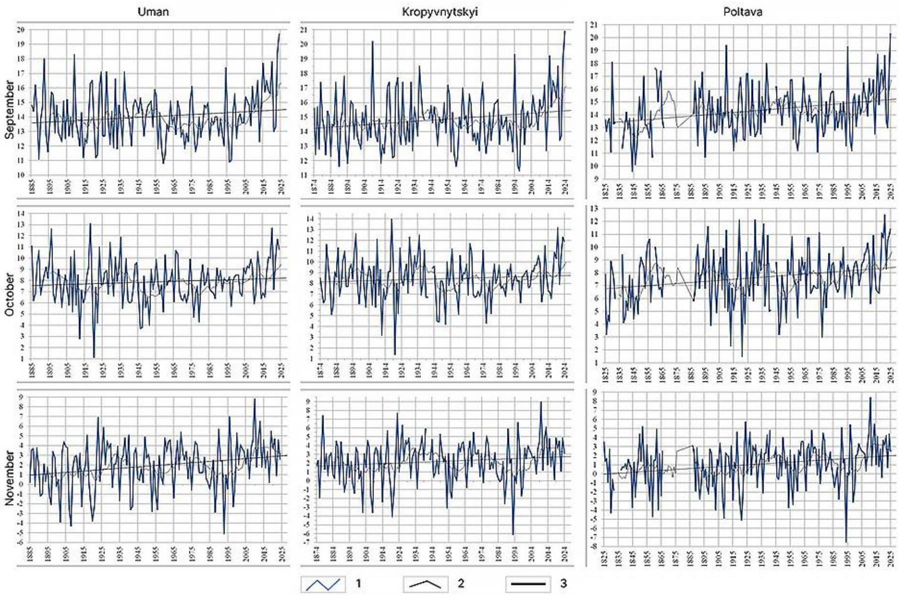

Fig. 5. Average temperatures in °C in the autumn months (September, October, November) in central Ukraine (Uman, Kropyvnytskyi, Poltava): 1 – empirical data; 2 – eleven-year moving averages; 3 – linear trend.

Source: results of own scientific research.

In Kropyvnytskyi, the average monthly temperatures among the studied weather stations are the highest +14.82°C. The lowest was observed in 1997 +11.3°C. The highest was also in 1909 at +20.2°C and in 2024 at +20.9°C. According to the linear trend graph, the average monthly temperatures in September for the entire observation period have almost not changed – it was +14.4°C, and now it is +15.4°C, that is, they have increased by 1.0 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished; from 1874 to 1954 – slight temperature fluctuations; from 1955 to 1966 – slight temperature decrease; from 1967 to 1997 – slight temperature fluctuations; from 1999 to 2024 – temperature increase (Fig. 5). The average September temperatures for the period 1874-1899 were +14.53°C (base period); for the period 1900-1924 they were +14.54°C (+0.010 relative to the base period); from 1925 to 1949 they were +14.9°C (+0.37°C relative to the base period); for the period 1950-1974 they were +14.5°C (-0.03°C relative to the base period); from 1975 to 1999 they were +14.53°C; for the period 2000-2024 they were +15.94°C (+1.41°C relative to the base period).

In Poltava, the average monthly temperature is +14.34°C. The lowest in 1843 is +9.6°C. The highest is also in 1909 +19.4°C and 2024 +20.9°C. According to the linear trend graph, the average monthly temperatures in September for the entire observation period increased slightly from +13.5°C to +15.1°C, i.e. by 1.6 degrees (from 1886 – from +14.0°C to +15.1°C, i.e. by 1.1 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1825 to 1997 – slight temperature fluctuations; from 1999 to 2024 – an increase in temperature (Fig. 5). The average September temperatures for the period 1824-1849 were +13.0°C (base period); 1850-1874 +14.51°C (+1.51°C relative to the base period); for the period 1875-1899 it was +14.44°C (+1.44°C relative to the base period); for the period 1900-1924 it was +14.13°C (+1.13°C relative to the base period); from 1925 to 1949 it was +14.42°C (+1.42°C relative to the base period); for the period 1950-1974 it was +14.31°C (+1.31°C relative to the base period); from 1975 to 1999 it was +14.19°C (+1.19°C relative to the base period); for the period 2000-2024 it was +15.68°C (+2.68°C relative to the base period).

At all studied weather stations, the highest average monthly temperatures in September for the entire observation period were recorded in 2024. For all three weather stations, there are common periods of temperature increases and decreases, in particular, from 1999-2001 to 2024 – an increase in air temperature.

October: in Uman, the average monthly temperature is +7.88°C. The lowest was in 1920 +1.1°C. The highest was recorded in 1918 at +13.1°C and in 2020 at +12.7°C. According to the linear trend graph, the average monthly temperatures in October for the entire observation period have almost not changed – it was +7.8°C, and became +8.1°C, that is, they increased by 0.3 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1885 to 1915 – a slight decrease in temperature; from 1917 to 1935 – a slight increase in temperature; from 1936 to 1951 – a slight decrease in temperature; from 1952 to 1966 – a slight increase in temperature; from 1967 to 2024 – slight temperature fluctuations. The average October temperatures for the period 1885-1899 were +8.51°C (base period); for the period 1900-1924 they were +7.32°C (-1.19°C relative to the base period); from 1925 to 1949 they were

+7.75°C (-0.76°C relative to the base period); for the period 1950-1974, they were +7.65°C (-0.86°C relative to the base period); from 1975 to 1999 they were +7.52°C (-0.99°C relative to the base period); for the period 2000-2024 they were +8.77°C (+0.26°C relative to the base period). In Kropyvnytskyi, the average monthly temperatures are the highest among the studied weather stations +8.44°C. The lowest was also observed in 1920 +1.4°C. The highest was in 1918 +14.0°C and 2020 +13.2°C. According to the linear trend graph, the average monthly temperatures in October for the entire observation period have almost not changed – it was +8.3°C, and became +8.4°C, that is, they increased by 0.4 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1874 to 1915 – a slight decrease in temperature; from 1917 to 1935 – a slight increase in temperature; from 1936 to 1951 – a slight decrease in temperature; from 1952 to 1966 – a slight increase in temperature; from 1967 to 2024 – slight temperature fluctuations. Average October temperatures for the period 1874-1899. were +8.54°C (base period); for the period 1900-1924 they were +8.02°C (-0.52°C relative to the base period); from 1925 to 1949 they were +8.58°C (+0.04°C relative to the base period); for the period 1950-1974 they were +8.24°C (-0.3°C relative to the base period); from 1975 to 1999 they were +7.94°C (-0.6°C relative to the base period); for the period 2000-2024 they were +9.3°C (+0.76°C relative to the base period).

In Poltava, the average monthly temperatures among the studied weather stations are the lowest +7.63°C. The lowest was also in 1920 +1.5°C. The highest was in 1918 at +12.1°C and 2020 at +12.5°C. According to the linear trend graph, the average monthly temperatures in October for the entire observation period increased slightly from +6.7°C to +8.3°C, i.e. by 1.6 degrees (from 1886 – from +7.30 to +8.30, i.e. by 1.0 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1825 to 1860 – a slight increase in temperature; from 1898 to 1923 – a decrease in temperature; from 1924 to 1939 – an increase in temperature; from 1940 to 1952 – a decrease in temperature; from 1953 to 2024 – a slight increase in temperature (Fig. 5). The average October temperatures for the period 1824-1849 were +6.32°C (base period); 1850-1874 +8.17°C (+1.85°C relative to the base period); for the period 1875-1899 they were +7.95°C (+1.63°C relative to the base period); for the period 1900-1924 they were +7.08°C (+0.76°C relative to the base period); from 1925 to 1949 +7.56°C (+1.24°C relative to the base period); for the period 1950-1974 they were +7.78°C (+1.46°C relative to the base period); from

1975 to 1999 +7.42°C (+1.1°C relative to the base period); for the period 2000-2024 it was +8.95°C (+2.63°C relative to the base period).

At all studied weather stations for the entire observation period, the lowest average monthly temperatures in October were recorded in 1920, and the highest in 1918 and 2020. For all three weather stations, there are common periods of increases and decreases in temperature, in particular, a decrease in average monthly temperatures in August occurred in 1915-1923; from 1917-1924 to 1935-1939 – a slight increase in temperature; from 1936-1940 to 1951-1952 – a slight decrease in air temperature.

November: in Uman, the average monthly temperature is +1.93°C. The lowest was recorded in 1993 at -5.1°C. The highest was in 2010 at +8.8°C. According to the linear trend graph, the average monthly temperatures in November for the entire observation period increased slightly from +1.0°C to +2.8°C, i.e. by 1.8 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished; from 1885 to 1922 – slight temperature fluctuations; from 1923 to 1934 – slight temperature increase; from 1935 to 1959 – slight temperature decrease; from 1960 to 1969 – slight temperature increase; from 1970 to 1993 – slight temperature decrease; from 1994 to 2024 – temperature increase. The average November temperatures for the period 1885-1899 were +1.19°C (base period); for the period 1900-1924 they were +0.95°C (-0.24°C relative to the base period); from 1925 to 1949 they were +2.26°C (+1.07°C relative to the base period); for the period 1950-1974 they were +2.07°C (-0.880 relative to the base period); from 1975 to 1999 they were +1.27°C (+0.08°C relative to the base period); for the period 2000-2024 they were +3.54°C (+2.35°C relative to the base period).

In Kropyvnytskyi, the average monthly temperatures are the highest among the studied weather stations +2.20°C. The lowest was observed in 1993 -6.1°C. The highest – in 2010 +9.0°C. According to the linear trend graph, the average monthly temperatures in November for the entire observation period have almost not changed – it was +1.8°C, and became +2.8°C, that is, they increased by 1.0 degrees. Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished; from 1874 to 1922 – slight temperature fluctuations; from 1923 to 1934 – slight temperature increase; from 1935 to 1959 – slight temperature decrease; from 1960 to 1969 – slight temperature increase; from 1970 to 1993 – slight temperature decrease; from 1994 to 2024 – temperature increase. Average November temperatures for the period 1874-1899. were +1.87°C (base period); for the period 1900-1924 they were +1.38°C (-0.49°C relative to the base period); from 1925 to 1949 they were +3.14°C (+1.27°C relative to the base period); for the period 1950-1974 they were +2.16°C (+0.29°C relative to the base period); from 1975 to 1999 they were +1.3°C (-0.57°C relative to the base period); for the period 2000-2024 they were +3.44°C (+1.57°C relative to the base period).

In Poltava, the average monthly temperatures among the studied weather stations are the lowest at +1.07°C. The lowest in 1993 was -7.5°C. The highest was observed in 2010 +8.4°C. According to the linear trend graph, the average monthly temperatures in November for the entire observation period increased slightly from +0.0°C to +1.9°C, i.e. by 1.9 degrees (from 1886 – from +0.3°C to +1.9°C, i.e. by 1.6 degrees). Analyzing the graph of the eleven-year smoothed trend, the following periods can be distinguished: from 1825 to 1921 – slight temperature fluctuations; from 1922 to 1945 – temperature increase; from 1946 to 1960 – slight temperature decrease; from 1961 to 1973 – slight temperature increase; from 1974 to 1994 – a slight decrease in temperature; from 1995 to 2024 – a slight increase in temperature (Fig. 5). The average November temperatures for the period 1824-1849 were +0.43°C (base period); 1850-1874 +0.61°C (+0.18°C relative to the base period); for the period 1875-1899 they were +0.35°C (+0.08°C relative to the base period); for the period 1900-1924 they were +0.15°C (+0.28°C relative to the base period); from 1925 to 1949 +1.83°C (+1.4°C relative to the base period); for the period 1950-1974 they were +1.3°C (+0.87°C relative to the base period); from 1975 to 1999 +0.55°C (+0.12°C relative to the base period); for the period 2000-2024 it was +2.85°C (+2.42°C relative to the base period).

At all studied weather stations for the entire observation period, the lowest average monthly temperatures in November were recorded in 1993, and the highest in 2010. For all three weather stations, there are common periods of temperature increases and decreases, in particular, from 1922-1923 to 1934-1945 – a slight increase in temperature; from 1935-1946 to 1959-1960 – a slight decrease in temperature; from 1994-1995 to 2024 – an increase in air temperature.

In general, the autumn season (September-November) for Uman is characterized by the following features:

- Average temperature of autumn months: +7.95°C.
- Extremely warm autumns: 1918 (October: +13.1°C), 2010 (November: +9.0°C), 2024 (September: +19.7°C).
- Extremely cold autumns: 1912 (October: +2.8°C), 1920 (October: +1.1°C), 1959 (September: +10.8°C), 1993 (November: -5.1°C).

The autumn season for Kropyvnytskyi is characterized by the following features:

- Average temperature of autumn months: +8.49°C.
- Extremely warm autumns: 1918 (October: +14.0°C), 2010 (November: +8.8°C), 2024 (September: +20.9°C).
- Extremely cold autumns: 1920 (October: +1.4°C), 1959 (September: +11.6°C), 1993 (November: -5.1°C), 1997 (September: +11.3°C).

The autumn season for Poltava is characterized by the following features:

- Average temperature of autumn months: +7.68°C.
- Extremely warm autumns: 2010 (November: +8.4°C), 2020 (October: +12.5°C), 2024 (September: +20.3°C).
- Extremely cold autumns: 1920 (October: +1.5°C), 1843 (September: +9.6°C), 1993 (November: -7.5°C).

So, the autumn season is the warmest in Kropyvnytskyi and the coldest (except September) in Poltava. The autumn season shows a moderate warming trend. The greatest warming is observed in September and November. A noticeable extension of the warm period.

Conclusions. Analysis of data from weather stations in central Ukraine for the entire observation period showed the following: average annual temperatures increased from 1.8°C in Kropyvnytskyi, 2.1°C in Uman to 3.0°C (since 1886 – 2.4°C) in Poltava. The highest average annual air temperatures at all weather stations were recorded in 2019, 2020, 2023, and 2024. The most stable in terms of temperature indicators (the least temperature increase) is the autumn months. Over the entire observation period, average monthly temperatures in September increased from 0.8 degrees in Uman, 1.0°C in Kropyvnytskyi to 1.6°C (since 1886 – 1.1°C) degrees in Poltava.

The average monthly temperatures in October increased from 0.3°C in Kropyvnytskyi, 0.4°C in Uman to 1.6 (since 1886 – 1.0°C) degrees in Poltava. The average monthly temperatures in November increased from 1.0 degrees in Kropyvnytskyi, 1.8°C in Uman to 1.9°C (since 1886 – 1.6°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in average monthly autumn temperatures occurred from 1999-2001 to 2024.

The summer months are quite stable in terms of temperature indicators. Over the entire observation period, the average monthly temperatures in June increased from 1.1 degrees in Kropyvnytskyi, 2.1°C (since 1886 – 1.5°C) in Poltava to 2.1°C in Uman. The average monthly temperatures in July increased from 0.7 degrees in Kropyvnytskyi, 1.3°C in Uman to 1.7 (since 1886 – 1.2°C) degrees in Poltava. The average monthly temperatures in August increased from 1.2°C in Kropyvnytskyi, 1.3°C in Uman to 1.9 degrees (since 1886 – 1.7°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the decrease in average monthly summer temperatures occurred from 1947-1969 to 1985-1995; and from 1986-1996 to 2024 – an increase in air temperature.

The spring months are less stable in terms of temperature indicators. Over the entire observation period, the average monthly temperatures in March increased from 2.7 degrees in Kropyvnytskyi, 3.3°C in Uman to 3.8 (since 1886 – 2.8°C) degrees in Poltava. The average monthly temperatures in April increased from 2.6 degrees in Kropyvnytskyi, 2.7°C in Uman to 4.3 (since 1886 – 3.2°C) degrees in Poltava. The average monthly temperatures in May increased from 0.6 degrees in Uman, 0.9°C in Kropyvnytskyi to 3.1 (since 1886 – 2.0°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, a slight increase in average monthly spring temperatures occurred from 1988-1990 to 2024.

The most unstable in terms of temperature indicators (temperatures increased the most) are the winter months. Over the entire observation period, average monthly temperatures in December increased by 2.4 degrees in Kropyvnytskyi, 3.0°C in Uman to 3.9 degrees (since 1886 – 2.8°C) in Poltava. Average monthly temperatures in January increased by 3.0°C in Kropyvnytskyi, 3.2°C in Uman, and up to 5.3 degrees (since 1886 – 3.8°C) in Poltava. The average monthly temperatures in February increased by 2.5 degrees in Kropyvnytskyi, 3.8°C in Uman to 4.3 (since 1886 – 3.2°C) degrees in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in the average monthly temperatures of the winter months occurred from 1987-1989 to 2024. The growth rate of the average annual temperature significantly accelerated at the beginning of the 21st century. Abnormally warm years: 2019, 2020, 2023, and 2024 became the warmest for the entire observation period, which confirms the global warming trend. The year 2024 attracts particular attention, demonstrating extremely high temperatures in all seasons and setting new temperature maximums.

In terms of months, for all three weather stations studied, the smallest temperature increase occurred in October (from 0.3°C in Uman, 0.4°C in Kropyvnytskyi, to 1.6 (since 1886 – 1.0°C) degrees in Poltava. The largest temperature increase for Uman and Kropyvnytskyi occurred in February (2.5°C in Kropyvnytskyi, 3.9°C – in Uman) and for Poltava – in January – 4.3 degrees (since 1886 – 3.2°C). Geographical patterns in the dynamics of the increase in both average annual and average monthly temperatures were identified: the smallest temperature increase occurred in the southernmost city – Kropyvnytskyi (from 0.4°C in October to 2.5°C in February over 150 years). and the largest temperature increase occurred in the northernmost and easternmost city – Poltava (from 1.6°C in October to 4.3°C in January over 200 years). That is, in the territory of central Ukraine, the temperature increase trends increase from south to north.

Analyzing the graphs of eleven-year sliding scales, one can notice the presence of periods of increase-decrease in average monthly temperatures, lasting about 33 years, or doubled periods lasting about 66 years. Due to the lack of meteorological data for a longer period, such patterns are quite difficult to detect, however, this is a promising direction for further research.

These climate changes are consistent with the general patterns of global climate change but are manifested more intensively, which is typical for the continental climate of temperate latitudes. Climate change has important consequences for agriculture, ecosystems, and the livelihoods of the population of central Ukraine and requires further monitoring and adaptation measures.

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Abstract

The climatic indicators of central Ukraine for the entire period of instrumental observations have been analyzed, in particular, air temperature indicators according to weather stations in the cities of Uman, Kropyvnytskyi, and Poltava. At all weather stations, a trend towards increasing average annual air temperatures and temperatures in individual months is observed. In particular, in Uman, average annual temperatures for the entire period of observations (139 years) increased from +6.7°C to +8.8°C, i.e. by 2.1 degrees. In Kropyvnytskyi, average annual temperatures for the entire period of observations (150 years) increased from +7.4°C to +9.2°C, i.e. 1.8 degrees. In Poltava, average annual temperatures over the entire observation period (200 years) increased from +5.8°C to +8.8°C, i.e. by 3.0 degrees (from 1886 – from +6.4°C to +8.8°C, i.e. by 2.4 degrees). At all weather stations, the most significant increase in average annual temperatures occurred in the period from 1989 to 2024.

The greatest increase in temperature occurred in the winter months. Over the entire observation period, the average monthly temperatures in December increased from 2.4 degrees in Kropyvnytskyi, 3.0 degrees in Uman to 3.9 degrees (since 1886 – 2.8°C) in Poltava. The average monthly temperatures in January increased from 3.0°C in Kropyvnytskyi, 3.2°C in Uman to 5.3 degrees (since 1886 – 3.8°C) in Poltava. The average monthly temperatures in February increased from 2.5 degrees in Kropyvnytskyi, 3.8°C in Uman to 4.3°C (since 1886 – 3.2°C) degrees in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in the average monthly temperatures of the winter months occurred from 1987-1989 to 2024.

Air temperatures in the spring months also increased significantly. Over the entire observation period, the average monthly temperatures in March increased from 2.7 degrees in Kropyvnytskyi, 3.3°C in Uman to 3.8 (since 1886 – 2.8°C) degrees in Poltava. The average monthly temperatures in April increased from 2.6 degrees in Kropyvnytskyi, 2.7 in Uman to 4.3 (since 1886 – 3.2°C) degrees in Poltava. The average monthly temperatures in May increased by 0.6 degrees in Uman, 0.9 in Kropyvnytskyi to 3.1 (since 1886 – 2.0°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, a slight increase in average monthly spring temperatures occurred from 1988-1990 to 2024.

The air temperatures of the summer months have increased quite noticeably. Over the entire observation period, the average monthly temperatures of June have increased from 1.1°C in Kropyvnytskyi, 2.1 (since 1886 – 1.5°C) – in Poltava to 2.1°C in Uman. The average monthly temperatures of July have increased from 0.7°C in Kropyvnytskyi, 1.3°C – in Uman to 1.7 (since 1886 – 1.2°C) degrees in Poltava. The average monthly temperatures of August have increased from 1.2°C – in Kropyvnytskyi, 1.3°C – in Uman to 1.9°C (since 1886 – 1.7°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, the increase in average monthly summer temperatures occurred from 1999-2001 to 2024.

The temperatures of the autumn months have increased the least. Over the entire observation period, the average monthly temperatures in September increased from 0.8 degrees in Uman, 1.0°C in Kropyvnytskyi to 1.6 (since 1886 – 1.1°C) degrees in Poltava. The average monthly temperatures in October increased from 0.3°C in Uman, and 0.4°C in Kropyvnytskyi to 1.6 (since 1886 – 1.0°C) degrees in Poltava. The average monthly temperatures in November increased from 1.0 degrees in Kropyvnytskyi, 1.8°C in Uman to 1.9 (since 1886 – 1.6°C) in Poltava. For all three weather stations, there are common periods of temperature increases and decreases, in particular, a decrease in average monthly summer temperatures occurred from 1947-1969 to 1985-1995; from 1986-1996 to 2024 – an increase in air temperature.

Keywords: climate, temperature, average monthly air temperature, territory of Ukraine, regional climate changes, seasons.

UDC 677.07-048.445, 664.661.2:005.591.6

Chapter 2.

SCIENTIFIC FOUNDATIONS OF COMPLEX PROCESSING AND USE OF STALKS AND SEEDS OF FLAX OIL

Olha Horach

2.1. Introduction

This monograph is devoted to highlighting the modern achievements of scientists in Ukraine and abroad on the issue of the comprehensive use of oil flax in the field of studying the anatomical, morphological and technological properties of seeds, straw and fiber of oil flax, processing seeds into biologically active substances and food products, developing innovative technologies for obtaining flax fiber and using it for the production of technical textiles. Oil flax crops in Ukraine and in the world are growing significantly. The increase in the area sown under this crop is explained by the fact that oil flax seeds have found wide use in the pharmaceutical industry abroad and in Ukraine to produce biologically active additives. Flaxseed oil contains 16-24% protein, many amino acids, alpha-linolenic acid Omega-3 and Omega-6, which are of great importance in the treatment of cancer, mineral supplements, trace elements and vitamins, as well as phytoreagents that have antioxidant and medicinal properties.

Flaxseed is currently very popular as a food supplement. Bakery products with the addition of flaxseed acquire a delicate taste, due to the large amount of fat, and an attractive crust. Studies have shown that the consumption of bread enriched with flaxseeds reduces cholesterol by 7-9% within four weeks. The possibility of using flaxseed flour for the preparation of gluten-free confectionery has also been proven. Analyzing the world experience in the use of flaxseed and oil, we can conclude that the scope of their application is expanding every year and has a rapid growth trend. This is explained by the unconditional value of the seeds, namely the presence of nutrients.

Production and scientific research indicate the prospects and economic feasibility of expanding the area of oil flax shown. But, unfortunately, the stems of this crop are practically not used. Oil flax straw is most often burned in the field. It is believed that it contains a small amount of fiber and its extraction is unprofitable. Therefore, at present, technologies for primary processing straw into bast, technologies for obtaining trusts and fiber have not been developed. But, as world experience in using oil flax straw shows, it is a valuable raw material for obtaining various types of products for many industries. Therefore, in modern conditions, the problem of developing new resource– and energy-saving technologies for processing oil flax straw stems has arisen, the use of which will solve the problems associated with the shortage of raw materials and energy reserves and will contribute to reducing the costs of producing various products.

The monograph is devoted to the issue of the integrated use of oil flax. To achieve the set goal, the following tasks were solved in the work: to study the domestic and world market for the production of oil flax, to give a general and agro-technological characteristic of oil flax, to analyze the world and domestic experience in the use of oil flax, to study the use of oil flax fiber for the production of technical textiles, to consider the problems and prospects of the production of technical textiles in Ukraine, to analyze the use of oil flax seeds in the food industry and to determine the methods of producing oil from oil flax seeds.

The scientific novelty of the monograph lies in the fact that, based on theoretical data and experimental studies, the feasibility of the integrated use of oil flax in industry has been substantiated. The possibility of using oil flax fiber in the production of technical textiles, oil flax seeds in food preparation technologies for enriching the nutritional composition of recipes and as biologically active additives has been scientifically substantiated.

Considering the above, the issue of the integrated use of flax oil is of particular relevance, since its implementation will contribute to increasing the profitability of growing flax oil and solving the problem of the crisis state of the domestic energy sector and providing raw materials for many industries. The integrated use of flax oil in industry will also allow solving problems associated with the shortage of raw materials obtained from industrial crops: long flax, cotton, hemp, etc. However, the use of flax oil as a raw material for obtaining cellulose-containing materials is possible provided that its physical and mechanical properties meet the requirements of the technology to produce industrial materials. These properties of flax raw materials must be formed under certain growing conditions and at certain stages of the technological process of its primary processing when using world innovative technologies for its integrated processing.

2.2. General and agro-technological characteristics of oil flax

Oil flax is a valuable technical crop with many uses (Fig. 1). Its botanical name Linum usitatissimum means «the most useful. Oil flax seeds (Fig. 2) contain 40-50% fat, which dries quickly (iodine value – 175-195), forming a thin, smooth, shiny film. The high-quality oil obtained from it is widely used in many industries: in the paint and varnish industry to produce natural drying oil, varnishes, enamels, various paints for underwater work; electrical, aviation, automotive, shipbuilding, foundry, metalworking, medical, perfumery and cosmetic, etc. Linseed oil is indispensable in the production of lithographic paints, linoleum, oilcloth, waterproof fabrics. Sometimes fresh flaxseed oil in its natural form is used as a food product.

Flax is an important medicinal plant. Flaxseed oil is used in the diet of patients with impaired fat metabolism, diabetes, atherosclerosis, ischemic heart disease, brain disease, hypertension, etc.[1]

Oilseed production waste – cake and oilcake – is a valuable concentrated feed containing up to 1.2 feed units, 31-38% digestible protein and about 9% fat. In terms of feed qualities, it surpasses other plants, because it is easily digested by animals.

Fig. 1. Flax seed

Source: Internet resource Liktravy. Access mode https://liktravy.ua/herbs/lonu-nasinnja

[1] Gorach, O., Dombrovska, O., Tikhosova, A. (2021). Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering. Vol. 65(3), 275-282. https://doi.org/10.35633/inmateh-65-29

Fig. 2. Boxes with flax seeds

Source: Proposal – The main magazine on agribusiness. Access mode – https://propozitsiya.com/ua/lon-oliynyy-osoblyvosti-vyroshchuvannya

As a result of research by several scientists of the last century, it was proven that the yield of fiber from oil flax is from 10.5 to 16.6% of the mass of all straw. If we assume that the average fiber yield is 12%, and the straw yield is 8.5 $c \cdot ha^{-1}$, then from one hectare of flax after processing you can get about a hundredweight of fiber. Straw, which contains up to 50% cellulose, is a raw material to produce cigarette paper and cardboard. From the waste of flax fiber production – flaxseed – by pressing, you can make boards that are used as a building material. In addition, flaxseed briquettes are high-quality fuel[2].

Flax has been part of human life since ancient times: in India, China, Egypt, and Transcaucasia it was used 3-4 thousand years BC. In fragments of fused buildings in Switzerland, dating back to the Stone Age, flax stalks

2 Nguyen, T.T, Indraratna, B, (2023). Natural fibre for geotechnical applications: concepts, achievements and challenges. Sustainability 15(11):8603. https://doi.org/10.3390/su15118603

with boxes and seeds, remains of flax fabrics, threads, ropes were found. 5 thousand years BC in Egypt flax was a well-known crop – mummies were wrapped in linen cloth. Ancient Slavic tribes also knew this crop well and knew how to make yarn from flax fiber, and oil from seeds. Flax began to be sown in the territory of modern Ukraine in the 6th century AD. During the time of Kievan Rus, all tribes were engaged in flax growing, according to chroniclers. In the 12th-16th centuries, flax became the main technical crop of all Russian principalities, was widely used in trade with overseas countries, and a state duty was imposed on it. According to FAO, the area shown for oil flax worldwide is almost 3.5 million hectares.

Flax is cultivated in many countries of the world (Fig. 3). More than 70% of the flax sown areas in the world are occupied by oil flax. Recently, Canada and the USA have been developing oil flax production very intensively[3]. Information on the areas shown under oilseed flax is presented in Table 1.

Fig. 3. Flax-growing countries (shaded)

Source: Scientific development of innovative technologies of obtaining composite materials from oilseed flax fibers. Access mode – http://vat.ft.tul.cz/2021/4/VaT_2021_4_4.pdf.

[3] Gorach, O., Dombrovska, O., Tikhosova, A. (2021). Scientific development of innovative technologies of obtaining composite materials from of oilseed flax fibers Vlákna a textil. Vol. 28(4), 25-30. http://vat.ft.tul.cz/2021/4/VaT_2021_4_4.pdf

Table 1. Flaxseed sowing areas in the world

Country name	Area, thousand hectares	Country name	Area, thousand hectares
Worldwide	3489,786	Mexico	0,002
Europewide	598,111	Nepal	55,000
By country:		Netherlands	4,000
Austria	4,000	New Zealand	0,500
Argentina	101,000	Pakistan	7,974
Afghanistan	39,000	Poland	3,724
Bangui	68,820	Russian Federation	61,250*
Belarus	70,000	Romania	2,504
Belgium	10,000	Slovakia	0,322
Bulgaria	0,058	United Kingdom	101,000
Brazil	17,000	United States	135,170
Hungary	0,200	Tunisia	2,200
Germany	110,048	Turkey	0,300
Egypt	15,000	Uzbekistan	3,000
India	930,000	Ukraine	26,000
Iraq	0,590	Uruguay	2,500
Iran, Islamic Republic of	0,744	France	44,500
Spain	91,000	Croatia	0,015
Italy	1,000	Czech Republic	2,017
Kazakhstan	50,000	Chile	1,000
Canada	811,500	Sweden	14,100
Kenya	0,900	Ecuador	0,075
China	570,000	Eritrea	3,000
Latvia	2,200	Estonia	0,323
Lithuania	6,100	Ethiopia	71,000

Source: Scientific development of innovative technologies of obtaining composite materials from oilseed flax fibers. Access mode – http://vat.ft.tul.cz/2021/4/VaT_2021_4_4.pdf.

Analyzing the data given in Table 1, we can conclude that the leading producers of oil flax in the world are now Canada, China, India, Argentina, the USA and Russia. The total gross seed harvest in these countries is 1.2 million tons. World experience in using oil flax straw shows that it has a wide range of applications. In Ukraine, this crop was unjustifiably forgotten for many years due to the socio-political processes that have taken place in our country for centuries. Today, oil flax is returning to Ukraine[4]. A large range of varieties, their diversity, and high profitability contribute to the rapid spread and annual increase in the area shown under this crop.

Flax is one of the few promising niche crops, the economic potential of which for agribusiness remains almost unknown. In the world in agriculture, this crop has been known for a long time, but in recent years it has been almost forgotten by domestic agribusiness. Both long flax and oil flax are grown in our conditions. Long flax is a spinning crop, the stems of which form fibers with valuable technological properties, namely flexibility, fineness and high strength. Oil flax is a crop from which raw materials to produce industrial oil are obtained. Flax also has a special agrotechnical value as the best precursor for winter cereals. In addition to the above, flax seeds are in demand as a useful dietary supplement, and its cake has a high feed value compared to others.

First, this crop is in high demand among traders on the market due to the high oil content of the seeds, which on average for different varieties ranges from 44% to 50%, and among farmers – due to the yield of up to 2.0-2.5 $t \cdot ha^{-1}$ and higher with low production costs during cultivation and minimal use of pesticides. Purchase prices for flax are less dependent on seasonal fluctuations and market conditions, unlike sunflower or soybean. The same applies to export prices, which are almost an order of magnitude higher than traditional grain and oilseed crops[5]. Table 2 shows the import and export of flax seeds by Ukrainian enterprises according to the analysis of customs statistics.

4 Anusudha, V., Sunitha, V., Mathew, S. (2020). Performance of coir geotextile reinforced subgrade for low volume roads. Int J Pavement Res Technol. https://doi.org/10.1007/s42947-020-0325-4

5 Gorach, O. (2023). Current state of production and prospects of the use of oily flax seed in the food industry. Intellectual and technological potential of the XXI century: Innovative technology, Computer science, cybernetics and automation, Architecture and construction, Chemistry and pharmaceuticals. Monographic series «European Science». Book 23. Part 1, 41-59. https://doi.org/10.30890/2709-2313.2023-23-01-014

Table 2. Import and export of flax seeds by Ukrainian enterprises

Years	Import volume, tons	Cost, $ thousand	Average import price of 1 ton, $	Export volume, tons	Cost, $ thousand.	Average export price of 1 ton, $
2011	137	110	802,92	10694	18640	1743,03
2012	184	162	880,43	22684	44956	1981,84
2013	84	45	535,71	7087	10935	1542,97
2014	75	83	1106,67	10221	22106	2162,80
2015	127	142	1118,11	12389	29462	2378,08
2016	133	134	1007,52	15300	44089	2881,63
2017	134	72	537,31	19394	56919	2934,88
2018	569	1522	2674,87	5878	12909	2196,16
2019	227	486	2140,97	5887	11269	1914,22

Source: Current state of production and prospects of the use of oily flax seed in the food industry. Access mode – DOI: 10.30890/2709-2313.2023-23-01

Analyzing the data in Table 2, we can conclude that today there is a significant demand in the global agricultural market for domestic flax seeds, which are purchased in many countries of the world at an attractive price. In 2016-2017, the average annual export price of 1 ton of flax seeds reached almost $ 3,000, while for rapeseed, for example, it did not exceed $ 394.8-412.7. The advantages of growing oil flax include firstly, that oil flax is not demanding on natural conditions. Flax is cold-resistant, so it is sown immediately after spring barley. Flax seeds begin to germinate at a soil temperature of 3-5°C, and at 7-8°C it can sprout in 5-7 days. Shoots withstand short-term frosts down to -3-4°C. Secondly, oil flax loves moisture, but tolerates drought well. The advantage of flax is its drought resistance due to the peculiarities of its root system. This is due to arid climatic conditions. Thirdly, it does not break. The growing season lasts 84-86 days. Seed moisture is not a problem. Although the harvest begins in August, it can stand until mid-late September. At the same time, it does not crumble. Fourthly, there is a small amount of seed material. The standard flax sowing rate is 4.5-5 million seeds·ha^{-1}, 30-35 kg·ha^{-1}. However, some practicing farmers stated that the rates could be reduced.

The disadvantages of flax cultivation include firstly, oil flax has high requirements for soil fertility. Flax has a higher yield on black soil, and it is not recommended to sow flax on heavily waterlogged and saline soils. In addition, it is recommended to plant crops mainly on soil with sufficient nutrient content. Secondly, oil flax is a crop with a small leaf area and cannot compete with weeds. Therefore, special attention should be paid to prevention and control before and after sowing. Thirdly, plant protection methods. Crops are sprayed to protect against pests such as fusarium, anthracnose, rust and flax flea. Affected flax crops are sprayed with herbicides from a tank mix. Fourth, flax needs fertilizer. Sulfur is added to the soil before planting. Phosphorus and potassium fertilizers are applied during the main plowing, and nitrogen fertilizers in the spring. Flax requires compliance with agricultural cultivation techniques. In addition, they will differ for different agroclimatic conditions[6].

Based on the advantages and disadvantages of growing oilseed flax, we can conclude that flax is a profitable crop, the cultivation of which is cheaper than traditional oilseed crops. However, it is necessary to develop your own cultivation strategy, which will allow you to get high yields. The issue of selling seed material remains unresolved. On the one hand, the price of flax is higher, but at the same time it is mainly an export crop. Therefore, traditionally, logistics costs and risks will fall on the farmers' wallets and reduce profitability.

The dynamics of the sown areas allocated for oilseed flax in Ukraine are shown in Fig. 4, Table. 3.

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6 Amna Pervaiz, Farooq Azam, Ahsan Ahmad. (2024). Investigation of Static and Dynamic Mechanical Properties of Eco-Friendly Textile PLA Composites Reinforced by Flax Woven Fabrics International Journal of Polymer Science. https://doi.org/10.1155/ijps/2821777

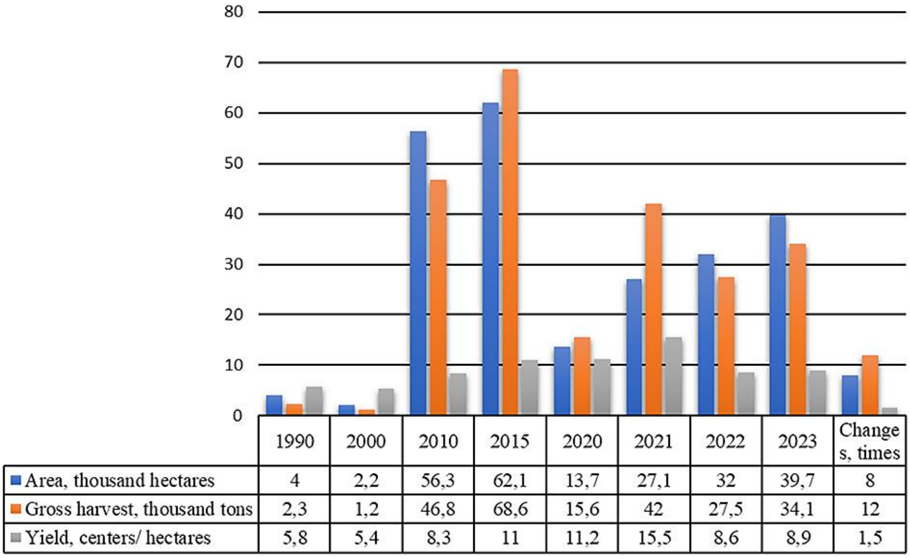

Fig. 4. Dynamics of sown areas allocated for oilseed flax in Ukraine

Source: according to the State Statistics Service of Ukraine. Access mode – https://www.ukrstat.gov.ua/

Table 3. Production of oil flax in Ukraine

Year	Area, thousand hectares	Gross harvest, thousand tons	Yield, centers/ hectares
1990	4,0	2,3	5,8
2000	2,2	1,2	5,4
2010	56,3	46,8	8,3
2015	62,1	68,6	11,0
2020	13,7	15,6	11,2
2021	27,1	42,0	15,5
2022	32,0	27,5	8,6
2023	39,7	34,1	8,9
Changes, times	8	12	1,5

Source: according to the State Statistics Service of Ukraine. Access mode – https://www.ukrstat.gov.ua/

The above diagram shows that there is a tendency to a rapid increase in the area sown under oil flax, but, unfortunately, this valuable crop is not fully used by industry. This is primarily due to the lack of technology for preparing straw from oil flax, which would allow obtaining fiber with new technological characteristics, suitable for use in many industries.

In recent years, in the south of Ukraine, such an unconventional crop as oil flax has been introduced into crop rotations. This is due to the fact that oil flax seeds can be an alternative to the seeds of other oil crops.

Oil flax has proven itself to be a drought-resistant, early ripening crop, resistant to lodging and cracking of the pods. In addition, the crop has proven to be a good precursor for winter crops.

Breeders of the Institute of Oilseed Crops of the Ukrainian Academy of Sciences have created a pipeline of technical varieties with different growing periods, which are characterized by a high oil content of 47-50% and a potential yield of up to 25 $c \cdot ha^{-1}$.

The Register of Plant Varieties Suitable for Distribution in Ukraine contains 52 varieties of flax, including long flax – 23 varieties, common winter flax – 1 variety, common spring flax – 1 variety, curly flax – 27 varieties, as well as 11 varieties of flax of foreign selection, which makes up 21% of their total number. Below is a description of some modern varieties of oilseed flax[7].

The Iceberg variety has been in the Register of Plant Varieties of Ukraine since 2001; it was created at the Institute of Oilseeds of the Ukrainian Academy of Sciences by the method of induced mutagenesis by irradiating seeds of the Tsian variety with gamma rays. The height of the plants is 54-57 cm. The duration of the growing season is 86-88 days. The variety is distinguished by its drought resistance and resistance to lodging of plants. In field experiments of the Institute of Agriculture of the Southern Region of the Ukrainian Academy of Sciences (2004), its seed yield was 20.8-21.8 $c \cdot ha^{-1}$. It is recommended for cultivation in the steppe zone of Ukraine.

The Vera variety was created at the Askaniyske State Agricultural and Food Plantation. It is positioned as a food variety. Plant height is 48-52 cm. The duration of the growing season is 75-88 days. Drought-resistant,

7 State Register of Plant Varieties Suitable for Distribution in Ukraine [Electronic resource]. Access mode: https://sops.gov.ua/ua/derzavnij-reestr

resistant to lodging of plants and disease. Average seed yield – 1.7-1.9 $t \cdot ha^{-1}$. Potential yield – up to 25 $c \cdot ha^{-1}$.

The VNIIMK variety was created by individual selection from a hybrid combination. Plant height – 61 cm, duration of the growing season – 88-92 days. Fiber productivity – 70-94 $g \cdot m^{-2}$. Fiber content is about 15%. The degree of damage by fusarium is very low, high resistance to lodging.

The Zolotysty variety was created by induced mutagenesis. Plant height – 65 cm. Duration of the growing season – 88-90 days. It has characteristic distinguishing features – chlorophyll deficiency of the plant apex throughout the growing season, white corolla and yellow seeds. Drought-resistant, resistant to lodging of plants and disease damage. Since 2005, the Zolotysty variety has been included in the State Register of Plant Varieties Suitable for Distribution in Ukraine.

The variety Debut has been in the Register of Plant Varieties of Ukraine since 2001; created at the Institute of Oil Crops of the UAAS by the method of individual selection from a variety sample from the collection of the Institute of Oil Crops of the UAAS. Plant height is 57-58 cm. The duration of the growing season is 85-87 days. The bush is compact, the stem is weakly branched. The variety is distinguished by its resistance to lodging of plants and shedding of seeds. It is characterized by high potential productivity. In field experiments of the Institute of Agriculture of the Southern Region of the Ukrainian Academy of Sciences since 2004, the seed yield is 23.7-27.2 $c \cdot ha^{-1}$. Recommended for cultivation in the steppe zone of Ukraine.

The Kivik variety has been included in the Register of Plant Varieties of Ukraine since 2007. It was created by the method of individual selection from a mutant line obtained by induced mutagenesis. The Kivik variety is distinguished by the changed chemical composition of the oil in the seeds, namely, a low content of linolenic acid and the presence of up to 40% oleic acid. Therefore, it is positioned as a food variety. Resistant to drought and diseases. It has a bright purple color of flowers. Plant height is 50-60 cm. The duration of the growing season is 75-83 days. The average seed yield is 1.7-1.9 $t \cdot ha^{-1}$. The potential yield is 25.3 $c \cdot ha^{-1}$.

The variety Pivdenna nich has been in the Register of Plant Varieties of Ukraine since 2001; it was created at the Institute of Oilseeds of the Ukrainian Academy of Sciences by the method of microgametophytic selection from a hybrid combination. The height of the plants is 52-55 cm. The duration of the growing season is 84-86 days. The variety is distinguished by its resistance to drought and lodging of plants. It is characterized by high potential productivity. In the demonstration experiment of the DPDG "Askaniyske" (2004), the seed yield was 18.0 $c \cdot ha^{-1}$, and in field experiments of the Institute of Agriculture of the Southern Region of the Ukrainian Academy of Sciences (2004) – 22.0-24.3 $c \cdot ha^{-1}$.

The Orpheus variety has been in the Register of Plant Varieties of Ukraine since 2002; it was created at the Institute of Oilseed Crops of the Ukrainian Academy of Sciences by individual selection from a hybrid composition. Plant height is 55-60 cm. The duration of the growing season is 86-88 days. The variety is distinguished by high resistance to shedding, resistant to lodging of plants. It is characterized by high potential productivity. Yield is 22.7 $c \cdot ha^{-1}$.

The Rucheek variety is a mid-ripening variety of oil flax. Highly productive, with a high oil content in seeds. The period from full germination to technical ripeness of seeds is 80-85 days. Resistant to fusarium. The optimal plant density is 500-600 $pcs \cdot m^{-2}$. Well adapted to various soil and climatic conditions. Potential seed yield and maximum yield in production are up to 25 $c \cdot ha^{-1}$.

Lights of Dniprohesu (2018). Mid-ripening. The duration of the growing season is 88 days. The marker trait is chlorophyll deficiency of the plant from the beginning of the growing season to ripening. The height of the plants is 50-51 cm. The weight of 1000 seeds is 7.7 g. The oil content in the seeds is 48-49%. The linolenic acid content in the oil is 70%. The potential yield is 2.0 $t \cdot ha^{-1}$. The variety is technological, does not lodge, does not crumble. Recommended for cultivation in all soil and climatic zones of Ukraine.

Zhivinka (2018). Mid-ripening, drought-resistant. The duration of the growing season reaches 88 days. The flower is medium-sized, the color of the corolla petals is blue, the anthers are blue, the seeds are moderately brown. The height of the plants is 50-52 cm. The weight of 1000 seeds is 5.5-6.2 g. The oil content in the seeds is 47%. It has a potential yield of about 1.8-2.0 $t \cdot ha^{-1}$. The food variety is characterized by a reduced content of linolenic acid in the oil (25.9%) and an increased content of oleic (20.6%) and linoleic (43.6%) acids. The variety is technological, does not settle, does not crumble, is suitable for mechanized cultivation.

Zaporizhia Bogatyr (2018). Mid-ripening. The duration of the growing season is 90–91 days. The height of the plants is 52 cm. Large-seeded, weight of 1000 seeds – 9.8 g. The oil content in the seeds is 49.5%.

The linolenic acid content in the oil is 65%. The potential yield is about 2.1-2.5 $t \cdot ha^{-1}$. The variety is technological, does not lodge, does not crumble. Recommended for cultivation in all soil and climatic zones of Ukraine.

Patritsii (2018). Mid-ripening, drought-resistant. The duration of the growing season is 86-87 days. Marker features are a semi-collapsed degree of flower opening, purple corolla petals and yellow seed color. Plant height is 50-55 cm. The weight of 1000 seeds is 7.0-7.2 g. The oil content in the seeds reaches 48%. The potential yield can be 2.0-2.5 $t \cdot ha^{-1}$. Technical variety, linolenic acid content in oil – 68.4%. Technological variety, does not lodge, does not crumble, suitable for mechanized cultivation.

Dobrodar (2022) Variety characteristics: seed yield – 2.5 $t \cdot ha^{-1}$, weight of 1000 seeds – 8.4 g, oil content in seeds – 48.1%, linolenic acid content in oil – 55.25%, linoleic acid – 11.51%, oleic acid – 23.24%. The duration of the growing season is 80-85 days, plant height – 58-69 cm. It is distinguished by high (9 points) resistance to lodging, drought, and shedding. Due to wild plasma, it has high (7-8 points) resistance to pathogens (fusarium wilt, rust, streak, anthracnose) and damage by pests (flax flea, flax thrips, flax fruit fly). Does not contain GMO structures. Recommended for cultivation in the Forest-Steppe and Steppe zones.

Linsan (2022). Variety characteristics: seed yield – 2.0 $t \cdot ha^{-1}$, weight of 1000 seeds – 5.1 g, oil content in seeds – 42.3%, changed ratio of unsaturated fatty acids in oil (reduced content of linolenic acid – 3.01%, increased content of linoleic – 72.32%, oleic – 16.90%). The duration of the growing season is 85-87 days, plant height – 55-68 cm. It has high (9 points) resistance to lodging, drought, and shedding. It is distinguished by a combination of distinctive (marker) morphological features – white color of corolla petals and spotted yellow-brown seeds. Does not contain GMO structures. It is recommended for cultivation in the Forest-Steppe and Steppe zones.

According to analysts' forecasts, the area of oilseed crops will be expanded due to their greater profitability compared to cereals, oilseed flax is no exception, remaining a niche crop.

The sown area may be the largest in the last 6 years. Current weather conditions give reason to expect a yield above the average for the last three years. The flax harvest is expected to be 40-41 thousand tons[8].

[8] Varietal resources of oilseed flax [Electronic resource]. Access mode: https://propozitsiya.com/ua/sortovi-resursi-lonu-oliynogo

The reason for the increase in the sown area is that flax does not require large capital investments, since its cultivation is 1.1-1.3 times cheaper than sunflower production. At a price of 12 thousand $t \cdot ha^{-1}$ and a yield of 0.7-0.8 $t \cdot ha^{-1}$, its profitability is positive.

Unfortunately, the market for counterfeit seeds in Ukraine is large: many producers grow flax varieties of unknown origin and with questionable seed quality. This affects the crop yield and the final price of the grown product[9].

Experts from the Research Institute of Oilseeds noted that high-quality and certified seeds produced as commercial flax are sold at lower prices, as a result of which farmers lose the yield of this crop. According to industry experts, one of the main tasks in growing flax is the varietal purity of seed material. Experts carry out two types of cleaning of flax crops: the first – during the flowering period, when the color of the flowers of the main varieties disappears, it is possible to distinguish impurities from other varieties, the second – at the early yellow stage of ripening, taking into account the height of the plant, the shape of the bush and the yield obtained. In accordance with current instructions, crop varieties are tested at the stage of full flowering of the plant.

Varietal renewal on the farm's seed plot occurs once every three years with seeds of the first reproduction of the entire area. The seeds must be free from weeds, sorted, disease-free, not less than the third time of reproduction, high-quality, with high germination up to 1000 seeds. Using most of the seeds for sowing helps to increase germination rates in the field. It is forbidden to sow seeds affected by the weevil. Seeds of quarantine weeds and live pests and their larvae are not allowed in the sowing materials.

One of the main reasons why it is worth taking care of growing flax for oil is the economic component. Due to the high oil content of 45-50% and the potential yield of 2.0-2.5 $t \cdot ha^{-1}$, oil flax is a highly profitable crop and very attractive to agricultural producers.

Growing oil flax does not require large material costs, since the cost of growing it is on average 1.1-1.3 times cheaper than production sunflower. The cost price per hectare is 8-10 thousand UAH, and the profit per hectare

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[9] Horach, O.O., Dombrovska, O.P., Chursina, L.A. (2021). Innovative directions of using oilseed flax and ecological safety of food products. Collective monograph “Formation of a new paradigm of the development of the agro-industrial sector in the 21st century”. Vol. 2. Kherson, 593-619. doi:10.30890/2709-2313.2023-23-01

reaches 8.0-11.5 thousand UAH per ton and the yield is 0.7-0.8 centners/hectare, so the profitability is positive[10].

A prerequisite for the development of resource-saving technologies for processing oil flax straw is a more in-depth study of the anatomical, morphological structure and chemical composition of oil flax and long flax stems. Knowing the morphological structure of the stems, it is possible to predict the fiber yield and its quality characteristics, and accordingly its functional purpose, within certain limits.

The stem is the productive part of flax. There are general and technical stem lengths. The first is measured by the distance from the place of attachment of the cotyledons to the top of the capsule, the highest located in the inflorescence, the second – from the place of attachment of the cotyledons to the beginning of the branching of the inflorescence.

The two groups of flax – oil flax and long flax – differ greatly from each other in the length and thickness of the stem.

It is known that fiber with higher quality indicators is obtained from thinner stems. Flax stems with a diameter of 1.1-1.3 mm are considered thin if their length exceeds 80-85 cm, and thick if their length is 50-55 cm. The stems of the studied varieties of oil flax with an average technical length of 44 cm have a diameter of 1.3 mm in the middle part, therefore they are thick. In long-stemmed flax, the length of the technical part of the stem is 60-90 cm, and the thickness is 0.8-1.2 mm, therefore it is classified as a thin-stemmed plant. The ratio between the length and thickness of the stems determines the value of such indicators as compactness and convergence.

The ratio of the thickness of the stem to its length is called convergence, and the ratio of the length of the stem to its thickness is called compactness. The results of studies by many scientists show that compactness and convergence characterize the content and quality of fiber in the stems. The anatomical structure of the stem largely depends on its external properties: total and technical length, thickness, branching, length of the branched part, color, degree of development of the root system, etc. The high content of wood in the stems affects the specific content of fiber in them, therefore, in stems with a wide cross-section, the fiber content is lower than in thin stems.

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10 Umair, M., Ullah, T., & Nawab, Y. (2023). 3D Natural Fiber Reinforced Composites in Natural Fibers to Composites. Engineering Materials. In book: Natural Fibers to Composites, 41-78. http://dx.doi.org/10.1007/978-3-031-20597-2_3

The external shape of the stem can determine the quality of the fiber contained in it. It is known that the bast bundles of long flax consist of longer cells than in oil flax. This determines their high specific strength. Long and thin elementary fibers provide a large surface of mutual contact, due to which the strength of the technical fiber increases. The strength of adhesions, in turn, depends on the chemical composition of adhesives, i.e. pectin and lignin. Lignin increases the strength of adhesions, and therefore of the technical fiber. Since the length of the elementary fibers in oil flax is shorter than in long flax, it is characterized by a high degree of lignification of the technical fiber, which is largely due to the cementing effect of lignin[11].

In addition, the fiber isolated from different areas of the stem differs significantly in chemical composition. The largest amount of lignin is contained in the fiber obtained from the basal part. In addition, a tendency to decrease in the content of pectin substances from the top to the bottom of the stem was found. The maximum cellulose content is characterized by the middle part of the stem, and the minimum is its basal part.

Low-growing oil flax has a branched stem and is very different from the tall thin and weakly branched long-stem flax not only in appearance, but also in anatomical structure. In the long-stem flax stem, the fibers are collected in wide and relatively deep (meaning the depth in the radial direction on the cross-section) bundles of regular shape. The cross sections of individual fibers have the shape of polyhedra, the cells fit tightly to each other, so the lignification of the middle plates is almost not noticeable in the places of their contact. In the stems of oil flax, the bundles of fibers are loose, with irregular serrated edges on the cross section. The cross sections of individual fibers are rounded, so they fit less tightly to each other.

The specific strength of the fiber, its ability to be divided into thin complexes and flexibility are the main properties that characterize the quality of the fibers. Length and thickness are of the greatest importance when assessing the stems as industrial raw materials. However, there are some other characteristics that make it possible to refine this assessment. Such characteristics include: branching of the stems, the degree of development of the root system, stiffness, weight, uniformity, clogging, damage.

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[11] Nitish, K., Ramesh, K.K., Surender, S. (2022). Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction – A critical review. Constr Build Mater 347:128606. https://doi.org/10.1016/j.conbuildmat.2022.128606

It is known that branching depends on the density of the stem. Flax in thinned crops has more branched stems, in which the wood layer is well developed, but the fiber content is quite low.

The fiber content in the stems depends on the degree of development of the root system. Fig. 5 shows the root system of oil flax and long flax.

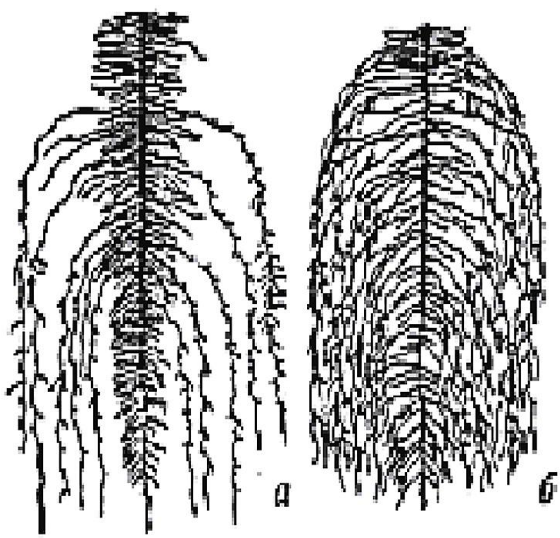

Fig. 5. Root system of long flax and oil flax:
a – long flax; b – oil flax.

Source: The relevance of developing regulatory documents for straw stalks and oil flax fiber. https://surl.gd/mwwuwg

Since the root system of oil flax is more developed, the fiber content in its stems is lower than in the stems of long flax.

The stiffness of the stems characterizes the degree of development of the wood, and therefore the fiber content in them.

The weight of the stems characterizes their structure: oil flax stems, which have a loose structure and a large internal cavity with a very developed core, are lightweight. Long flax stems have a denser structure, so they produce heavier and stronger fiber than oil flax[12,13].

12 Umair, M., Ullah, T., & Nawab, Y. (2023). 3D Natural Fiber Reinforced Composites in Natural Fibers to Composites. Engineering Materials. In book: Natural Fibers to Composites, 41-78. http://dx.doi.org/10.1007/978-3-031-20597-2_3.

The elementary fibers of oil flax are shorter than those of long flax due to the peculiarities of the morphological structure of this group of flax, therefore the strength of the technical fiber of oil flax is somewhat lower. Having analyzed all the above-mentioned differences in the anatomical structure and chemical composition of oil flax from long flax, we can make an important theoretical assumption: the strength of elementary fibers depends on the content of cellulose, lignin and pectin substances in them and the structure of the cell walls. As a rule, a completely non-lignified, thick-walled fibrous cell is the strongest. Along with this, the nature of the connection of the fibers between themselves and their shape in cross sections, give an idea of the strength of their connection. Both of these factors together will determine the features of the spreading process of long flax and oil flax, and therefore the quality of the resulting fiber and products made from it.

Based on the analysis of the anatomical structure and chemical composition of flax, it can be concluded that since there are significant differences between the two groups of this crop, the nature of the technological process of obtaining trusts from oil flax straw will differ significantly from the dew soaking of long flax. As a result, the technological parameters, modes and methods of obtaining trusts from long flax straw cannot be used to obtain trusts from oil flax straw.

Therefore, the development of a technology for obtaining high-quality trusts from oil flax straw for processing into fiber is an important task in conditions of a shortage of domestic raw materials for light industry.

Recently, the issue of comprehensive use of oil flax has been given great attention in many countries of the world. The current task is to use all the potential inherent in the plant: fiber, seeds and processing waste (cake, meal, coir, etc.). However, most of the technologies for processing oil flax straw developed by leading scientists in the world are suitable only for obtaining sacking, coarse fabrics, twine and tow[14].

In the USSR in 1933, the area under oil flax reached 400-500 thousand hectares, and large-scale research was carried out on the production of tow bast and its use.

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[13] Nitish, K., Ramesh, K.K., Surender, S. (2022). Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction – A critical review. Constr Build Mater 347:128606. https://doi.org/10.1016/j.conbuildmat.2022.128606

[14] Chand, N., Fahim, M. (2021). Natural Fibers and their composites; Tribology of Natural Fiber Polymer Composites (Second Edition). Paper back ISBN: 9780128189832; eBook ISBN: 9780128190739 http://dx.doi.org/10.1016/S1369-7021(09)70093-8

Modification of tow on coarse and fine carding machines contributed to its good cleaning from smut and impurities. The length of the resulting fibers was 40-100 mm, and their average metric number was 320. This fiber and even tow after passing through the twice were suitable for the production of clothing wadding[15].

As studies have shown, the fiber from oil flax tow, obtained at enterprises with tow preparation equipment and then modified on the developed line, is suitable for the production of hygroscopic medical cotton wool according to the technology proposed by this institute. In addition, studies carried out at the Institute of Natural Fibers (Poznan, Poland) have shown that oil flax fiber can be successfully used to produce cellulose esters and all other products obtained on its basis. In Western Canada, oil flax is traditionally cultivated on 700-800 thousand hectares. The annual harvest of oil flax straw is about 1 million tons, and only 15-20% of this straw is used in production, mainly for the manufacture of cigarette paper. Pulp and paper factories are located in the states of North Carolina and New Jersey (USA)[16]. However, recently new companies have started to modify flax fiber for industrial purposes. The fiber is used as a raw material for the production of nonwovens, fiber-reinforced polymer composites, and fiberboards.

In Europe, there is great interest in the use of natural fibers (such as flax) for the production of interior panels for automobiles. The United States is starting to purchase flax fiber from Canada as an industrial material. In addition, Canada itself imports some flax straw.

In Italy, according to the Department of Economy, the yield of flax straw averages 1.5-2.5 $t \cdot ha^{-1}$. The straw harvested at harvest (cutting the straw 10 cm above the ground) has an average length of 28.8 cm, and the average length of the stubble left is 13 cm. The fiber obtained using the technology of the Rome Research Center (IPZS), after enzymatic treatment, spinning, active thermal ventilation and carding, is used for the production of composite materials, and the sphagnum is used for the production of boards[17].

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15 Gorach O., Dombrovska O., Tikhosova A (2021). Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering.. Vol. 65. № 3/2021. P. 275-282. https://doi.org/10.35633/ inmateh-65-29

16 The return of flax cultivation to the United States [Electronic resource]. Access mode: https://surl.gd/peimeq

17 Flax field in Astino: after more than 60 years, a dream came true [Electronic resource]. Access mode: https://www.linificio.it/en/linen-from-astino/

Thorough research on the non-textile use of flax and hemp fibers is carried out at the Polish Institute of Natural Fibers (Poznań) under the leadership of its director R. Kozlowski. Similar research is being conducted by other scientific institutions[18].

Recently, Europe and other countries of the world have shown increased interest in the use of oil flax for the manufacture of various types of products in many industries. Based on the vast world experience in the use of oil flax straw, it can be concluded that oil flax straw is a very valuable raw material. Although today it remains a secondary product, with appropriate preparation it can be used to manufacture various consumer goods. However, there is a certain technological and marketing barrier to the industrial use of straw – this is the lack of information about the physical and mechanical properties of oil flax fibers. In addition, there are still no necessary production contacts between flax straw producers and industrial enterprises that could use it. In order to compete with the currently widely used industrial fibers (glass, synthetics, sisal, etc.), it is necessary to consult with specialists who use flax fibers and know their properties.

Summarizing the above, we can conclude that only on the basis of a thorough study and analysis of the technological and morphological properties of oil flax is it possible to develop resource-saving technologies for the comprehensive use of all the potential inherent in the plant. Use of oil flax straw and its further mechanical processing to obtain fiber for various functional purposes, through the introduction and use of sufficiently effective technologies for processing oil flax straw. The development and use of new resource-saving technologies for the integrated use of oil flax stalks and seeds suitable for use in many industries is an important task of today.

2.3. Global and domestic experience in using flax oil

In recent years, technical textiles have gained great popularity in the world due to the expansion of their range. The production of new textile products is associated with the use of advanced technologies.

The main producers of technical textiles are North America, Europe and Japan. The European market is approximately 2/3 of the American market

[18] Gorach, O., Dombrovska, O., Tikhosova, A. (2021). Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering.. Vol. 65. № 3/2021. 275-282. https://doi.org/10.35633/inmateh-65-29

and is twice as large as the Japanese market. Thus, in 2012, 3.2 million tons of cotton fabrics, 6.8 million tons of nonwovens, and more than 1 million tons of knitted materials were produced for technical products, almost 11.2 million tons of products, which is 19% of the total fiber consumption in the world[19].

Currently, the scope of application of technical textiles covers more than a hundred functional objects, and new directions and objects arise on the basis of a combination of inventive activity and marketing methodology based on the study of the needs of society. This is what gave impetus to the creation of a new range of household products. One of the main areas of use of innovative products is the production of non-woven materials of such types as fibrous webs, batting and geotextile materials.

Fibrous webs are pressed layers of fibers that are used for building insulation, protection against solar radiation, snow drifts, in landscape design, for strengthening slopes.

Batting is narrow strips of pressed fibers, thinner than webs, used during construction as heat-, vibration-, sound-insulating, wiping materials, etc.

Geotextile materials are composite materials, the reinforcement of which uses non-woven webs. They are used for:

- construction and repair of highways and railways;
- temporary roads, access roads;
- main roads, runways, airport runways;
- warehouses, parking lots;
- drainage of any type – trench, layer, gallery, vertical;
- protection against erosion of slopes, banks, embankments, hydraulic structures;
- construction of sports grounds, artificial landscapes, swimming pools, sidewalks, lawns, flower beds, strengthening of the coastal strip, protection of soils from erosion, drainage.

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19 Global Technical Textiles Market Size, Share, Growth Analysis, By Material, By Manufacturing Process, By Product Form, By Application – Industry Forecast 2024-2031. https://surl.li/mkwohl

The use of such products for the manufacture of complex technical objects allows solving various target tasks and achieving high operational performance of these objects (accuracy, safety, etc.)[20].

Today, in Ukraine, technical textiles are made only from expensive imported synthetic raw materials and the production of technical textiles from natural fibers is almost completely absent, mainly due to the lack of its own raw material base.

Thus, it can be concluded that the in-depth processing of oil flax straw stalks in order to obtain bast, and subsequently fiber, with the necessary physical and mechanical indicators for the production of environmentally friendly organic technical textiles of various functional purposes is an important task of the flax processing industry.

Leading domestic and foreign scientists L. Murphy, X. Bering, X. Wieland (Germany), R. Kozlowski (Poland), P.L. Capoletto (Italy) have proven that oil flax fiber is suitable for the production of technical textiles of various purposes[21].

In economically developed countries of the world, technical textiles made of both synthetic and natural fibers are widely used in various areas of industrial production. Currently, the world's leading machine-building companies, namely "DiloTemafa" (Germany), "LAROCHE" (France), "Charle & Co" (Belgium), etc., have developed new technological equipment for obtaining fibers from plant raw materials – long flax, oil flax, hemp, jute, nettle – and for the production of needle-punched and many other types of technical fabrics[22].

Analysis of the development of the technical textile sector in the world indicates its high profitability and sustainability due to the wide range of products and the variety of areas of their application in various industries. Today, presentations of new types of products and equipment for the production of technical products are held in many countries, which is a strong evidence of the high demand for technical textiles. Experts consider this indus-

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20 Ahrari, M., Karahan, M., Karahan, N. (2023). Competitiveness Factors in Textiles and Composites Industry and Transformation into Value-Added Products. Recent – Rezult. Cercet. Noastre Teh.24, 132–141. doi:10.31926/recent.2023.70.132

21 Karahan, M., Ahrari, M., Karahan, N. (2023). Technical Textiles Market Research and Added Value Analysis: A Regio-Global Case Study. Recent – Rezult. Cercet. Noastre Teh. 24, 162–180. doi:10.31926/recent.2023.71.162

22 Chursina, L.A., Tikhosova, G.A., Horach, O.O., Yanyuk,T.I. (2011). Scientific foundations of complex processing of stalks and seeds of oil flax. Monograph. Kherson: Oldiplu. 356 p. https://surl.gd/zkdukm

try to be one of the five most high-tech sectors of the world industry with high development potential. That is why restructuring is underway in the textile industry – many companies are betting on the production of technical textiles, thereby choosing:

– more sustainable and less competitive areas of global production (new textile products for various industries);
– more reliable placement of investments in goods with high added value and more flexible service and logistics to ensure optimal asset management in crisis situations.

A study of the main trends in the development of technical textile production in leading countries of the world allows us to conclude that today one of the most successful and financially attractive industries in Ukraine can also be the production of technical textiles, for the production of which it is possible to use domestic annually renewable raw materials – oilseed flax.

Ukrainian manufacturers should study in detail the experience of Asian and Eastern European countries, which are now actively entering this market sector. First of all, this applies to China, but especially to South Korea, where the government is increasing funding for research and development in the above-mentioned area and plans to invest in the production infrastructure of the industry.

In economically developed countries of the world, the production volumes of technical textiles are constantly growing. Thus, currently, this sector of the French economy employs from 300 to 370 companies (17% of the entire textile industry of the country). They provide jobs for 21,000 people (25% of all workers employed in the textile industry of the country) and produce 700 thousand tons of textile products per year. The total annual turnover is 3.3 billion EUR (27% of the turnover of the entire textile industry). The products of the technical textile sector account for 33% of all textiles exported by France. Among the companies engaged in this sector of the country's economy, the largest share falls on manufacturers of textile products (31%), yarn and technical fabrics (27%). The shares of manufacturers of technical knitwear are much smaller – 8.1%, chemical products for the sector – 6.5%, special clothing – 6.0% and textile equipment – 5.4%. The remaining 16.0% produce a wide range of products, respectively, their shares in the market structure are minimal.

850 companies (42 thousand employees) are associated with the technical textiles sector in Italy, of which 300 (15 thousand jobs) are engaged only in technical textiles. Annual turnover is 3.2 billion EUR, annual exports of products amount to 1.25 billion EUR. The sector's share in the country's textile industry is 8%. Companies specialize mainly in the production of protective textiles for special-purpose clothing, as well as transport and interior textiles[23].

In Turkey, before the economic crisis, the textile industry was formed by about 30 thousand companies, 90% of which were small and medium-sized. However, only 150 of them were employed in the technical textile sector. Technical textile exports (1.39 billion USD/year) and imports (1.24 billion USD/year) in the country are more or less balanced. Despite the crisis, Turkey is becoming one of the major players in the global technical textile market with a domestic market capacity of over 1.5 billion USD. Turkish companies produce mainly interior textiles for the hotel industry, protective, transport, agricultural textiles and export them to the USA, EU countries and Russia for about 900 million USD annually. In addition, Turkey plays an increasingly significant role as an importer of technical textiles, exporting them mainly from Germany, Italy, China, the Czech Republic, South Korea, Israel, Japan and India for up to 700 million USD/year.

The rapid growth of the Indian economy is evidenced, in particular, by the positive dynamics of the country's textile industry. It grew by 275% in the period 2001-2007 alone. The reasons for the stability of the Indian economy during the global crisis lie in its relatively weak dependence on exports, including in the textile industry. Indian textiles provide 4% of the country's GDP and employment for about 85 million people. At the same time, the country needs to solve a number of problems to ensure the competitiveness of products from the technical textile production sector.

According to IFAI, the structure of the American textile market has undergone significant changes over the decade (1998-2008). While maintaining a constant share of home textiles (37%), the share of clothing decreased from 38% to 20%, and the share of technical textiles increased from 25% to 43%. Currently, about 7,000 companies are engaged in technical textiles (of which 1,500 are suppliers, manufacturers of semi-finished products, raw materials

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23 Horach, O.O. Dombrovska, O.P. (2021). Use of oilseed flax and hemp in the food industry Bulletin of the University of Trade and Economics. Lviv. Publishing House of the University of Trade and Economics, 2021. Issue 28. P. 18-22. https://doi.org/10.36477/2522-1221-2021-28-03

and service companies, 5,500 are manufacturers of final products). In 2008, 1.56 million tons of nonwovens were produced in the USA. Some of them were exported, with the largest deliveries to Asian countries (56,893 tons), while imports from Asian countries this year amounted to 80,849 tons[24].

The main growth trends in the technical textile market are primarily associated with high-tech textiles of the new generation, the production of geosynthetic materials, environmental, medical and protective textiles (mainly for the needs of the military department).

In Canada, 118 out of 400 textile companies have chosen the production of technical textiles as a business that guarantees a fairly high added value. In total, the Canadian textile industry employs more than 40,000 people. The industry's enterprises work in the areas of hybrid technologies (warp knitwear and nonwovens), the creation of "smart textiles" based on the application of nanotechnological and biotechnological treatments, the use of special high-performance fibers. Up to 82% of these products are exported to the USA.

The sixth place in the top ten largest global suppliers of textile products is occupied by South Korea. The industry structure optimized over 60 years and highly developed information technologies allow directing joint efforts of business and the state to develop new generation textile products based on the symbiosis of textile, bio-, nano– and IT-technologies. For this purpose, the Ministry of Education and Economy allocated 20 billion KRW (11.63 million EUR) under a special program that started in April 2009. 7 more billion KRW (over 4 million EUR) is invested in scientific research and development and development of combined fibers and nanotextile products. It should be noted that the total amount of investment support fund for South Korea's processing industries from the budget and large corporations is 73.5 billion KRW (42.76 million EUR). In addition, the municipality of Daegu (2.5 million inhabitants, the center of the Korean textile industry) allocates 200 billion KRW (116 million EUR) to implement a five-year plan for the development and production of textile products based on aramid and carbon fibers for use in semiconductors, batteries and high-precision filters. The structure of the textile industry in Taiwan (a total of 5,000 enterprises providing 186 thousand jobs) currently consists of clothing production (60%), textiles and textile products (30%), and chemical fibers (10%).

[24] Bayar, G. (2022). Türkiye's sectoral exports: A competitiveness approach. International Journal of Finance and Economics, eISSN 2146-4138, Vol. 27, 2268-2289. https://doi.org/10.1002/ijfe.2272

The reorientation of priorities, with which the development prospects are associated here, consists, first of all, in the transition from mass industrial production to the production of products with high added value, in particular, environmentally friendly medical, functional and "smart textiles", which will contribute to energy and resource conservation. The projects of the Taiwan Textile Research Institute (TTRI) include work on the development of textile nanoproducts, new chemical and artificial fibers, industrial and medical textiles.

The economic programs of the Chinese government are aimed at the development of infrastructure (about 390 billion EUR allocated for the expansion of the network and modernization of railways, the construction of subways in the largest cities, the construction of 50 new airports and the reconstruction of 90 existing ones), environmental protection and health care (about 21 billion EUR).

Both of these areas are related to the needs for technical textiles. The China Nonwovens and Industrial Textiles Association (CNITA) has identified four “success factors” for technical textile enterprises that have achieved high results: equipping production with the latest technological lines; mastering new high technologies; developing or releasing innovative products; producing dual-purpose products that are both in demand on the commodity market and supplied under state orders[25].

According to experts' forecasts, the volume of textile imports will increase. It is assumed that the need for textile products will grow due to imports by 30-40% annually. It should be noted that 90% of this growth will fall on the technical textile sector, since at present the demand for it is satisfied by only 17%. This is explained by the fact that Russian manufacturers cannot compete in the domestic market due to:

- technical backwardness of production (a significant part of the technological equipment park has been used for over 20 years);
- the need for large-scale investments in the development of the industry; conflict of interests: according to the government, the technical textile sector should develop not to meet the needs of industries that ensure the development of the country's infrastructure, but in the direction of pro-

[25] Karabay, G. & Sarıçoban, K. (2021). Research on Competitiveness in Technical Textiles: Comparison of Countries Having the Lion’s Share of Technical Textile World Exports and Türkiye. Fibres and Textiles in Eastern Europe, eISSN 2300-7354, Vol. 29, is. 6(150), 22-31, http://dx.doi.org/10.5604/01.3001.0015.2718

ducing a narrow range of products, for example, technical textiles with innovative nano-coating.

According to industrial markets, bleached cellulose and bicomponent staple fibers are required for the production of new generation technical textiles. Scientists have developed and adopted a program for the production of medical textiles and disposable hygiene products. The production of these products also requires environmentally friendly cellulose-containing raw materials with appropriate physical and mechanical characteristics[26].

In Germany, the share of technical textiles has reached almost 50% of the total textile production. This was the result of the implementation of the economic program of the German government to support the development of domestic demand for geotextiles and industrial textiles. It should be noted that German enterprises are leading manufacturers of automotive textiles.

In general, the analysis of the German and world markets for these products indicates their significant differences. Germany dominates in the field of manufacturing textile materials for transport construction (Fig. 6), medicine, sports and industrial purposes, while in the whole world the production of textile products for agricultural, geotextile (Fig. 7) and construction purposes is developing faster (compared to Germany) (Table 4).

Fig. 6. Car interior floor mat made of non-woven materials

Source: Natural Fiber Composites: An Overview https://www.kompozit.com/post/natural-fibre-composites-an-overview

[26] Park, H. (2022). The Current State of the Korean Technical Textile Industry and Tasks for Policy. KIET Industrial Economic Review, ISSN 1598-947X, Vol. 27, is. 2, 19-29, Paper № 22/IER/27/2-2. http://dx.doi.org /10.2139/ssrn.4190717

Fig. 7. Creation of an anti-filtration screen using geotextile material during the construction of a landfill for waste storage

Source: Natural Fibres: A Sustainable Material for Geotextile Applications Indian Geotech J https://doi.org/10.1007/s40098-023-00862-w

Table 4. Structure of consumption of technical textiles

Technical Textile Groups	Consumption volumes,%	
	Germany	world market
Agrotextiles	7	12
Construction Textiles	10	15
Geotextiles	3	9
Industrial Textiles	18	16
Medical Textiles	13	10
Transport Textiles	22	17
Packaging Materials	5	6
Protective Textiles	10	7
Sports Textiles	12	8
Total	100	100

Source: History, technology and types of technical textiles https://surl.gd/rkyonn

Due to the projected growth in demand for technical textiles, the problem of finding raw materials for the manufacture of these products is acute. Currently, the main raw materials for the production of technical textiles are synthetic fibers, the share of which is 77%, and the share of cotton in technical materials is constantly decreasing.

Thus, the use of synthetic fibers in the manufacture of technical textiles for clothing, footwear, household needs and medical purposes is inappropriate, but on the contrary, for this type of products it is necessary to use environmentally friendly raw materials from natural fibers.

In general, the analysis of the technical textile market allows us to conclude that such product groups as agro-, geo-, construction, protective, automotive, medical, packaging textiles, filtering and sorption materials, which are in greatest demand among domestic consumers, can be produced from natural raw materials, namely using annually renewable oilseed flax fiber[27].

At the end of the 20th century, clothing and home textile manufacturing enterprises moved to Southeast Asian countries due to the availability of cheaper labor in this region. Europe and the USA focused on developing more complex and science-intensive technical textiles. In the USA and Western Europe, the share of technical textiles is 40% of production and consumption, and in China – 20%. The results of a study of changes in the volume of consumption of technical textiles in different regions of the world are presented in Table 5.

Table 5. Dynamics of the use of technical textiles in different regions of the world

Region	Volumes of use, thousand tons			
	2005 y.	2010 y.	2015 y.	2020 y.
North America	3584	4184	4774	5591
South America	705	874	1004	1230
Western Europe	3002	3614	4107	4760
Eastern Europe	493	548	666	817
Asia excluding China	3895	4449	5220	6348

27 Shahata Hassan, N., Ahmed, Sadek M., Said, Shamandy, E. (2019). The use of glass technology and technical textiles in the production of printed textile hangings to increase the awareness of the aesthetic side in medical institutions. Journal of Architecture and Arts. eISSN 2357-0342, is. 19. https://doi.org/10.21608/mjaf.2019.13553.1198

Region	Volumes of use, thousand tons			
	2005 y.	2010 y.	2015 y.	2020 y.
China	1515	2155	2871	3808
Other countries	778	917	1014	1219
Total	13972	16741	19656	23773

Source: Classification of technical textiles – the path to quality and safety of goods https://surl.gd/mrlnmj

Based on the data in Table 4, it can be concluded that the countries of Asia, North America and Western Europe are the largest consumers of technical textiles in the world. The total amount of technical textiles used in Asian countries in 2020 exceeded 10 thousand tons. The volume of consumption of technical textiles from 2010 to 2020 in North American countries increased by 56.0%, and in China and other Asian countries by 87.7%. It should be noted that in the use of technical textiles, the countries of Eastern Europe, including Ukraine, lag significantly behind all regions of the world. The volume of use of technical textiles in Eastern Europe is 12.4 times less than in Asian countries and China and 5.8 times less than in Western Europe[28].

Ukraine's accession to the WTO has intensified the competitive struggle for the Ukrainian market, which objectively requires constant improvement of the quality and expansion of the range of products produced through the use of environmentally friendly materials and the development of innovative technologies for the production of technical textiles for various functional purposes.

The main area of application of flax fiber abroad is the reinforcement of composite polymer materials. Reinforcement of composite materials can be carried out with oriented or unoriented (entangled) fiber and nonwoven materials obtained from it, yarn or even fabric. If a nonwoven material or fabric is used, the composite is formed in the form of a sandwich or pressed, located inside a layer, for example, polypropylene (Fig. 8 a). This results in a very strong, unbreakable structural material. The fiber or bast

[28] Holderied, P., Mutschler, T., Tresp, S., et al. (2023). Development of a new yarn supply for weft knitting machines to produce innovative knitwear. Communications in Development and Assembling of Textile Products, ISSN 2701-939X, Vol. 4, is. 1, 51-60, https://doi.org/10.25367/cdatp.2023.4.p51-60

is inside the polypropylene, that is, they are protected from the environment and are not subject to biological destruction.

Flax fiber material can be used to reinforce structural polymer materials not only in the form of a pre-formed nonwoven material, but also in the form of a mixture with a heated polymer, and obtained in the processes of casting, extrusion (Fig. 8 b) or pressing. Glass fiber, used in our time in composite polymer materials, is replaced by flax fiber, which makes them cheaper, less dangerous to manufacture, and easier to process. In addition, products that contain bast fibers, rather than glass fiber, are lighter and less brittle (Fig. 8 c).

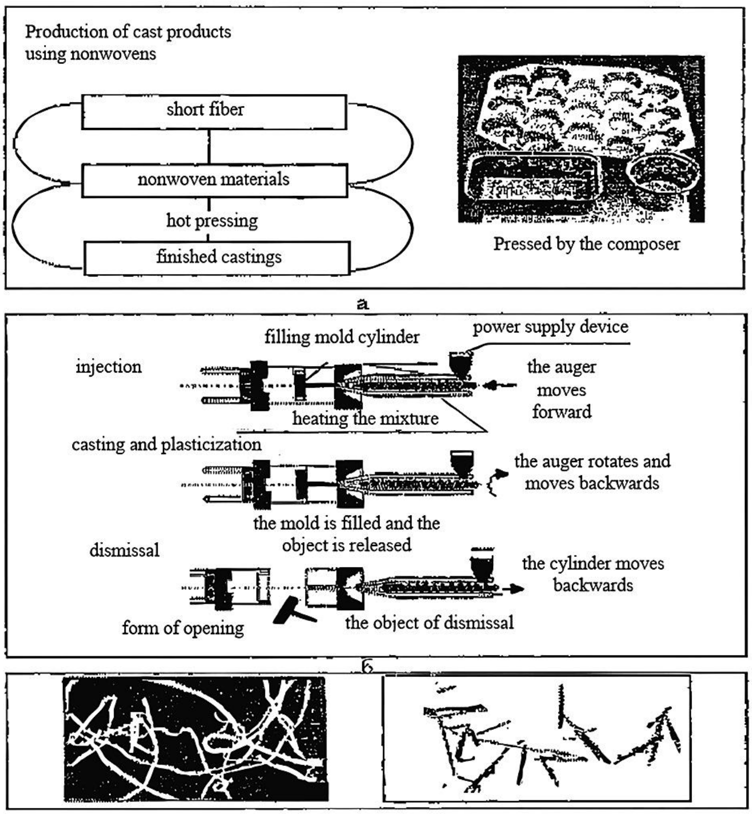

Fig. 8. Reinforced composite materials: a – production of composite materials reinforced with non-woven materials from flax; b – injection molding; c – fiber obtained from injection molding; on the left – flax, on the right – glass

Source: Natural Fiber for Geotechnical Applications: Concepts, Achievements and Challenges. https://www.mdpi.com/2071-1050/15/11/8603

In composite polymer materials, where flax fiber is used as a reinforcing material, the range of polymers used is limited. The fact is that at high temperatures (220°C) pyrolytic decomposition of flax fiber may begin. Therefore, polyolefins are most often used for this purpose, which have lower softening points than other polymers.

Composite materials reinforced with plant fibers are most widely used in the automotive industry. In this case, various natural fibers can be used to reinforce structural polymer materials: flax, hemp, jute, sisal, coconut. In countries with a developed automotive industry, these materials are usually imported. Strong, corrosion-resistant, lightweight polymer composites are increasingly used in cars. In modern cars, they account for more than 10% (by weight) and their content is constantly increasing[29].

The pioneer of the use of plastics in the automotive industry was Henry Ford in 1941. In 1953, Chevrolet manufactured many parts from polypropylene materials reinforced with various fibers. This allowed to reduce the weight of the car by 85 kg. In 1991-1992, plastics accounted for 149 kg of the car's weight (or 10.1%) in BMW. The first bumper was manufactured by Ford in 1968. Renault in 1971 manufactured a polyester bumper reinforced with fiberglass. A polypropylene bumper reinforced with natural vegetable fiber was installed by Fiat in its 126 and 128 models. Natural vegetable fibers are also used in various structural elements of the Daimler-Benz car (Fig. 9). Reinforcing plastics with natural fibers, such as flax fiber, significantly simplifies the recycling of parts that have reached the end of their useful life, compared to fiberglass reinforcement[30].

[29] Azam, F., Ahmad, F., et al. (2022). The Role and Applications of Aerogels in Textiles. Advances in Materials Science and Engineering, eISSN 1687-8442, Vol. 2022. https://doi.org/10.1155/2022/2407769

[30] Chursina, L.A., Tikhosova, G.A., Horach, O.O., Yanyuk,T.I. (2011). Scientific foundations of complex processing of stalks and seeds of oil flax. Monograph. Kherson: Oldiplu. 356 p. https://surl.gd/zkdukm

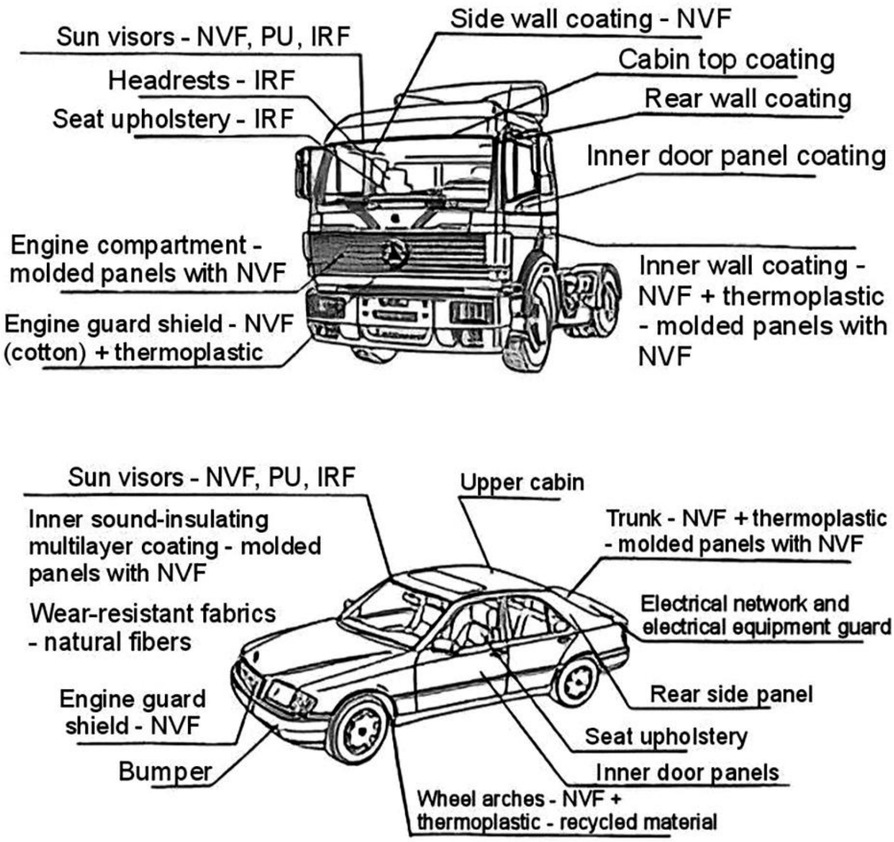

Fig. 9. The use of natural vegetable fibers in various structural elements of the Daimler-Benz car (NVF – natural, vegetable fibers, PU – polyurethane, IRF – India rubber fibers)

Source: The use of natural plant fibers in various structural elements of the Daimler-Benz car. https://surl.li/xtfjhw

The strength characteristics of the fiber used for reinforcement are given in Table 6.

Table 6. Strength characteristics of the fiber used for reinforcement

Fiber	Density, g/cm	Diameter, µm	Elongation at break, %	Modulus E,%	Ultimate strength, g/tex	Moisture content, %	Permissible molding temperature, °C
Cotton	1,20	11-22	7	500	0,8	7	220 destructive
Linen	1,30	5-40	3	1840	1,3	7	
Jute	1,50	8-30	2	1750	0,5	12	
Sisal	1,45	8-40	2	2500	0,5	8	
Glass	2,55	5-24	2-5	3000	1,0	1	800
Hydrocarbon	1,90	5-7	2	10000	10,0	1	1200

Source:. Verification of material characteristic of natural fibers for concrete reinforcement. https://surl.gd/lihqlw

The relationship between the load and elongation of reinforcing fibers and similar relationships for finished composite materials with different flax fiber contents and without the use of fiber are shown in Fig. 10, 11.

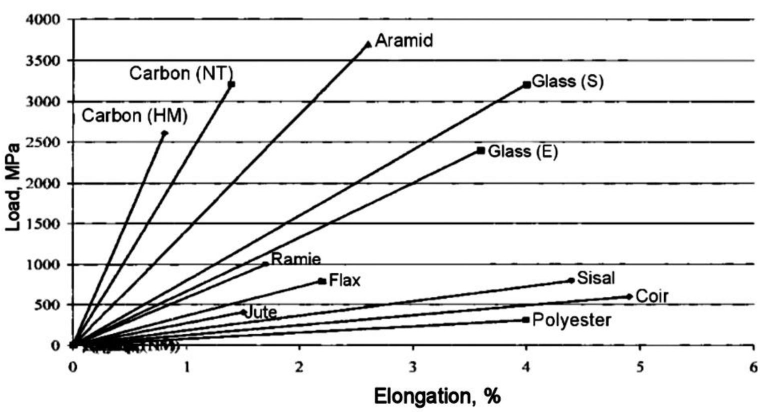

Fig. 10. Relationship between load and elongation of reinforcing fibers and unsaturated polyester resin

Source: Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering https://surl.li/escnwn

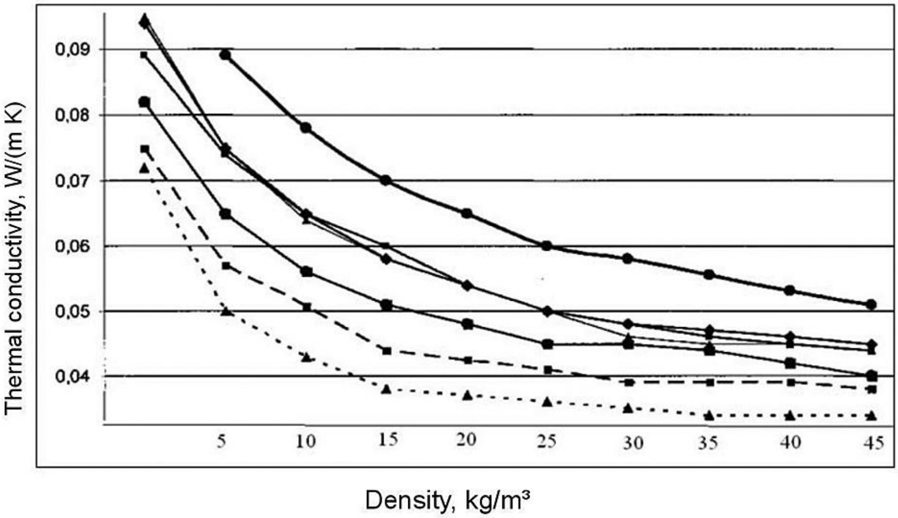

Fig. 11. Dependence between load and elongation of composite materials with plant fibers according to Folster and Micheli: a – epoxy resin + flax (55% flax by volume); b – flax, sisal with polypropylene; c – polyester + flax; d – polypropylene + flax (30% by volume); e – polyester + jute; f – epoxy resin without fiber; g – polypropylene without fiber

Source: Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering https://surl.li/escnwn

The use of natural fibers, in particular low-grade long-flax fiber, as well as oil flax fiber in composites for the automotive industry in the CIS countries is still at the stage of research and development.

Analyzing the world experience in the use of flax fibers to obtain reinforced materials, we can conclude that oil flax fiber, having the appropriate physical and mechanical characteristics, can be widely used in the automotive industry for the production of composite materials.

Composite materials reinforced with bast fibers are now used not only in the automotive industry, but also for the production of window frames. It should be noted that to prevent fire, they have a coating of polyacrylic plastic and fast-drying fasteners.

An important area of use of oil flax fiber is the production of nonwoven materials. In many countries, extensive experience in the production of nonwoven materials from various fibrous waste and low-grade long-flax fiber has been accumulated. The production of nonwoven materials from long flax fiber involves the use of waste from the spinning process and short fiber after processing on the fiber separating machine fiber separating machine[31].

Unfortunately, Ukraine has not developed a technology for the production of nonwoven materials from oilseed flax fiber. However, the experience of scientists from different countries in the use of oilseed flax fiber to produce nonwoven materials can be used at domestic enterprises. Scientists from the German Institute of Agricultural Construction and the Federal Agricultural Research Center (L. Murphy, X. Bering, X. Wieland) studied the thermal insulation properties of nonwoven fabrics of different densities (Fig. 1.7) obtained from different materials (fiberglass, fine and coarse bast fibers).

The results of the studies show that the thermal insulation properties of fabrics obtained from different raw materials differ significantly. If fabrics made of fine muslin or even chemically treated flax fiber are close in thermal conductivity to glass wool fabrics, then fabrics made of coarse fibers provide the necessary thermal insulation only with their high density. At the same time, in the range of low density (10-20 kg/m3), the difference between the thermal insulation properties of different materials is quite significant, and after 35 kg/m3 this difference becomes completely insignificant. Glass wool sheets will have a thermal conductivity of 0.05 W/(m·K) at a density of 10 kg/m3, and coarse bast fiber sheets will have a thermal conductivity of only 25-40 kg/m3. Therefore, as the density of nonwoven materials increases, their thermal conductivity decreases. If nonwoven materials are used for thermal insulation, then during their manufacture it is necessary to use a thinner fiber and produce a material with a density of at least 35 kg/m3, which is sufficiently breathable. For this purpose, the most suitable is oil flax fiber (Fig. 12).

[31] Azam F., Ahmad F., et al. (2022): The Role and Applications of Aerogels in Textiles. Advances in Materials Science and Engineering, eISSN 1687-8442, Vol. 2022. https://doi.org/10.1155/2022/2407769

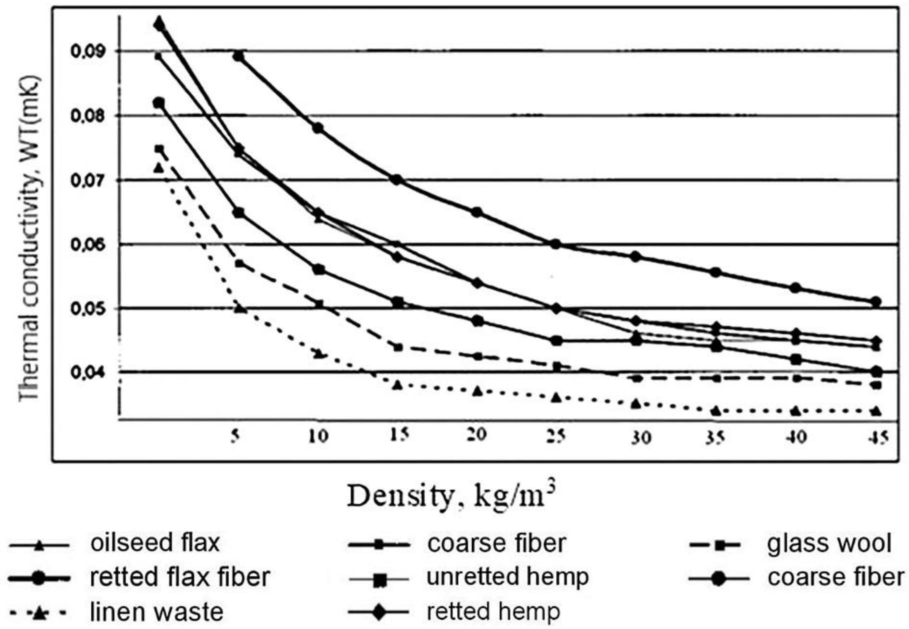

Fig. 12. Dependence of thermal insulation properties of nonwoven materials made from different raw materials on their density

Source: Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering https://surl.li/escnwn

Further increase in the density of these materials almost does not reduce thermal conductivity and only leads to an increase in the mass of the material, and a decrease in density causes a significant increase in thermal conductivity. This fully corresponds to the well-known definition of fiber thickness by air permeability (airflow). Nonwoven materials of the same density, but with a lower (due to the greater thickness of the fiber) resistance to air passage, have a higher thermal conductivity.

Summary of world and domestic experience in the manufacture of technical textiles from oilseed flax fibers (Fig. 13)[32].

[32] Emmanuella, K.T. (2022). A Comparison of financial performance in textile industry: KPR Mill Ltd vs Arvind Ltd. Business dissertation report, Pandit Deendayal Energy University, School of Petroleum Management, Gandhinagar, Gujarat, India, http://localhost:8080/xmlui/ handle/123456789/539

Technical textiles are usually made from chemical fibers (viscose, polyester, polyamide, polypropylene, etc.). The proportion of natural fibers (linen, jute, coconut, cotton, wool) used in the manufacture of these materials does not exceed 23%.

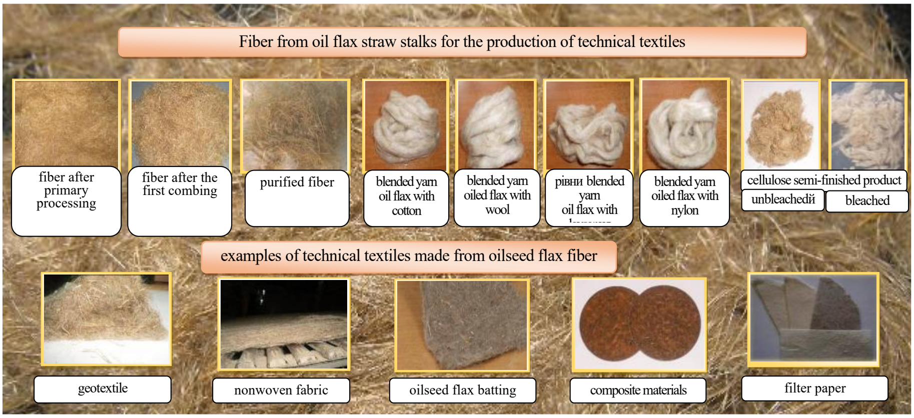

Fig. 13. Samples of technical textiles made from oilseed flax fibers

Source: The latest comprehensive systems for assessing the quality and processing of flax-containing materials chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ https://lib.lntu.edu.ua/sites /default/files/2024-02/MONOGRAFIA.pdf

Based on the analysis of world experience in the use of technical textiles, it can be concluded that recently the production of textile products in the world has been developing rapidly and is characterized by investment attractiveness and rapid payback of costs. Technical textiles have gained great popularity due to the expansion of the range and areas of application, the emergence of the latest progressive methods and technologies of production, the use of new types of raw materials. The main areas of application of technical textiles are: road and railway construction, landscape design, agriculture, hydraulic structures, laying tunnels and pipelines, protection of underground parts of residential and industrial buildings, land restoration after hostilities, etc.

In Ukraine, the production of technical textiles from natural fibers is almost completely absent, mainly due to the lack of its own raw material base. However, it should be noted that our country has great potential for the production of organic technical textiles from cheap cellulose-containing raw materials – oil flax.

Therefore, the development of domestic technologies for advanced processing of oil flax straw stalks, the determination of rational technological parameters and modes of their processing in order to obtain flax fibers with the necessary quality indicators suitable for the production of organic technical textiles of various functional purposes, is an urgent scientific and technical problem.

2.4. Application of oil flax fiber for the production of technical textiles

The global market for technical textiles, which at the beginning of the 21st century was estimated at 120 billion US dollars per year, is characterized by a tendency to constant growth, as new areas of application for technical materials appear. Experts claim that there are practically no limits for this sub-sector of light industry and it develops in parallel with all other industries. According to experts, in 2020 the global market for technical textiles grew to 193 billion US dollars, while the volume of the global market for technical textiles in 2015 was about 155 billion US dollars[33].

According to the study "Technical Textile Market: Global Industry Analysis and Opportunity Assessment 2015-2020" by Future Market Insights, the largest market for the production and consumption of technical textiles in the world today is the Asia-Pacific region. This region is home to the two most densely populated regions of the planet, and textile production is one of the main sources of jobs for the local population. High demand for technical textiles forces manufacturers to invest in research and development activities and increase production volumes. In 2015, the Asia-Pacific region occupied almost 40% of the global technical textiles market in monetary terms. According to forecasts by experts in the field of technical textiles, this dominance will continue until 2025. Two other profitable markets for the technical textiles industry are Western Europe and North America. The leading manufacturers of this product are: Polymer Group Inc., Ahlstrom Corporation, DuPont Chemicals Company, Freudenberg & Co.KG, TWE Group.

The analysis of literature sources indicates the growth of global production volumes and use of technical textiles. The dynamics of changes in de-

[33] Mushtaq, B., Ahmad ,A., Ali Z., et al. (2022). Core Spun Based Helical Auxetic Yarn: A Novel Structure for Wearable Protective Textiles. Journal of Natural Fibers, ISSN 1544-0478, Vol. 19, is. 16, 15058-15070, https://doi.org/10.1080/15440478.2022.2070322

mand for technical textiles in almost all industries of modern production are presented in Table 7.

Table 7. Dynamics of the use of technical textiles in 2005-2020 y.

Areas of application	Volumes of use, thousand tons			
	2005 y.	2010 y.	2015 y.	2020 y.
Agriculture	1173	1381	1615	1958
Construction	1261	1648	2033	2591
Workwear	1072	1238	1413	1656
Geotextiles	196	255	319	413
Furniture	1864	2186	2499	2853
Industry	1846	2205	2624	3257
Medicine	1228	1543	1928	2380
Vehicles	2117	2479	2828	3338
Packaging	2189	2552	2990	3606
Technical protection	184	238	279	340
Sporting goods and equipment	841	989	1153	1382
Total	13971	16714	19681	23774

Source: Classification of technical textiles. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ http://tr.knute.edu.ua/files/2018/02(26)/7.pdf

Analysis of Table 6 shows that the greatest demand is for technical textiles for the production of packaging materials – 3606 thousand tons, and the least technical textiles are used for technical protection and environmental protection – 340-413 thousand tons. Thus, we can conclude that in the future technical textiles will be widely used in various branches of modern production. However, in Eastern European countries, the development of the industry for the production of technical textiles requires great attention and thorough scientific research[34].

[34] Cardoso, A.C. (2021). Potencial de própolis no desenvolvimento de têxteis com propriedades funcionais (Potential of propolis in the development of textiles with functional properties). Master thesis, Universidade do Minho, Brasil, Dissertacao-PG37988.pdf, https://hdl.handle.net/1822/79512

The areas of application of technical textiles are practically limitless. It is difficult to find a branch of economy or sphere of human life, wherever textile technical materials are used.

In our opinion, in Ukraine, the prospects for the development of innovative technologies for the production of technical textiles of various functional purposes, as a subsector of light industry, are associated, first of all, with the use of oil flax fiber.

In 2016, 66.8 thousand hectares were allocated for sowing this crop in Ukraine. In economically developed countries of the world – Canada, Belgium, France, Germany – there is extensive experience in using seeds, straw, trusts and oil flax fiber to create environmentally friendly products, which are widely used in various areas of industrial production. Today, the requirements of European manufacturers of technical products made from short flax fiber require a minimum content of flaxseed in the fiber. Leading European manufacturers of industrial equipment use modern technologies for the production of nonwoven materials from flaxseed fiber: air-laying, carding, etc.

The technology for the production of nonwoven materials (insulation materials) by the air-laying method "AIRLAY LAROCHE" (France) involves the purification of short flax fiber to a flax content of no more than 7-8%. The cost of such fiber on the European market is 560-600 euros per ton[35].

The smut content of flax fiber suitable for the production of nonwoven materials (insulation) by carding on the equipment of this company should not exceed 2-3%. The price of such fiber that meets the specified requirements on the European market is from 750 euros per ton.

If the fiber is prepared using existing technologies on the "LAROCHE" line for the purpose of producing paper pulp, then it should have a smut content within 1-25%. The cost of such fiber with a smut content of 25% on the European market is 300 euros per ton. Thus, the lower the smut content, the higher the quality of the fiber and, accordingly, its cost. For comparison, the price of coniferous bleached cellulose for the production of paper pulp on the European market is 800 euros per ton.

At present, the cost of oilseeds on the international market is on average 1000 euros per ton. The use of modern advanced technologies will allow the

[35] Fiber processing equipment [Electronic resource]. Access mode: https://www.textiletech nology.net/ news/news/Laroche-Fiber-processing-equipment-13595

production of technical textiles for various functional purposes based on flax fiber, that is, to use the entire potential inherent in the plant, which will contribute to increasing the profitability of flax growing. Flax fiber can be used in the pulp and paper industry for the production of special durable banknote, cigarette and other types of paper. Due to its heat and sound insulation properties, the fiber and husk of this crop are suitable for use in the construction industry. Flax can also be used in the automotive industry for the production of insulation, parts, panels, in the production of geotextiles and composite materials, in agriculture, etc.

The literature review conducted on the topic of the dissertation allows us to conclude that the importance of technical textiles is difficult to overestimate, since its areas of application are practically limitless. However, until recently, there was no generally accepted classification system for technical textiles and nonwovens in the world. Yes, each country had its own approach to what products should be classified as technical textiles. Until 1993, Western European countries did not have a single classification of technical textiles. Creation of the European Union has intensified work on developing a unified system for classifying and accounting for technical products. One of the principles of classification can be considered division by the composition of the raw materials from which the products are made. This classification is based on the origin of the fibers (natural or chemical) used to produce the material. Another principle was proposed by the organizers of the largest international exhibitions of technical textile products – the company "Messe Frankfurt"[36]. This classification was based on the following criterion: the purpose of technical textiles.

According to the areas of use, technical textiles were divided into 12 categories:

– agrotextiles (Agrotech, for agriculture);
– construction (Buildtech, for construction);
– household (Hometech, for household use);
– industrial (Indutech, for industry);
– sports (Sportech, for sporting goods);
– packaging (Packtech, for packaging materials);

[36] Techtextil i Texprocess 2022 [Electronic resource]. Access mode: https://surl.li/cyrgaz

– transport (Mobiltech, for transport, automotive and aircraft construction);
– medical (Meditech, for medicine);
– clothing (Clothtech, for clothing production);
– geotextiles (Geotech, geotextiles);
– protective (Protech, for protective equipment);
– ecotextiles (Oekotech, for environmental protection).

Such areas of application of technical textiles as industrial, packaging and transport provide the highest income from the sale of this type of product. Thus, in 2015, the total income of manufacturers of industrial and packaging textiles was almost the same and amounted to 21.8 billion US dollars for each of both product groups, and the total volume of technical transport textiles was estimated at 20.7 billion US dollars. According to expert forecasts, by 2030 the highest average annual growth rates should be shown by such new types of technical textiles as eco-textiles, geotextiles and sports textiles.

Eco-textiles are technical textiles for use in the environmental protection sector and the recycling of industrial waste, which are very popular in the world due to the growing attention to the rational use of natural resources. In the future, by 2030, eco-textiles should show the highest average annual growth rate of production volumes – up to 4 billion US dollars.

Geotextiles are technical textiles for engineering and geological purposes, used during the construction of roads and bridges, to strengthen rail tracks, road slopes, etc. According to expert forecasts, by 2030 the average annual growth rate of this sector of technical textile production will reach 6%. Sports textiles are technical textiles used for the production of various artificial sports surfaces, fishing gear, parachute fabrics, etc. It is expected that due to the high demand for sports textiles, this market segment will have an average annual growth rate of 5.5% by 2020.

By type of production processes, technical textiles are divided into nonwoven, composite and other (knitted, woven, woven). Nonwoven technical textiles are in the greatest demand in the world. In 2015, its total volume was estimated at more than 80 billion US dollars. In the future, if the growth in this market segment is maintained, by 2030 nonwoven technical textiles will have the highest average annual growth rates and will retain a larger market share.

It should be noted that not all industry experts agreed with the above classification. The members of the European Technical Textiles Club (ETT Club) have decided to classify only 9 market segments for technical textiles instead of the 12 defined fifteen years ago by the exhibition company Messe Frankfurt [37]. According to this classification, technical textiles are divided into:

– agrotextiles;
– geotextiles;
– construction textiles;
– industrial textiles;
– medical textiles;
– automotive textiles;
– packaging textiles;
– protective textiles;
– textiles for the production of sportswear and accessories.

Specialists from leading industries (machine-building, chemical, automotive, aviation, construction, packaging) together with 16 German textile institutes carry out all the necessary research and development work to improve manufacturing technologies and expand the range of technical textiles in Germany. As a result of this cooperation, many innovations and promising developments of innovative types of technical textiles have been introduced into production. Thanks to the cooperation of industrial enterprises and research and development organizations, the production of technical textiles is constantly growing in all segments of the commodity market.

Currently, in the EU and the USA, the concept of technical textiles includes all materials that are not used directly for the production of household clothing, bed linen and interior items.

In the USSR, only heavy technical fabrics and technical silk were considered technical textiles, and products for the production of uniforms and ammunition for law enforcement agencies, protective and sportswear, etc. were never considered to be part of this group of products. Today. Various types of these products are distributed in the following ratio: fabrics for rub-

[37] Mezrea, P.E., Ispir, M., Balci, I.A., et al. (2021). Diagonal tensile tests on historical brick masonry wallets strengthened with fabric reinforced cementitious mortar. Structures, eISSN 2352-0124, Vol. 33, 935-946, https://doi.org/10.1016/j.istruc.2021.04.076

ber and technical products – 59.75%; fabrics for the tire industry – 6.09%; filter fabrics – 7.45%; fabrics for mine ventilation pipes and awnings – 13.16%; non-woven materials – 11.59%; other fabrics – 1.96% of the total volume of technical textile production.

As already noted, Western experts classify technical textiles only by areas of application. It is this difference in classification that led to the fact that in the USSR the share of industrial fabrics in 1990 was only 1/12 of the total volume of textiles produced in the country. At the same time, in the developed countries of the world it was equal to: 1/3 in the USA, 1/4 in Japan and Germany[38].

Technical textiles are also classified by production technology (Table 8). Traditionally, technical textiles were divided into only two categories: fabrics (all products for technical purposes) and nonwovens. Japanese specialists, when classifying, pay attention to production technologies and types of raw materials used to manufacture this group of goods.

Table 8. Distribution of technical textile materials by technology and production volumes

Material Type	Share in EU countries,%
Fabrics	37,0
Nonwoven Fabrics	27,0
Combined	16,0
Other	20,0

Source: Problems of forming composite materials reinforced with bast fibers. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://journals.indexcopernicus.com/api/file/viewByFileId/1182909

The share of technical textiles produced from chemical fibers and yarns in the EU countries is more than 2 times higher than the volume of fabric production. For example, in Germany, when classifying technical products, only the areas of application of technical textiles are taken into account. Japanese colleagues pay primary attention to production technologies and types of raw materials used to manufacture this group of goods. Recently, there

38 Official Website of the International Trade Administration [Electronic resource]. Access mode: https://www.trade.gov/sites/default/files/2020

has been a tendency to increase the capacity of technical goods on the Ukrainian market. According to the results of literary studies, the volume of consumption of technical textiles has increased by 40% since the mid-1990s, and nonwovens by 67%. However, this growth is not provided by a significant increase in domestic production, but by imports. A characteristic feature of the Ukrainian technical textile market today is the very large advantage of imported goods over similar domestically produced goods. Currently, the volume of imports of nonwovens exceeds the volume of national production by 3.7 times. Unfortunately, the growth rate of domestic production of nonwoven materials in our country is significantly lower than the growth rate of imports[39].

It should also be noted that over the past 18 years, the domestic light industry has been in a state of protracted systemic crisis: business ties with traditional suppliers of raw materials have been destroyed, the production of equipment for light industry has practically ceased. In Ukraine, there are no state-owned enterprises for the production of nonwovens, there are only a small number of private enterprises. These are mainly joint-stock companies of a closed, open or public type and collective organizations.

Today, in Ukraine, the classification of technical textiles is carried out in accordance with the Ukrainian Classification of Goods for Foreign Economic Activity (UKT FEA) in accordance with the Law "On the Customs Tariff of Ukraine" dated 19.09.2013. No. 584-VII (as amended on 01.01.2017 in accordance with the amendments made by the Laws of 24.12.2015 No. 909-VIII, of 04.10.2016 No. 1645-VIII, of 20.12.2016 No. 1791-VIII) technical textiles belong to Section XI, Group 59 – textile materials, impregnated, coated or laminated; textile products for technical purposes[40].

In Ukraine, there are practically no government programs to support and develop the textile and light industry, as well as the production of raw materials for it. There is no general information and analytical center for light industry, no one carries out detailed statistical accounting of output volumes and other economic indicators of enterprises. Classification, as a method of commodity science, will allow systematizing the entire variety of modern goods on the world market. The presence of a clear classifica-

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39 International Trade Administration [Electronic resource]. Access mode: https://www.trade.gov/get-ndustry-updates-textilesapparel

40 Law of Ukraine № 2697-IX On the Customs Tariff of Ukraine [Electronic resource]. Access mode: https://zakon.rada.gov.ua/laws/show/2697-IX#Text

tion of goods according to certain characteristics will allow limiting access to the domestic market of potentially dangerous products.

Based on the results of the analysis, an expert survey conducted at enterprises manufacturing technical fabrics and among specialists engaged in the production of technical textiles, it can be concluded that technical and special fabrics can be divided according to the following characteristics:

1. Scope of application: textiles for agriculture; construction textiles; textiles for the production of footwear and ammunition; geotextiles (textiles for earthworks); textiles for the home; industrial textiles; medical textiles; textiles for mechanical engineering; environmental protection textiles; packaging textiles; sports textiles and textiles for tourism and recreation.
2. Types of raw materials: natural fibers, synthetic fibers, glass fibers; metal fibers; basalt and carbon fibers; other fibers.
3. Production technology: woven materials, woven, knitted, knitted products; non-woven materials (filtering, insulation, fillers, absorbers, bases for other industries and other materials); coated textiles; textiles with additives.

In this regard, based on the analysis of existing approaches to the classification of technical textiles in the world, the work identifies the main criteria by which technical textiles in Ukraine could be classified. We have proposed a hierarchical classification of technical textiles, which is presented in Fig. 14.

Based on the analysis of works in the field of classification of technical textiles, it can be concluded that the importance of technical textiles is difficult to overestimate, since its areas of application are practically limitless. Today, there is a huge difference in the approach to the classification of technical textiles, therefore, for the further development of the production of technical textiles, a more in-depth study of the properties of materials and the unification of work on assessing the quality of products of this subsector, the presence of a clear classification is extremely important.

Despite the wide spread of technical textiles, there is no consensus in the textile industry on the creation and organization of a classification for technical textiles. It has also been established that there is no international system for the classification of technical textiles, as a result of which there is a certain technological and marketing barrier to industrial production and use of technical textiles in various industries, which is a significant obstacle to investing in this subsector of the industry at all levels of production and consumption of finished products[41].

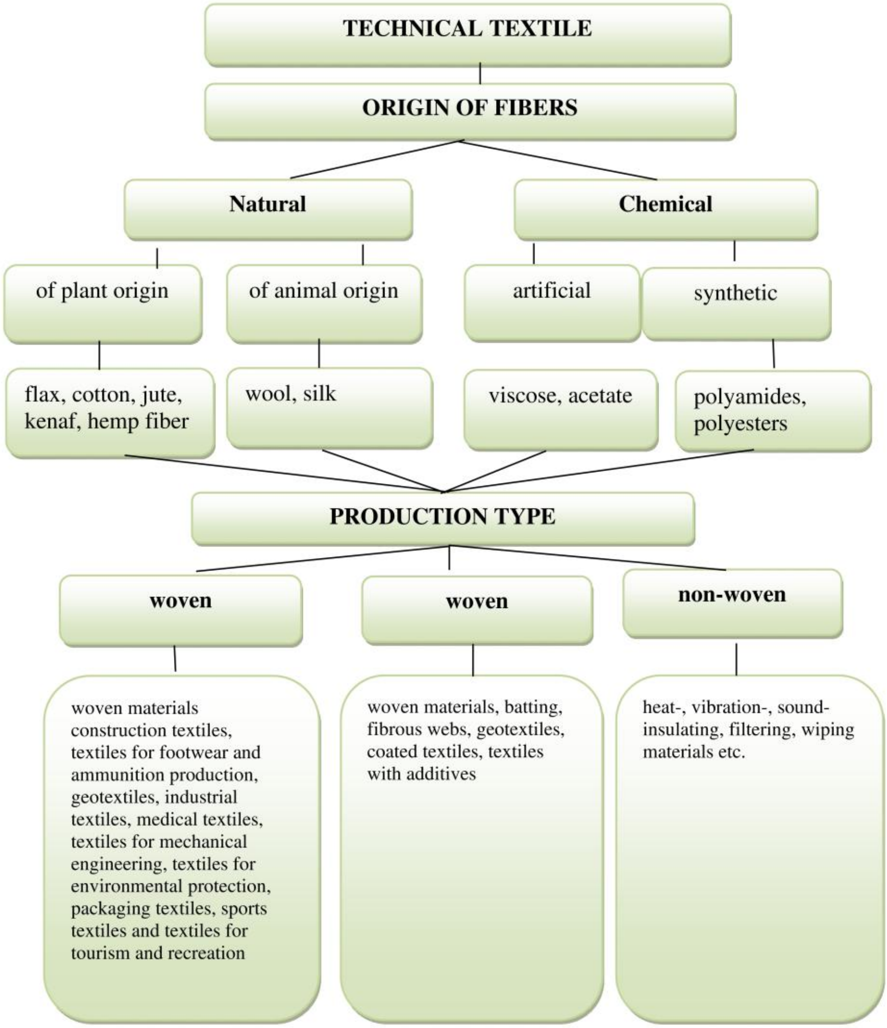

Fig. 14. Classification of technical textiles

Source: Classification of technical textiles. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ http://tr.knute.edu.ua/files/2018/02(26)/7.pdf

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41 Chursina, L., Gorach, O. (2020). Classification of technical textiles – the path to quality and safety. Collection "Scientific Bulletin of the Poltava University of Economics and Trade" series "Technical Sciences" №. 1 (96), 113-120. GOODS doi:10.37734/2518-7171-2020-1-14

Therefore, to ensure high quality of textile materials for technical purposes, it is necessary to invest and restructure the textile industry, develop processing production, and conduct scientific research to improve the effectiveness of protective equipment to provide special properties to textile materials depending on their purpose and operating conditions.

Analysis of the world production of technical textiles allows us to conclude that the further development of the market for these products, according to experts, will be associated with the production of protective textiles, geosynthetics, "smart fabrics", medical materials and products, as well as environmentally friendly technical textiles for various functional purposes. The economic growth of the Western European textile industry is due to its transition from the production of clothing fabrics to the production of industrial fabrics using natural raw materials. In recent years, technical textiles have become the most high-tech product of the modern world economy, thanks to their inherent complex of physical, chemical, and functional properties.

Thus, taking into account the above and analyzing the areas of application of technical textiles and its classification in different countries of the world, we can conclude that an important task of this dissertation is to establish the physical and mechanical characteristics of oil flax fibers, which would become the basis for determining the criteria for their suitability for the production of high-quality technical materials and products for a specific purpose.

The national economy needs deep transformations, particularly in light industry. In Ukraine, domestic producers continue to gradually lose many segments of the domestic market of goods, which is associated with the low competitiveness of domestic enterprises in the conditions of economic openness and accession to the WTO.

In our country, practically none of the government programs for the support and development of the textile and light industry, as well as the production of raw materials for it, are currently operating. There is no general industry information and analytical center for light industry, and no one carries out detailed statistical accounting of production volumes and other economic indicators of the work of enterprises.

However, the light industry of Ukraine is an industry with a powerful production potential, capable of producing a wide range of consumer products, including technical products. In our opinion, in order to successfully compete at the domestic, European and global levels, it is necessary to apply a new approach to production using innovative technologies for obtaining technical textiles of various functional purposes based on our own cheap environmentally friendly raw materials – oil flax fiber.

Thanks to scientific and technological progress, significant changes have occurred in the cultivation of industrial crops in Ukraine in recent years. Sowings of long flax have significantly decreased, and oil flax has increased significantly. For 11 years, it has been ranked 3rd in the list of the most profitable industrial crops after sunflower and rapeseed. This is due to the increasing demand in Europe for seeds of this crop. World production of oil flax seeds also tends to increase every year[42].

The unconditional value of the seeds of this crop is associated with the presence of various organic compounds in it. Flax seeds are an excellent source of balanced essential fatty acids, especially omega-3 acid, which is responsible for the growth and normal state of the body, and also contains such biologically active compounds as sterols, squalene, vitamin E and some other substances. That is why it is widely used in many countries.

The main consumer of the seeds of this crop, from which flax oil and meal are obtained, in Ukraine is the processing industry. Flax oil is also a raw material for technical purposes in the chemical industry. Flax meal is an excellent component with a high protein content for the production of compound feed. However, the chemical industry and livestock farming in Ukraine are currently in decline, so flax is processed only by individual private companies. Flax meal is actively used as feed for the private sector only in the regions where the seeds of this crop are grown and processed.

Since 2008, when GM additives were found in Canadian flaxseed, the EU has shown great interest in seeds from the CIS countries, as they are environmentally safe. Thus, the total volume of exports of this product from Kazakhstan and Ukraine as of the end of July 2012 was 510 thousand tons, which is 2 times more than the indicators of the previous year (237 thousand tons). The main buyers of Ukrainian oilseed flax were Belgium – 8659 tons, Poland – 4286 tons, Lithuania – 2945 tons, Germany – 2048 tons, Italy – 1542 tons. In 2012, an unexpected importer of Ukrainian flax appeared – Vietnam, which purchased almost 10 thousand tons of seeds. In total,

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[42] Horach O.O., Tikhosova G.A., Zabrodina O.S. (2021) Problems of forming composite materials reinforced with bast fibers Tovaroznavchy visnyk: collection of scientific papers. Issue 14. Lutsk: RVV Lutsk National Technical University. P. 267-274. https://doi.org/10.36910/6775-2310-5283-2021-14

Ukraine exported 30 thousand tons of flaxseed, or almost 5.9% of the above-mentioned total exports[43].

The increase in global demand for Ukrainian flaxseed contributes to the constant growth of the sown areas allocated for this crop.

Despite the fact that flaxseed export is a promising direction due to its growing popularity on the world market, so far flax straw in Ukraine is almost not used in industrial production. However, there are potential consumers of this raw material in our country.

According to statistical data from state institutions, in 2015, Ukraine had 58 firms and companies producing technical textiles, more than 100 pulp and paper enterprises and 2,424 small and large light industry enterprises producing household textiles.

Thus, today in Ukraine there are successfully operating enterprises engaged in the manufacture of a wide range of technical products. Thus, the company "VELAM" produces high-quality environmentally friendly products, using modern technologies and European quality standards in production. Currently, the company is represented by about 500 enterprises in our country. The successful development of the company indicates that technical products are in great demand both in the domestic and foreign markets[44].

The list of products currently manufactured is represented by the following technical products: mattresses, sleeping bags, non-woven materials, as well as upholstered furniture. Non-woven materials are widely used for the production of mattresses by the VELAM company. They are diverse in purpose, properties, structure and physical and mechanical characteristics.

The most actively used materials are Sprut, Thermoflex, Thermofelt and Velaflex (Fig. 15-18). Some of them act as a frame, thanks to which a stable shape of mattresses is formed and the load is distributed. Bulky but dense materials in combination with other floorings (latex, coir) form an obligatory soft element of mattresses. Quilted covers contain light bulk fillers, including those containing siliconized polyester fibers.

All non-woven materials used are products of the VELAM company. The main component of the raw materials is various polyester fibers.

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43 Mezrea, P.E., Ispir, M., Balci, I.A., et al. (2021). Diagonal tensile tests on historical brick masonry wallets strengthened with fabric reinforced cementitious mortar. Structures, eISSN 2352-0124, Vol. 33, 935-946, https://doi.org/10.1016/j.istruc.2021.04.076

44 Gorach, O., Dombrovska, O., Tikhosova, A. (2021). Scientific development of innovative technologies of obtaining composite materials from of oilseed flax fibers Vlákna a textil. Vol. 28(4), 25-30. http://vat.ft.tul.cz/2021/4/VaT_2021_4_4.pdf

To simulate the properties of these materials, natural fibers are introduced into their composition: cotton, linen, hemp, wool, coconut fibers, including regenerated fibers.

Fig. 15. Bulk nonwoven material "Sprut"

Source: Velam. www.velam.com.ua/ua/catalogue/netman/nikotex

The bulk nonwoven material "Sprut" is no longer a novelty on the Ukrainian materials market. Its production was first started in the post-Soviet space in Mykolaiv in 1998. After long tests, changes and improvements to its production technology, its use as a flooring material in furniture based on spring blocks was recognized as the most optimal. The material allowed finding new solutions in the technology of mattress production.

"Sprut" is a bulk nonwoven fibrous flooring material. It is distinguished by its ability to increase the effect of elasticity and durability of mattress surfaces. The author's (company "VELAM") technologies of combining PET fibers with cotton, wool and hemp fibers in optimal ratios ensure high quality materials for mattresses: maximum degree of air permeability, heat generation and heat exchange. The material is environmentally safe, exposed to high temperature.

"Thermoflex" material from the company "VELAM" is an analogue of the "Sprut" material. For its production, a similar raw material is used – a mixture of polyester fibers and regenerated cotton and wool fibers, however, due to the change in technology, the orientation of the fibers in the structure of the material has also changed from vertical to horizontal. As a result, the non-woven material "Thermoflex" differs in properties from the material "Sprut": it is more elastic and wear-resistant; both of these materials have high air permeability. The elastic volumetric structure of the material "Thermoflex" from compacted horizontal layers of fibers combines stability and elasticity of the surface, increases the height of the mattress and at the same time evenly distributes the load.

Fig. 16. Thermoflex nonwoven material

Source: Velam. www.velam.com.ua/ua/catalogue/netman/nikotex

"Thermofelt" is a flooring material from the company "VELAM", a product of thermal bonding of fibers and an integral element of a quality mattress. It is designed to distribute the load and create stable protection of soft flooring from the metal structure of the spring block.

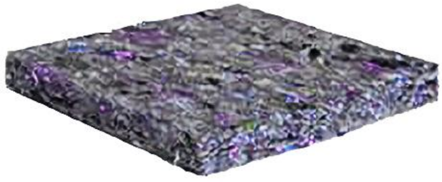

Fig. 17. Non-woven material "Thermofelt"

Source: Velam. www.velam.com.ua/ua/catalogue/netman/nikotex

Selection of the optimal fiber composition and material density allows you to simulate certain properties of different mattress models, leveling or enhancing the level of their rigidity and elasticity.

The material is produced in the form of plates and in the form of rolls of 10-50 m, depending on the density of the material.

Areas of application: furniture industry – hard flooring during the production of mattresses, forming upholstered furniture; automotive industry – for reinforcing parts, as a sound-absorbing insulation.

"Velaflex" is a volumetric material from a combination of PET fibers, which have increased biostability. It is characterized by antistatic and hypoallergenic properties. Due to these properties, "Velaflex" improves not only the quality of mattresses, but also the quality of a person's rest environment.

Advantages of the material: absence of adhesive components, high elasticity and breathability, that is, the presence of higher-level properties that determine its quality, comfort and durability. Additional advantages of mattresses using Velaflex are increased elasticity of mattress surfaces, creation of conditions for active air exchange inside the products, and therefore, improvement of the ecology of the recreation area.

Fig. 18. Non-woven material "Velaflex"

Source: Velam. www.velam.com.ua/ua/catalogue/netman/nikotex

Based on the analysis of nonwovens currently used to manufacture products of the company "VELAM", it can be concluded that the main component of the raw materials for their production are various polyester fibers. And only for modeling the properties of materials is used a small amount of natural fibers, which are mainly represented by coconut fiber and regenerated natural fibers.

Analysis of the results of experimental studies of the quality indicators of oil flax fiber, which were carried out in recent years, conducted by scientists of the Kherson National Technical University, allows us to conclude that the production of environmentally friendly technical textiles of various functional purposes using oil flax fiber is an urgent task for Ukraine in the conditions of a market economy. Successful introduction into production at domestic enterprises of annually renewable oil flax fiber will contribute to the production of high-quality competitive products of technical purpose in our country[45].

The cost of coconut fiber, which is currently used for the production of non-woven materials by the company "VELAM", is 38,000 UAH/t. The price of domestic annually renewable oil flax fiber is 18,000 UAH/t, that is, it is half the cost of coconut fiber. In addition, this fiber does not require customs clearance and transport costs for delivery, since it does not need to be imported into the territory of Ukraine.

The use of oil flax fiber will allow farms that grow this crop to successfully sell straw at commercial prices, as is currently the case in European countries. The use of all the potential inherent in the plant – seeds, fiber and coir – will improve the environmental situation in Ukraine, reduce the fire hazard situation in the south of Ukraine, where oil flax crops are mainly concentrated, and fill the domestic market with environmentally friendly products that will also find their consumer abroad.

The use of flax bast and oilseed fiber for the manufacture of technical products with the introduction of innovative technologies will allow domestic manufacturers to compete with foreign companies in the technical textile segment, which is the fastest growing in the global textile market. However, in order for the resulting products to compete with imported products, it is necessary to carry out scientific research and introduce innovative technologies for the use of flax oilseed fiber for the manufacture of technical products[46]

Currently, due to the increase in prices for cotton and wool raw materials, as well as taking into account the shortage of natural fibrous materials for textile enterprises in Ukraine, the question of replacing imported cotton with domestic raw materials has become acute. One of the sources of raw materials is oil flax, which until recently was considered a poorly suited or even unsuitable raw material, since the stems of this crop contain mostly short fibers. Until a certain time, oil flax fiber was not used effectively

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45 Horach, O.O., Tikhosova, G.A., Zabrodina, O.S. (2021). Problems of forming composite materials reinforced with bast fibers Tovaroznavchy visnyk: collection of scientific papers. Issue 14. Lutsk: RVV Lutsk National Technical University, 267-274. https://doi.org/10.36910/6775-2310-5283-2021-14

46 Khan, S.U.; Labonne, L.; Ouagne, P.; Evon, P. (2021). Continuous mechanical extraction of fibres from linseed flax straw for subsequent geotextile applications. Coatings. 11, 852. [CrossRef] https://doi.org/10.3390/coatings11070852

enough, and even then only for the production of packaging materials, ropes, ropes, twine. However, provided that modern progressive technologies for the production of technical products currently used in the EU countries are used, the fiber of this crop can be used for the production of technical textiles: nonwovens, insulation, geotextiles and agrotextiles. Therefore, oil flax fibers are a worthy alternative to cotton, which is imported into our country on order of domestic textile manufacturers. The use of our own cheap annually renewable raw materials in the domestic textile industry will contribute to solving the problem of import substitution and will allow filling the Ukrainian market with environmentally friendly and safe products for technical purposes[47].

Cellulose-containing fiber of oil flax is much superior to cotton in its medical-biological and physical-mechanical properties. Due to such a unique complex of properties of flax as hygiene, high strength, low electrical resistance and ability to absorb dust, comfort, natural bactericidal properties (antiseptic and anti-rot), the demand for flax and flax-containing textile materials around the world is growing from year to year. Being an alternative to cotton fiber, flax can replace it in the production of products of leading sectors of the economy by 30-40% and thereby increase the country's financial independence from imports of cotton and finished products, including those of strategic purpose.

Introduction into production of innovative technologies for obtaining technical textiles of various functional purposes using oil flax fiber is an important task of today, which will ensure the expansion of the scope of its application in industry. Since flaxseed is an environmentally friendly raw material, it will allow for import substitution of cotton in the production of cellulose, geotextiles, composite and nonwoven materials, sanitary and hygienic products, etc. A promising area of application of flaxseed is also the production of composite materials. Fifty years ago, composite materials were not so widely used, and only a narrow circle of specialists knew about the modern concept of "composites". However, the rapid development of science and technology leads to the creation of new materials on the existing raw material base, but using new component formulations and manufacturing technologies. This provides the possibility of obtaining materials that have high operational properties, are characterized by durability and reliabil-

[47] Hägglund, M. (2020). Rebuilding Sweden's crisis preparedness : Lack of clarity impedes implementation. FIIA. Finnish Institute of International Affairs, ISSN 1795-8059, Vol. 5, https://www.fiia.fi/wp-content/uploads/2020/05/bp283_sweden_crisis-preparedness.pdf

ity[48]. Many composites surpass traditional materials and alloys in their mechanical properties; they are characterized by high strength, rigidity, and at the same time they are lighter. The use of composites usually allows you to reduce the mass of the structure while maintaining or improving its mechanical characteristics.

According to the structure of the filler, composite materials are divided into:

- fibrous – reinforced with fibers and filamentary crystals;
- layered – reinforced with films, plates, layered fillers;
- dispersion-reinforced – with fillers in the form of finely dispersed particles.

Fig. 19 shows a diagram of the structure of composite materials.

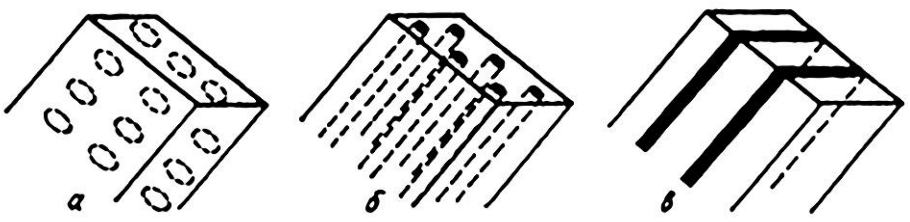

Fig. 19. Structural scheme of composite materials:
a – dispersion-reinforced; b – fibrous; c – layered

Source: Composite materials.
https://stud.com.ua/36297/tovaroznavstvo/kompozitsiyni_materiali

The choice of reinforcing fiber is determined primarily by the requirements for the quality of the final product. The main materials from which reinforcing fibers are made (both short and long) are glass, graphite, aluminum, carbon, boron and beryllium. Natural fibers such as flax, hemp, jute, sisal, coconut, etc. are also used for reinforcement.

Currently, Finland and Germany produce structural materials reinforced with flax fiber. North America has also begun to use composites made of natural fibers.

48 Ahrari, M., Karahan, M., Karahan, N. (2023). Competitiveness Factors in Textiles and Composites Industry and Transformation into Value-Added Products. RECENT journal, Vol. 24, is. 2(73), pp. 132-141, https://doi.org/10.31926/RECENT.2023.70.132

Composite materials reinforced with plant fibers are most widely used in the automotive industry. Today, strong, corrosion-resistant, lightweight polymer composites are increasingly used for the production of cars. In modern cars, they make up more than 10% (by weight) and their content is constantly increasing[49].

Reinforcing plastics with natural fibers, such as flax fiber, allows you to significantly simplify, compared to fiberglass reinforcement, the processing of parts that have served their time. Thus, the fiber of this crop, having the appropriate physical and mechanical characteristics, can be widely used in the automotive industry for the production of composite materials. Therefore, the development of domestic resource-saving technologies for processing flax straw stalks in order to obtain cellulose-containing semi-finished products suitable for reinforcing composite materials is an urgent task today.

Flax fiber filler can be used to reinforce structural polymer materials both in the form of a pre-formed non-woven material and in the form of a mixture with a heated polymer. It is obtained in the processes of casting, extrusion or pressing. The interaction of fibers with the matrix should ensure high realization of the mechanical properties of the fibers in the reinforced material and its monolith city. This requires: high wettability of the fibers by the matrix; high adhesion between the fiber and the matrix, which is characterized by shear strength at the fiber-matrix interface; absence or minimal change in the properties of the fibers under the action of the matrix components; relaxation of internal stresses in the elementary volume of the fiber-matrix during heat treatment or under the action of the binder components and other factors[50].

The selection of components of composite fibrous materials is carried out taking into account the individual properties of the fibrous semi-finished product and the polymer matrix, as well as their mutual influence, which is determined by many factors, the main of which are: strength, deformation and other properties of the fibers, heat resistance, length and diameter of the

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49 Ari A., Karahan M., Karahan N. (2024). Competency Mapping of Textile and Composite Industries: A Regional-Global Case Study. RECENT, eISSN 2065-4529, Vol. 25, is. 1(72), 20-39, https://doi.org/ 10.31926/RECENT.2024.72.020

50 Karahan, M., Ahrari, M., Karahan, N. (2023). Composite Materials Market Research and Export Potential Analysis:A Regio-Global Case Study. RECENT journal, Vol. 24, is. 2(73), 113-121, https://doi.org/ 10.31926/RECENT.2023.70.113

fibers, structure of the fibrous material, viscosity of the polymer matrix under processing conditions.

Reinforcing fibrous semi-finished products are intermediate materials containing a given amount of fibrous filler and polymer matrix, prepared for direct use. They are a convenient release form of semi-finished products prepared for the production of composite materials and products. Most often they are produced in granular form, but can also be in the form of threads, bundles, tapes, fabrics, non-woven fabrics and paper.

It should be noted that reinforcing fibrous semi-finished products made on the basis of chopped fibers containing a given amount of starting components – thermosetting monomers or oligomers, hardeners and other components – look like fibrous pieces of mass of irregular shape. These can be fibers, tablets, granules, as well as a thick dough-like mass.

The method of reinforcing with natural fibers makes it possible to obtain a diverse range of products that are widely used in mechanical engineering, for the manufacture of building and furniture boards, window frames, etc.

The main advantages of natural fibers are:

- lower specific gravity;
- better heat and sound insulation properties;
- the process of producing natural fibers does not require large labor costs and capital investments;
- depending on the polymer matrix, the fibers can be processed;
- easier disposal.

The length of the fibers is most often in the range from 3 to 20 mm. As binders, phenol-formaldehyde resins are usually used, less often melamine, epoxy and other thermosetting resins. The binder content reaches 40-50% of the mass of the semi-finished product[51].

Reinforced fiber semi-finished products are obtained by combining fiber fillers with a polymer matrix. As a result of research by scientists from different countries of the world, it has been found that sometimes it is necessary to modify the surface of the fibers or the composition of the polymer

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[51] Karahan, M., Ari, A., Karahan, N. (2024). Examination of R&D Capacity in the Technical Textile Sector: A Regio-Global Case Study. RECENT, eISSN 2065-4529, Vol. 25, is. 1(72), 4-19, https://doi.org/10.31926/RECENT.2024.72.004

matrix to improve wettability and adhesion[52]. For this purpose, various methods are used: chemical modifying treatments of fibers, etching with oxidizing agents, surface hydrolysis, etc. Thus, it can be stated that a very important characteristic of reinforced fibrous semi-finished products is the achievement of high quality impregnation and the absence of air inclusions both at the fiber-binder interface and in the binder layer. Only under these conditions can the production of high-quality monolithic fibrous composites be ensured.

In addition, an equally important problem is ensuring a long shelf life of reinforced fiber semi-finished products without losing their technological properties. This is mainly due to the choice of binders, the curing rate of which is quite low under the conditions of storage of reinforced fiber semi-finished products. The properties of composite materials obtained from reinforced fiber semi-finished products are determined by their physico-chemical characteristics.

The leading manufacturer of composite materials, including those reinforced with natural fibers, in Ukraine is the subsidiary enterprise "Plastmas" of the limited liability company "Trading House Plastmas – Pryluky" (hereinafter the leading manufacturer of these products in Ukraine is the enterprise of the State Enterprise "Plastmas" LLC "TD Plastmas-Pryluky"). It was established in 2003 on the basis of the Pryluky Plastics Plant, founded in 1931.

Currently, the range of products manufactured by the enterprise includes over 90 items. The basis of the product range is:

– polyvinyl chloride plastic compounds, which are the raw material for the production of insulation of protective sheaths of wires and cables;
– phenolic molding compounds (phenolic compounds), which are the raw material for the production of reinforced and unreinforced products for technical purposes;
– parts made of general and special-purpose plastics;
– high-pressure polyethylene compositions;
– polyvinyl chloride blocks made of PP-45 plastic compound;
– polyethylene pipes, bakelite varnishes, etc.

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[52] Horach, O.O., Tikhosova, G.A., Zabrodina, O.S. (2021). Problems of forming composite materials reinforced with bast fibers Tovaroznavchy visnyk: collection of scientific papers. Issue 14. Lutsk: RVV Lutsk National Technical University, 267-274. https://doi.org/10.36910/6775-2310-5283-2021-14

The enterprise operates stably, monthly increasing the production volumes of products that are consumed not only in Ukraine, but also exported to the CIS countries. SE "Plastmas" LLC "TD Plastmas-Pryluky" has an ISO 9001:2000 certificate for the quality management system.

The company's products are widely used in mechanical engineering, mining, oil and gas, electrical engineering, transport and other industries, the military-industrial complex, the production of sports and recreation goods and footwear. In addition, the State Enterprise "Plastmas" LLC "TD Plastmas-Pryluky" operates a workshop for processing secondary materials, which produces polyvinyl chloride, polyethylene, polypropylene, containers and packaging materials (cardboard and paper bags). Cotton fiber imported from Uzbekistan is used to reinforce phenolic plastics at the enterprise.

Thus, the State Enterprise "Plastmas" LLC "TD Plastmas-Pryluky" can become a potential consumer of domestic raw materials – bast and oil flax fiber, using them in the production of fillers for composites and the manufacture of packaging materials.

It is known from the works of domestic and foreign scientists that flax fiber is widely used for the manufacture of composite materials. In some northern countries (Finland, Norway, Germany) flaxseed crops are oriented towards the industrial use of fiber for the production of composite materials. Scientists from different countries of the world, in particular, Langer E. (Germany), Kathleen VDV. (Belgium), Ton-That MT, Denault J. (Canada), Mieleniak V., Bagley S., d'Anselme T., Guyader J. (USA), Pallesen (Denmark) and others. are successfully conducting research on the modification of natural fibers to obtain polymer composite materials with natural fibers as fillers. However, the theoretical justification of this process and a detailed description of the technologies for manufacturing polymer composite materials reinforced with natural fibers are not given in their works[53].

Taking into account the above, the direction of research was chosen during the implementation of this dissertation work – the development of a technology for obtaining from flax straw stalks oil technical textiles with certain physical and mechanical characteristics and physical and chemical indicators, suitable for reinforcing composite materials.

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53 Gorach, O., Dombrovska, O., Tikhosova, A. (2021). Development of resource-saving technologies for obtaining composite materials based on the use of oilseed flax fibers Inmateh – agricultural engineering. Vol. 65(3), 275-282. https://doi.org/10.35633/inmateh-65-29

Successful production implementation at Ukrainian enterprises of the developed innovative technology for the production of technical textiles using annually renewable raw materials – oil flax fibers – will contribute to the entry of domestic competitive products into the world market.

2.5. Use of oil flax seeds in the food industry

In the history of Slavic peoples, flax has been of great importance since ancient times as a technical crop in weaving and as a medicinal agent in folk medicine. Today, flax seeds produced by ZAO "Liktravy" are a recognized medicinal product, and flax seed oil is a valuable dietary supplement to the diet. It contains valuable PUFAs necessary for all vital processes of the body. At the same time, flax seed oil is ahead of other vegetable oils in terms of the content of omega-3 PUFAs. These acids help strengthen immunity, help in the fight against inflammatory, cardiovascular and endocrine diseases, and help remove harmful substances from the body. And lignans (plant hormones) contained in flax seed oil are well-known antioxidants that prevent the development of malignant tumors. Vitamins A, B, E, F regulate lipid and cholesterol metabolism, enrich the body with vitamins of youth (A, E). Of course, what oil is without trace elements? Yes, flax seeds and products made from them are an important source of selenium, an element important in the prevention of cancer[54].

Recent studies have revealed the extraordinary medicinal properties of flaxseed oil. Unsaturated fatty acids accelerate the metabolism of cholesterol in the blood and promote its excretion, improve metabolism, have a positive effect on blood pressure, reduce the risk of cardiovascular and cancer diseases, and allergic reactions. Preparations made on the basis of flaxseed oil successfully treat burns and skin inflammation. In turn, flaxseed processing products, namely cake and meal, are very valuable feed for livestock.

The domestic market is characterized by a balance between supply and demand for oil flaxseed. This is influenced by the fact that not all oil and fat processing plants are engaged in the processing of flaxseed. In order to process such seeds, it is necessary to form appropriate reserves of raw materials

[54] Horach, O.O., Dombrovska, O.P., Chursina, L.A. (2021). Innovative directions of using oilseed flax and ecological safety of food products. Collective monograph "Formation of a new paradigm of the development of the agro-industrial sector in the 21st century". Vol. 2. Kherson, 593-619. doi:10.30890/2709-2313.2023-23-01

to ensure the continuous operation of technological lines and the production of oil in a sufficient volume to form a commodity batch. It should be borne in mind that some processing enterprises temporarily or completely refuse to process oil flax in the middle of the season. In addition, the processing plant in the city of Donetsk, which specialized in such seeds, suspended its activities due to military operations in the region.

Flaxseed is an export crop. Its internal processing is insignificant. More than 30 thousand tons of this seed are exported annually. The main buyers of Ukrainian flax are Belgium, Poland, Lithuania, Germany, and Italy. The main products of processing are linseed oil, cake, and meal. In turn, flaxseed cake is used by the private sector only in the regions where the product is produced[55].

The supply of oilseed to processing enterprises has its own specifics. The greatest trading activity on the market was observed in August-September, in the period after the harvest of the crop. It is at this time that the main commercial volumes of products are sold. In the middle of the season, commercial seeds enter the market in limited quantities. For the most part, these are batches of up to 10 tons, which are of little interest to buyers. Export-oriented companies are ready to purchase oilseeds at the highest existing prices, but the market has formed a shortage of large-tonnage batches of the appropriate quality of this seed.

The sale of the grown crop is carried out from the producers' own warehouses. Ukrainian elevators do not accept oilseeds for storage due to the small volumes and the need for significant seed processing. Batches of this product must meet the following requirements: moisture content of up to 9%, waste impurities of 2%, oil impurities of 4%, oil content of at least 35%, and be free from pests, which can be achieved through additional cleaning and drying. In addition, sending the product for export requires its packaging in bags or big bags, and most elevators do not have the necessary equipment for this[56].

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55 Ahmad, A., Zulfiqar, S., & Chatha, Z. A. (2020). Development of roasted flax seed cookies and characterization for chemical and organoleptic parameters, Pakistan Journal of Agricultural Sciences, 57, 229-235. https://doi.org/10.21162/PAKJAS/20.6552

56 Ahmad, N., Manzoor, M. F., Shabbir, U., Ahmed, S., Ismail, T., Saeed, F., Nisa, M., Anjum, F. M., & Hussain, S. (2020). Health lipid indices and physicochemical properties of dual fortified yogurt with extruded flaxseed omega fatty acids and fibers for hypercholesterolemic subjects. Food Science & Nutrition, 8(1), 273-280. https://doi.org/10.1002/fsn3.1302

Flaxseed oil is a source of nutrients and can be used as a food product. The benefits of natural flaxseed oil have been known since ancient times. So, in the 19th century, it was the main source of vegetable fats in the diet of the population. The unique composition of flaxseed oil is so valuable for the human body that it can be the most important among other edible vegetable oils[57]. Flaxseed oil is a source of polyunsaturated fatty acids: linolenic, linoleic, oleic, which are better known as acids under the general name "Omega". The human body does not produce these acids and can only obtain them from the outside. The composition of linseed oil is so rich in useful substances that it is enough to eat 1-2 tablespoons of it to meet the daily need of the body in fatty acids and fats of vegetable origin.

Flaxseed oil (Fig. 20) is gaining popularity among the population of Ukraine. Despite the fact that it is more expensive than sunflower and has a specific taste, the demand for it remains stable due to the presence of a huge amount of useful substances in its composition. That is why many manufacturers of vegetable oils, seeking to expand their range, choose linseed oil.

Fig. 20. Flaxseed oil and seeds

Source: Flax seeds. Useful properties, use for weight loss and is there any harm. https://belok.ua/blog/ua/semena-lna-polza-i-primenenie/

57 Ahmadniay motlagh, H., Aalipanah, E., Mazidi, M., & Faghih, S. (2021). Effect of flaxseed consumption on central obesity, serum lipids, and adiponectin level in overweight or obese women: A randomised controlled clinical trial. International Journal of Clinical Practice, 75(10), e14592. https://doi.org/10.1111/ijcp.14592

Linseed oil is used in cooking, perfumery, and medicine. Recent studies have revealed extraordinary therapeutic and prophylactic properties of linseed oil, thanks to which its use helps to reduce blood cholesterol levels and its excretion, improves protein and fat metabolism, has a beneficial effect on blood pressure, relieves spasms of blood vessels, and prevents the formation of blood clots and tumors. Biological compounds such as lignins cause the blocking of enzymes involved in hormonal metabolism, inhibit the growth and spread of cancer cells. Preparations made from linseed oil are used externally for radiation skin lesions and burns. Linseed oil is the best helper for the immune system[58].

The composition of flaxseed oil includes such fatty acids as: palmitic (5-7%), stearic (3-4%), oleic (16-20%), linoleic (14-17%), linolenic (50-60%). Flaxseed oil can be divided into four categories according to its linolenic acid content: linolenic acid content of more than 50% – high, the oil is suitable mainly for technical purposes; linolenic acid content of 36-49% – medium, the oil is suitable for technical purposes, in medicine, perfumery; linolenic acid content of 10-35% – low, the oil is suitable mainly for food purposes; linolenic acid content of less than 10% – very low, the oil is suitable only for food purposes[59].

It should be noted that all flaxseed oil can be consumed, but the high content of linolenic acid in the oil leads to its rapid oxidation and rancidity, shortens the shelf life of food to two months and thus limits the widespread introduction of flaxseed oil into the pharmaceutical and food markets, and reduces its commercial value in industrial production.

The problem of long-term storage of flaxseed oil in the world is solved by breeding special varieties with a reduced content of linolenic and increased oleic acids. The most suitable for food purposes are varieties of medical and food flax with increased oxystability due to the changed qualitative composition of the oil and the content of antioxidants (tocopherols, flavonoids, etc.), which significantly extends the shelf life of the oil.

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58 Horach, O.O., Dombrovska, O.P., Chursina, L.A. (2021). Innovative directions of using oilseed flax and ecological safety of food products. Formation of a new paradigm of the development of the agro-industrial sector in the 21st century" edited by Avercheva O.V. Collective monograph. Kherson: Liga-Press, Volume 2, 593-619. https://doi.org/10.30890/2709-2313.2023-23-01-014

59 Akter, Y., Junaid, M., Afrose, S. S., Nahrin, A., Alam, M. S., Sharmin, T., Akter, R., & Hosen, S. Z. (2021). A comprehensive review on Linum usitatissimum medicinal plant: Its phytochemistry, pharmacology and ethnomedicinal uses. Mini Reviews in Medicinal Chemistry, 21(18), 28012834. https://doi.org/10.2174/1389557521666210203153436

Currently, consumers are increasingly turning to flaxseed because of its beneficial effects on human health. Studies have shown that consuming flax seeds improves digestion, stimulates the activity of the gastrointestinal tract and helps regulate blood glucose levels. Flax seeds have also been widely used since ancient times as a medical remedy for preparing decoctions. Flax seeds contain 100 times more biologically active substances – lignans – than other plants. They have a positive effect on the body's immune system, reduce the risk of cancer and diabetes[60].

The nutritional value of flaxseed protein in a point estimate (casein, taken as 100) is estimated at 92 units. It does not lose its properties for three years and is widely used in countries around the world as an additive to various types of bread, sprinkling confectionery. The foreign baking industry widely uses flaxseed as a component for baking baked goods. In addition to usefulness, pastries acquire a tenderness of taste caused by the fat component and a characteristic crunchiness. In Germany, more than 60 thousand tons of flaxseed are used annually in baking and for preparing various dishes. On average, this is about 1 kg per person per year, or 2.5 g per day. Flaxseed can be used in yogurts, grain dishes and salads. The Ministry of Health of Canada and the USA recommends the mandatory daily consumption of flaxseed in food. In Canada, flaxseed is even considered a separate type of food product, rather than a food supplement. In supermarkets in North and South America, as well as in Europe and Asia, you can buy chicken eggs enriched with flaxseed nutrients[61]. Fig. 21 shows a sample of the range of flaxseed oil that can be purchased as a dietary supplement at a pharmacy.

Fig. 21. Flaxseed oil producer LYKTRAVY (Ukraine)

Source: Flaxseed. https://liktravy.ua/lonu-nasinnja-dd-200-g-p22055502800000

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60 Bennato, F., Ianni, A., Innosa, D., Grotta, L., D'Onofrio, A., & Martino, G. (2020). Chemical-nutritional characteristics and aromatic profile of milk and related dairy products obtained from goats fed with extruded linseed. Asian-Australasian Journal of Animal Sciences, 33(1), 148-156. https://doi.org/10.5713/ajas.18.0868

61 Danish, M., Ahmad, T., Ayoub, M., Geremew, B., & Adeloju, S. (2020). Conversion of flaxseed oil into biodiesel using KOH catalyst: Optimization and characterization dataset. Data in Brief, 29, 105225. https://doi.org/10.1016/j.dib.2020.105225

In the range of varieties of oil flax, included in the State Register of Plants of Ukraine, the mass of 1000 seeds varies within 7-8 g. A feature of food varieties is lower than that of technical varieties, the mass of 1000 seeds (within 5-6 g). Such seeds meet the requirements of the confectionery industry on the world market.

Edible oil, which is used in the food, pharmaceutical and cosmetic industries, is obtained only by cold pressing (at temperatures below 35°C). The main advantage of such technology is that it does not require the use of chemical solvents and allows you to produce a natural product with the preservation of all useful substances in their natural state.

A mandatory requirement for the production of edible oil is high-quality raw materials. The quality of raw materials that are sent for processing is characterized by moisture and dirtiness. Selected, fresh dried seeds with a moisture content of no more than 10% are used. In terms of contamination, flaxseed with a content of up to 1% of impurities is considered clean. The use of stale, old seeds leads to a deterioration in the quality of the final product – the oil will be rancid, and the shelf life will be noticeably reduced.

Edible oil has its own characteristics: color – light yellow of various shades, transparent after settling, without foreign odor, taste, bitterness. Acid number – no more than 2.0 (oil with an acid number of 2.2 and above is considered technical). Specific gravity – 0.928-0.942. Refraction – 68-79. Iodine number – 157-205. Saponification number – 184-194. Unsaponifiable matter – no more than 1%. Flaxseed oil should only be used cold. During the processing of edible flax seeds into linseed oil, another by-product is formed – cake, which can be used as a protein additive for organic feed[62].

The oilcake processing technology improved at the Institute of Oil Crops by introducing an additional operation of mechanical fractionation of crushed oilcake into protein and husk fractions allows to isolate more than 40% of protein powder with a protein content of at least 38%. The husk fraction, which includes the bulk of fiber, is used to produce fuel briquettes.

The content of 8-12% of oil in protein powder contributes to its rapid oxidation, which leads to a decrease in the quality of the protein supplement. To increase the time of the oxidation process, it is proposed to produce the protein fraction in the form of pellets. In addition to avoiding rapid oxida-

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[62] Deng, Y., Chen, J., Huang, J., Yang, X., Zhang, X., Yuan, S., & Liao, W. (2020). Preparation and characterization of cellulose/flaxseed gum composite hydrogel and its hemostatic and wound healing functions evaluation. Cellulose, 27(7), 3971-3988. https://doi.org/10.1007/s10570-020-03055-3

tion, the pelleting process will reduce the volume of product storage in warehouses and reduce the costs of their transportation. Therefore, solving the issues of mechanization of oilcake processing by improving the technology and equipment for separating it into protein fraction (pellets) and husk (fuel briquettes) is quite relevant[63].

The Institute of Oilseeds of the NAAS has proposed a line for processing edible flax seeds, which includes the following stages of the technological process. Unfiltered oil and cake are obtained from commercial oilseeds using a press. Unfiltered oil passes through a filtration line, as a result of which purified oil is released, which is used for food purposes, and fuzz, which is used as a highly nutritious feed additive. The cake is crushed and divided into two fractions: protein and husk. The husk fraction is used as one of the components for the manufacture of fuel briquettes, and the protein fraction can be used as a component for obtaining dry feed pellets. Also, the protein fraction, together with fuzz, feed grain, grain waste and premixes, are processed into liquid feed using a cavitation disperser[64].

Recently, the consumption of flax seeds and flax oil has become very popular. The healing properties of flax seeds are due to its lignans, which have a wide range of biological activity, including antibacterial, antiviral and antifungal effects. Polyunsaturated fatty acids and soluble fiber have anticancer properties and have been called the elixir of life. In this regard, flax should be used not only as a raw material for the production of oil and fat products, but also for the production of a wide range of products, in particular bakery, cereal, confectionery, culinary and food additives based on flax products. Therefore, the main task of domestic breeders is to create new varieties of flax that meet the requirements of the food industry, taking into account the need to preserve the functional properties of flax during storage and processing into food products[65].

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63 Gorach, O. (2023). Current state of production and prospects of the use of oily flax seed in the food industry / Intellectual and technological potential of the XXI century: Innovative technology, Computer science, cybernetics and automation, Architecture and construction, Chemistry and pharmaceuticals. Monographic series «European Science». Book 23. Part 1, 41-59. https://doi.org/10.30890/2709-2313.2023-23-01-014

64 Offer – The main magazine on agribusiness https://propozitsiya.com/ua/harchoviy-napryam-vikoristannya-lonu-oliynogo

65 Drozłowska, E., Łopusiewicz, Ł., Mężyńska, M., & Bartkowiak, A. (2020). The effect of native and denaturated flaxseed meal extract on physiochemical properties of low fat mayonnaises. Journal of Food Measurement and Characterization, 14(2), 1135-1145. https://doi.org/10.1007/s11694-019-00363-6

The composition of flaxseed determines its value as a dietary product, which is widely used in the food industry today. Flaxseed is rich in proteins, fats, gluten and fiber. The composition of flaxseed of Canadian varieties, which dominate the world production of flax, in terms of dry matter is as follows: fat component – 41%, proteins – 21%, fiber – 28%, aromatic acids, lignin and hemicellulose, sugars – 6%, ash residue – 4%[66].

Fig. 22. Flaxseed oil

Source: Flax seeds: healing properties and benefits for the body.
https://ptv.ua/news/d6ee5f04-e1a4-4c37-8825-42aeb7d7a89a

The composition of flaxseed varies significantly depending on the variety, growing environment, and flax processing methods[67,68].

The content of nutrients, namely calories, proteins, fats, carbohydrates, vitamins and minerals per 100 g of edible part is given in Table 9-13.

[66] Duman, M. (2020). Nutritional value and sensory acceptability of fish burger prepared with flaxseed flour. Food Science and Technology (Campinas), 42, e27920. https://doi.org/10.1590/fst.27920

[67] Ghafouri-Oskuei, H., Javadi, A., Asl, M. R. S., Azadmard-Damirchi, S., & Armin, M. (2020). Quality properties of sausage incorporated with flaxseed and tomato powders. Meat science, 161, 107957. https://doi.org/10.1016/j.meatsci.2019.107957

[68] Gorach, O. (2023). Current state of production and prospects of the use of oily flax seed in the food industry. Intellectual and technological potential of the XXI century: Innovative technology, Computer science, cybernetics and automation, Architecture and construction, Chemistry and pharmaceuticals. Monographic series «European Science». Book 23. Part 1, 41-59. https://doi.org/10.30890/2709-2313.2023-23-01-014

Table 9. Vitamin content in flax seeds

Name	Number
Lutein + Zeaxanthin	651 мкг
Vitamin B1, thiamine	1.644 мг
Vitamin B2, riboflavin	0.161 мг
Vitamin B4, choline	78.7 мг
Vitamin B5	0.985 мг
Vitamin B6, pyridoxine	0.473 мг
Vitamin B9	87 мкг
Vitamin C, ascorbic acid	0.6 мг
Vitamin E, alpha tocopherol, TE	0.31 мг
gamma tocopherol	19.95 мг
delta tocopherol	0.35 мг
Vitamin K, phylloquinone	4.3 мкг
Vitamin PP, NE	3.08 мг
Betaine	3.1 мг

Source: Ways to increase the nutritional and biological value of bakery products
https://surl.li/rhhvzg

Table 10. Nutritional value of flax seeds per 100 g

Name	Number
Calories	534 ккал
Protein	18.3 г
Fat	42.2 г

Name	Number
Carbohydrates	1.6 г
Carbohydrates (total)	28.9 г
Dietary fiber	27.3 г
Water	7 г
Ash	3.7 г

Source: Ways to increase the nutritional and biological value of bakery products
https://surl.li/rhhvzg

Table 11. Amino acid composition of flaxseed

Name	Number
Essential Amino Acids	
Arginine*	1.925 г
Valine	1.072 г
Cytidine*	0.472 г
Isoleucine	0.896 г
Leucine	1.235 г
Lysine	0.862 г
Methionine	0.37 г
Threonine	0.766 г
Tryptophan	0.297 г
Phenylalanine	0.957 г
Essential amino acids	
Alanine	0.925 г

Name	Number
Aspartic acid	2.046 г
Hydroxyproline	0.175 г
Glycine	1.248 г
Glutamic acid	4.039 г
Proline	0.806 г
Serine	0.97 г
Tyrosine	0.493 г
Cysteine	0.34 г

Source: Ways to increase the nutritional and biological value of bakery products https://surl.li/rhhvzg

Table 12. Mineral content in flaxseed

Name	Number
Trace elements	
Potassium, K	813 мг
Calcium, Ca	255 мг
Magnesium, Mg	392 мг
Sodium, Na	30 мг
Sulfur, S	182.9 мг
Phosphorus, P	642 мг
Trace elements	
Iron, Fe	5.73 мг
Manganese, Mn	2.482 мг

Name	Number
Copper, Cu	1220 мкг
Selenium, Se	25.4 мкг
Zinc, Zn	4.34 мг

Source: Ways to increase the nutritional and biological value of bakery products https://surl.li/rhhvzg

Table 13. Fatty acid content in flaxseed

Name	Number
Fatty acids	
Omega-3 fatty acids	22.813 г
Omega-6 fatty acids	5.91 г
Sterols (sterols)	
Campesterol	45 мг
Stigma sterol	11 мг
beta Sito sterol	90 мг
Saturated fatty acids	3.663 г
14:0 Miristinic	0.008 г
15:0 Pentadecanoic	0.005 г
16:0 Palmitic	2.165 г
17:0 Margarine	0.018 г
18:0 Stearic	1.33 г
20:0 Arachidonic	0.052 г
22:0 Behenic	0.052 г

Name	Number
24:0 Lignoceric	0.031 г
Monounsaturated fatty acids	7.527 г
16:1 Palm oleic (ud)	0.024 г
18:1 Oleic (ud)	7.359 г
20:1 Gad oleic (omega-9)	0.067 г
22:1 Erucic (ud)	0.013 г
24:1 Nervonic (omega-9)	0.064 г
Polyunsaturated fatty acids	28.73 г
18:2 Linoleic (ud)	5.903 г
18:3 Linolenic (ud)	22.813 г
20:2 Omega-6	0.007 г

Source: Ways to increase the nutritional and biological value of bakery products https://surl.li/rhhvzg

Analyzing the data in Tables 8-12, we can conclude that flax seeds are rich in such vitamins and minerals as: vitamin B1 – 109.6%, choline – 15.7%, vitamin B5 – 19.7%, vitamin B6 – 23.7%, vitamin B9 – 21.8%, vitamin PP – 15.4%, potassium – 32.5%, calcium – 25.5%, magnesium – 98%, phosphorus – 80.3%, iron – 31.8%, manganese – 124.1%, copper – 122%, selenium – 46.2%, zinc – 36.2%, which indicates its benefits. For example, vitamin B1 is a part of the most important enzymes of carbohydrate and energy metabolism, which provide the body with energy and plastic substances, as well as the metabolism of branched-chain amino acids. The lack of this vitamin leads to serious disorders of the nervous, digestive and cardiovascular systems.

Choline is a part of lecithin, plays a role in the synthesis and metabolism of phospholipids in the liver, is a source of free methyl groups, acts as a lipotropic factor.

Vitamin B5 is involved in protein, fat, carbohydrate metabolism, cholesterol metabolism, the synthesis of a number of hormones, hemoglobin, promotes the absorption of amino acids and sugars in the intestine, supports the function of the adrenal cortex. A lack of pantothenic acid can lead to damage to the skin and mucous membranes.

Flax is distinguished by the yellow color of the seeds, a thin shell and a low content of linolenic acid. Today, the company has developed a grinding technology that maximizes the phytochemical potential of the raw material being processed. This allows for a new grain processing product based on grinding the grain and separating it into separate parts – the seed coat, embryo and endosperm – as a source of substances used to prevent cancer, cardiovascular, gastrointestinal and kidney diseases, diabetes, arthritis and to strengthen the immune system. In addition, new varieties of flax are known, in which the fatty acid composition of edible flax is similar to that of wheat flour, which makes it more suitable for storage[69]. The high fat content in flax flour and bran makes it possible to enrich flour with fatty acids and produce new products with increased nutritional, biological and medicinal properties.

The main advantage of bread made from flax flour or flax bran is its consumer characteristics, i.e. taste and aroma. As an oilseed, flax must meet safety requirements in accordance with established regulatory documents. A balanced and nutritious diet is important for the full development and vital activity of a person. However, with the development of the chemical industry, the nutritional value and quality of many food products not only raises great doubts, but also their usefulness is lost. One of the modern trends in the food industry is the introduction of new waste-free technologies. This involves a more complete extraction of useful components from agricultural raw materials and an increase in the degree of its processing, which makes the issue of developing technologies and recipes for enriched food products relevant. For example, the use of new technologies in the processing of flax seeds would allow the extraction of biologically active compounds, such as sterols, squalene, vitamin E and many other compounds, on the basis of which new domestic groups of biologically active drugs can be created, including medical and health-improving drugs. According to expert esti-

[69] Ghosal, S., & Bhowal, J. (2021). Bioethanol production from enzymatic hydrolyzates of pretreated flaxseed meals by baker's yeast. https://doi.org/10.21203/rs.3.rs-599700/v1

mates, the cost of biologically active substances obtained from flax can reach 80,000 US dollars per ton of processed flax seeds[70].

New technological processes have been introduced in the dairy industry, aimed at the full use of all components of milk and its processing into various food and feed products and semi-finished products. Specialized workshops and sections have been created at the enterprises for the processing of dairy by-products. Equipment and technological lines have also been developed for the processing of skim milk, cheese and whey by traditional and new methods.

Over the past decade, there has been a clear trend towards increasing the production and consumption of low-fat dairy products, for the manufacture of which by-products of dairy production are widely used. Skim milk, cheese and whey are used in the production of various drinks, semi-finished products, desserts, puddings, ice cream and jelly products.

Flaxseed is currently very popular as a food additive. Baking with the addition of flaxseed has a delicate taste due to its high fat content and an attractive crust. Studies have shown that eating bread with the addition of flaxseed for four weeks reduces cholesterol levels by 7-9%.

Flaxseed flour has also been shown to be useful in making gluten-free baked goods. The proteins and gummies of flaxseed are used in products such as ice cream, powdered sauces, and soups. The fatty acid composition of flaxseed oil is unique and contains high levels of polyunsaturated essential fatty acids (PUFAs), which are very important for the healthy functioning of the human body. Western doctors recommend that patients add 1-2 teaspoons of flaxseed oil to their diet to prevent cardiovascular disease and alleviate the progression of diabetes.

Flaxseed oil has been found to improve the adaptation of newborns, promote breastfeeding in women, increase immunity in children with lung diseases, and shorten the duration of treatment for peptic ulcer disease. It has also been proven to improve blood composition by lowering total cholesterol levels[71].

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70 Kairam, N., Kandi, S., & Sharma, M. (2021). Development of functional bread with flaxseed oil and garlic oil hybrid microcapsules. LWT-Food Sci. and Technol., 136, 110300. https://doi.org/10.1016/j.lwt.2020.110300

71 Karwasra, B. L., Kaur, M., Sandhu, K. S., Siroha, A. K., & Gill, B. S. (2021). Formulation and evaluation of a supplementary food (Panjiri) using wheat and flaxseed flour composites: Micronutrients, antioxidants, and heavy metals content. Journal of Food Processing and Preservation, 45(1), e14998. https://doi.org/10.1111/jfpp.14998

Margarine is a well-known edible fat made from a mixture of vegetable and animal fats, milk and other ingredients. Until recently, margarine was made from liquid, refined and deodorized vegetable oils. Sunflower, soybean, cottonseed, sesame and coconut oils were mainly used.

The widespread production of margarine and other soft oils with a reduced content of animal fats was due to the desire to limit the diet of foods containing animal fats, which produce cholesterol. After the health benefits of linseed oil were discovered, the margarine industry, mainly in Canada and the United States, switched to using linseed oil.

After pressing the oil from flax seeds, cake remains. The protein content of this cake increases in proportion to the amount of oil produced, varying between 25% and 54%. Previously, this cake was used only for animal feed. In recent years, the technology for producing flour, protein and other food products from flax seeds has been developing rapidly. Flax seeds can provide up to 70% of the total amount of complete protein in the form of a complex, including more than 20% pure protein. Semi-fat flax flour is now commercially available. Flax flour is used in the production of bakery, confectionery and concentrated products and is suitable for adding protein, dietary fiber and polyunsaturated fatty acids to products[72].

Due to the need to use natural emulsifiers and stabilizers, flaxseed meal is currently used as a natural structure-forming natural ingredient in the production of mayonnaise. The inclusion of flaxseed meal in mayonnaise can affect the mechanisms of formation and stabilization of oil-fat emulsions, change viscosity and increase resistance to thermal oxidation. The structure-forming properties of semi-skimmed flaxseed meal led to the development of dessert products based on whey with a jelly-like lush consistency. Calculations showed that the energy value of the mixture of whey and flaxseed meal was low – 32.45 Kcal per 100 g, and its biological value was significantly higher due to the high content of essential amino acids. It was added to a mixture of flour and whey in a ratio of 1:7, with citric acid and cherry syrup to give the dessert a delicate taste and pleasant color. This product contributes to the full functioning of the gastrointestinal tract and removes toxins, parasites and lipids from the body.

[72] Marand, M. A., Amjadi, S., Marand, M. A., Roufegarinejad, L., & Jafari, S. M. (2020). Fortification of yogurt with flaxseed powder and evaluation of its fatty acid profile, physicochemical, antioxidant, and sensory properties. Powder Technology, 359, 76-84. https://doi.org/10.1016/j.powtec.2019.09.082

The main problem of processing flax seeds to extract the protein component is that the polysaccharides in the seed coat bind to protein molecules during extraction, which makes it difficult to precipitate and purify when obtaining protein. In the case of flax seeds, the outer shell is firmly attached to the kernel and cannot be removed by conventional methods of removing the shell, so flax is processed without separating the shell. In this regard, a technology has been developed that involves pre-cleaning flax seeds using a vibration extractor. This allows you to extract polysaccharides from the seed coat and obtain a new product – flax seed mucus[73]. In connection with the emergence of new by-products of flaxseed processing, a fermented milk product based on skim milk with flaxseed mucus was developed.

Thermophilic streptococci were chosen as starter cultures, which have a positive effect on human microflora, synthesize polysaccharides during fermentation and secrete them into the environment, making the dairy product more concentrated and delaying stratification. With prolonged systematic use, the developed product can reduce the activity of inflammation of the gastric mucosa. The inclusion of medicinal flax mucus can also be used both for the treatment of exacerbations of chronic gastritis and for the prevention of relapses[74].

From the analysis of the nutritional value of flax seeds, we can conclude that flax is a valuable industrial raw material that contains many phytochemical properties that increase the biological value of food products. Therefore, an important task today is to create functional products from natural raw materials that should be safe, affordable, nutritious and beneficial for humans. Thus, oil flax is widely used in the food industry, mainly due to the healing properties of seeds and products of its processing. The number of technologies and recipes using flax oil is increasing every year both in Ukraine and on the world market. Therefore, the need to develop functional preparations makes it relevant to further implement and develop recipes for the production of food products of a wide range of uses[75].

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73 Sanmartin, C., Taglieri, I., Venturi, F., Macaluso, M., Zinnai, A., Tavarini, S., Botto, A., Serra, A., Conte, G., Flamini, G., & Angelini, L. G. (2020). Flaxseed cake as a tool for the improvement of nutraceutical and sensorial features of sourdough bread. Foods, 9(2), 204. https://doi.org/10.3390/foods9020204

74 Sapozhnikov, A. N., Kopylova, A. V., Gurova, D. V., & Bolshakov, K. A. (2021). Obtaining of gluten-free pizza dough based on flaxseed flour. IOP Conference Series: Earth and Environmental Science 677(3), 032056. https://doi.org/10.1088/17551315/677/3/032056

75 Toulabi, T., Yarahmadi, M., Goudarzi, F., Ebrahimzadeh, F., Momenizadeh, A., & Yarahmadi, S. (2021). Effects of flaxseed on blood pressure, body mass index, and to-

In addition, flaxseed is widely used in cosmetics. The unique properties of flax are associated with its chemical composition. Due to the high content of essential oils, omega-polyunsaturated acids and vitamins F, A, B and E, flaxseed actively affects the human body and restores its normal functioning. Saturated organic acids, plant mucus, enzymes and phytoestrogens have an additional strengthening and health-improving effect.

The main products of the European Union are food and feed products made from hemp and flax, that is, seeds obtained from them for the production of medicines. For medical purposes, flaxseed oil is usually made from flaxseed, which is a more concentrated and effective product. The seeds crushed into powder are mixed with warm water, and the proportions may be different (more water for decoctions, less for pastes).

Adding seeds to food is an easy way to increase fiber intake. There are known technologies for adding flaxseed flour in the production of gluten-free baked goods. For example, 20 g of chia seeds contain 6.8 g of fiber, flax seeds – 5.4 g, and pumpkin seeds – 1.3 g. In Ukraine, flaxseed is exported as raw material for sowing and for use in the food and cosmetic industries in Europe[76,77,78].

The main part of exports is raw materials for industrial processing; in 2018-2019, the amount of organic products increased: in 2018, such seeds accounted for 6% of the total volume of supplies; in 2019, it was 14%. However, in Ukraine, studies of the quality indicators of these products have not yet been conducted, and there is no regulatory document that would define them. As a rule, the quality of "superfoods" is assessed according to the technical conditions developed by the manufacturer. Domestic publications do not contain information about national regulatory documents that can be used to assess the quality and consumer characteristics of functional food

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tal cholesterol in hypertensive patients: A randomized clinical trial. Explore. https://doi.org/10.1016/j.explore.2021.05.003

[76] Gorach, O., Dzyundzya, O., Rezvykh, N. (2024). Innovative Technology for the production of gluten-free food products of a new generation. Current Nutrition & Food Science. № 20 (6), 734-744. https://dx.doi.org/10.2174/0115734013280307231123055025

[77] Wirkijowska, A., Zarzycki, P., Sobota, A., Nawrocka, A., Blicharz-Kania, A., & Andrejko, D. (2020). The possibility of using by-products from the flaxseed industry for functional bread production. LWTFood Science and Technology, 118, 108860. https://doi.org/10.1016/j.lwt.2019.108860

[78] Horach, O.O. (2022) Justification of innovative technologies of functional formulations. Tavria Scientific Bulletin. Series: Technical Sciences. Kherson State Agrarian and Economic University. Kherson: Publishing House "Helvetica", Issue 6, 52-58. http://journals.ksauniv.ks.ua/index.php/tech/article/view/311/287

products made from flax seeds. Unfortunately, the existing regulatory framework of foreign manufacturers is not available.

2.6. Methods of producing oil from flaxseeds

Mechanical oil pressing from oilseeds is one of the most commonly used methods for extracting oil from oilseeds. This method has relatively low operating costs and, similar to the supercritical CO_2 extraction method, yields uncontaminated oil. However, currently available mechanical oil pressing equipment and processes are not considered the most efficient for this purpose, since the extraction of flaxseeds by pressing allows for the extraction of only 60-70% of the oil. The yield obtained from mechanical pressing is usually lower than that obtained from extraction with solvents such as hexane, for example. Only in the last century has solvent extraction been used in this field. The advantage of solvent extraction technology is the high yield of oil that can be obtained using this method, almost 100% of the oil contained in the oilseed[79].

Two technologies are used in the production of linseed oil: cold or hot pressing and extraction. Depending on the type of processing, it can be unrefined, refined, hydrated and deodorized.

The cold pressing method preserves the maximum beneficial properties of the product, since its composition contains valuable vitamins, phospholipids, unsaturated fatty acids and other biologically active substances.

The ancient method of obtaining oil involved roasting and crushing the seeds in a mortar. Modern technology involves heating the seeds to 35-40 ° C and pressing. Fresh oil is golden or light brown in color with a pleasant sweetish taste and aroma. This is the most useful product, but more expensive than that obtained by any other method: more raw materials are used for its production. Among the disadvantages are a short shelf life and the formation of a natural precipitate.

Unrefined oil can be subjected to further purification: (filtration, hydration, centrifugation, settling), refining (clarification using sorbents), as well as deodorization (neutralization of odor). After such treatment, the oil is obtained clean, transparent, greenish-yellow in color, without a special

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[79] Linseed Oil Production Technology [Electronic resource]. Access mode: https://www.bestoilmillplant.com/linseed-oil-production-technology.html

taste and smell. Unfortunately, some of the beneficial substances are lost. Such oil is used for technical purposes.

The raw material is placed in a press extruder, in which it is crushed and heated to 120ºC. In this way, it is possible to achieve a higher yield of the final product, but the effect of high temperature destroys many important components of the oil and reduces its biological value.

This method consists of two stages. First, the raw material is crushed and oil is extracted from it using special solvents. Then the resulting product is driven through a distiller and purified from impurities. This oil loses vitamin E and plant styrenes, but the fatty acid content becomes higher, which worsens its taste and smell, and also reduces its shelf life[80].

When using the extraction method, flaxseed oil contains almost no nutrients, because a lot of chemistry is used to obtain it. At the first stage of extraction, the oil is obtained using solvents, which are subsequently removed by distillers. Oil obtained by hot pressing also loses many of its beneficial properties due to the high temperatures to which the seeds are exposed before extraction. The temperature of the hot press reaches 120 degrees.

The best and most common method of producing flaxseed oil is cold pressing. As the name suggests, here the cleaned and crushed seeds are sent to the press without preliminary heating. About 300 grams of oil is obtained from 1 kg of seeds. Such oil retains its beneficial properties, does not contain traces of synthetic compounds and even retains its specific natural smell.

In recent years, when nutritionists have discovered the medical and biological benefits of flaxseed oil, the margarine industry, primarily in Canada and the USA, has been switching to using flaxseed oil in the manufacture of margarine. Analyzing the above data, it becomes clear why interest in flaxseeds is constantly growing. However, research in this regard is fragmented, there is practically no information on the change in the nutritional value of flaxseeds during storage and processing of semi-finished products[81].

The physical and mechanical properties of flax seeds differ sharply from those of grain and other crops. Flax seed mass is extremely dense, difficult to blow through and "flowing". Many weeds are difficult to separate

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80 Linseed oil: composition, use, benefits [Electronic resource]. Access mode: https://fitomarket.com.ua/ fitoblog/lnjanoe-maslo-sostav-ispolzovanie-polza

81 Farag, M.A.; Elimam, D.M.; Afifi, S.M. (2021). Outgoing and Potential Trends of the Omega-3 Rich Linseed Oil Quality Characteristics and Rancidity Management: A Comprehensive Review for Maximizing Its Food and Nutraceutical Applications. Trends Food Sci. Technol. 114, 292-309. http://dx.doi.org/10.1016/j.tifs.2021.05.041

from the seeds of the main crop. Freshly harvested seeds have a high intensity of metabolic processes, they are unstable in storage, and are characterized by reduced technological properties. Therefore, post-harvest processing of oil flax seeds is more complex. It includes, as in other crops, preliminary cleaning, drying and final cleaning. Flax seeds are cleaned of impurities by blowing with an intense stream of air on sieves with a diameter of 1.7-2.0 mm. Flax seeds are dried in a moving, loosened layer at a temperature of 48-50 ° C, while the temperature of the seeds at the outlet of the dryer should be 38-39 ° C. Heating seeds causes a number of interrelated biochemical processes in them, in particular, a decrease in the acid number of linseed oil as a result of the formation of a protein-lipid complex that binds fatty acids formed during the hydrolysis of fats.

Analysis of literary sources showed that of all the methods of processing flax seeds, the process of obtaining oil is the most well-studied. Also, sufficient attention was paid to the possibilities of using oil production – cake and meal.

Cake is obtained during oil production by pressing, meal – when obtaining oil by extraction. In cake, the amount of crude fat is 5-6%, in meals – 2-3%. Flax cake and meal are excellent protein feed. In order to increase production efficiency and reduce the cost of production, it increases income. Many oil production enterprises are modernizing the classical scheme for obtaining oils. The choice of the method of preparing the material for extraction depends on the composition of the technological scheme, the type of raw material and the extractor equipment[82].

Since the main criterion for product preparation is the creation of favorable conditions for more effective penetration of the solvent into each particle, as well as its distribution between the product particles and the return of dissolved oil to the external solution. With increasing porosity, the specific surface area increases, which is an important parameter that determines permeability – the ability of a porous material to pass liquid through it.

The solvent penetrates more intensively through the pores into the granule, removing oil from capillaries located not only on the surface, but also in the depth of the particle. The interaction of the liquid and the space filled with oil with a fenced or intact cell membrane leads to an increase

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[82] Farag, M.A.; Elimam, D.M.; Afifi, S.M. (2021). Outgoing and Potential Trends of the Omega-3 Rich Linseed Oil Quality Characteristics and Rancidity Management: A Comprehensive Review for Maximizing Its Food and Nutraceutical Applications. Trends Food Sci. Technol. 114, 292-309. http://dx.doi.org/10.1016/j.tifs.2021.05.041

in its yield and a decrease in the residual oil content of the meal. Processing of flax seeds to obtain oil is a sequence of a number of technological stages. The gradual removal of oil from flax seeds contributes to an increase in protein in the final product. The technological cycle in this case can be presented as follows: grinding of natural flax seeds – removal of oil by the method of "cold" pressing – grinding of flax cake – removal of residual oil by the method of extraction – grinding of flax meal. At the same time, for the purposes of food production, it is necessary to carry out washing and heat treatment of raw materials, in this case flax seeds. Washing of flax seeds is complicated by the presence of mucus that is well soluble in water and a significant amount of water-soluble proteins.

To create porous pellets of oil cake with certain parameters, a granulation line is introduced into the production chain between grinding and extraction. The shell-shaped oil cake enters the grinding section, where it is ground to a grain size of less than 3 mm and through a cyclone enters an intermediate bunker for storing raw materials. A magnetic separator is installed in front of the granulator, on which the grain is cleaned. Then it is dosed and fed into a continuous mixer, where mixing and steam treatment are carried out to give the product homogeneity and plasticity. Adding steam helps to reduce energy consumption and reduce wear on the working parts of the granulator.

The prepared product enters the granulator. Granulation occurs in the pressing chamber by pushing it through the gears. Hot granules (temperature about 80°C) are cooled by an air flow in the cooler to the temperature required for extraction – 55-60°C. After unloading from the cooler, the cooled granules are separated from small particles on screening and sent to the extraction workshop, and small particles are sent for repeated granulation. For the most complete removal of oil by the extraction method from oil raw materials, traditional solvents are usually used: ethyl alcohol, hexane. Therefore, it is necessary to determine the optimal solvent for removing residual oil from flaxseed cake[83].

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[83] Qiu, C.; Wang, H.; Guo, Y.; Long, S.; Wang, Y.; Abbasi, A.M.; Guo, X.; Jarvis, D.I. (2020). Comparison of Fatty Acid Composition, Phytochemical Profile and Antioxidant Activity in Four Flax (Linum usitatissimum L.) Varieties. Oil Crop Sci. 136–141. https://doi.org/10.1016/j.ocsci.2020.08.001

The use of all the listed technological operations allows us to substantiate a comprehensive technology for using flax seeds to obtain various functional properties[84]. The structural features of flax seeds determine the uniqueness of the technological process for obtaining the final product. Flax seeds are small-seeded, the shell of which fits tightly to the kernel, so the stages of fractionation and crushing are not introduced into the technological process. The shell of flax seeds contains a significant amount of valuable nutritional components. Unlike other oilseeds, the shell of flax seeds contains a small amount of cellulose (no more than 18% in terms of dry matter) and up to 62% of other carbohydrates, primarily mucus, which are easily dispersible carbohydrates in water, as well as fats, proteins, and minerals. Preservation of the entire complex of flax seed nutrients in the final product increases its nutritional and biological value.

The seeds undergo triple purification: purification from metallomagnetic impurities in a metallomagnetic separator; purification from organic impurities in an air-sieve separator; removal of mineral impurities on a vibropneumatic stone separator. Thus, the technological scheme includes the following sequence of main stages:

– cleaning of flax seeds from mineral, organic and metallomagnetic impurities;
– short-term washing of flax seeds for 5-10 min;
– heat treatment of flax seeds by convection at T 70 °C for 5 min;
– grinding of food seeds to obtain full-fat flax flour;
– removal of oil from flax seeds by the method of "cold" pressing;
– grinding of defatted flax seeds (flaxseed cake) to obtain semi-defatted flax flour;
– granulation of flaxseed cake;
– additional removal of oil by extraction;
– sieving of ground seeds sequentially on sieves with a hole diameter of 1 mm and 0.5 mm.

[84] Aliyev, E.B., Mykolenko, S.Yu., Sova, N.A., Aliyeva O.Yu., Malegin R.D., Lupko K.O., Linko, M.O., Ya.V. Gez, Bezugla, L.S. (2022). Technical and technological support for waste-free processing of grain raw materials into food products and feed. Collective monograph. ed. E. B. Aliyeva. Dnipro: LIRA. 192 p. https://surl.gd/uwnflw

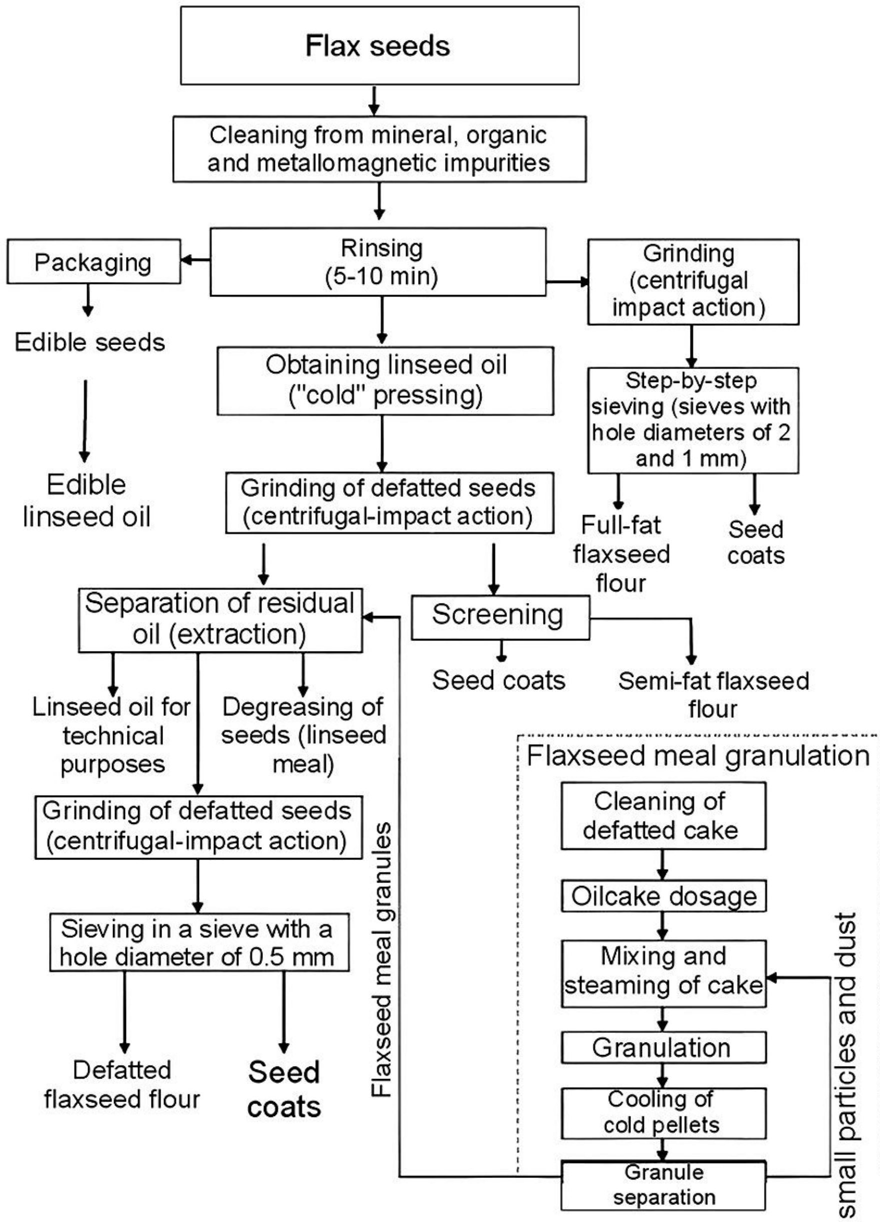

Fig. 23. Technological scheme of complex processing of oilseed flax to obtain products of various functional purposes and raw materials for the production of compound feed

Source: Vegetable oil production technology https://studfile.net/preview/5350038/page:49/

The final products are the following products: edible flax seeds; edible and technical flax oil; full-fat, semi-skimmed and skimmed flax flour. To use the shell fraction with a high content of lignans as a raw material for a biologically active food additive, it must be additionally crushed to a size of no more than 0.4 mm, which is a technological feature of further processing.

From the analysis of the nutritional value of flaxseed oil and seeds, it can be concluded that flaxseed oil and seeds are valuable industrial raw materials that contain many phytochemical properties that increase the biological value of food products. Therefore, the current task of today is the production of functional products from natural raw materials that are safe, affordable, nutritious and beneficial for the human body. Flaxseed oil is one of the natural raw materials that has great potential for the production of food products with a wide range of applications. As noted above, the possibility of growing flax for seeds and oil would provide consumers with products with a large number of nutrients.

Conclusions. The need and feasibility of increasing the volume of oil flax cultivation in the world, as well as in Ukraine, is justified by many factors, in particular the sustainable development of its potential raw material base – the expansion of the sown areas allocated for oil flax. Recently, Western Europe and other countries of the world have shown increased interest in the use of oil flax for the manufacture of various types of technical products in many industries. Based on the world experience of using flax straw, it can be concluded that it is a valuable raw material for the manufacture of technical products, which are widely used in many industries. Although today in our country the straw of this crop remains a secondary product, with a certain processing technology it can be used for the manufacture of the above-mentioned consumer goods. However, there is a certain technological and marketing barrier to the industrial use of flax straw – the lack of sufficient information on the development and testing of technologies for obtaining fiber with the necessary physical and mechanical characteristics, suitable for the production of technical textiles for reinforcing composite materials. The comprehensive use of flax in industry will also solve the problems associated with the shortage of raw materials, which were previously obtained from technical crops: long flax, cotton, hemp, etc. However, the use of flax oil as a raw material for obtaining a wide range of technical textiles of various functional purposes is possible only if its physical and mechanical properties meet the requirements of the production technologies of specific groups and types of industrial materials. These properties of flax raw materials must be formed under certain regimes and parameters of the technological process of its primary processing when applying innovative technologies for the complex processing of flax straw stalks.

Thus, based on the analysis of the use of flax oil seeds, it can be concluded that the possibility of using them in the food industry is difficult to overestimate due to the discovery of new properties of the seeds. Therefore, from the point of view of environmental safety and balanced use of nature in agro-industrial production, innovative directions for the use of flax oil seeds will allow filling the Ukrainian market with domestic environmentally safe food products, which have a tendency to be widely implemented in many areas of modern food industry production aimed at the manufacture of innovative food products of various functional purposes.

Based on the analysis of the nutritional value of flaxseed oil and seeds, it can be concluded that this is a valuable industrial raw material with a high content of phytochemical properties, which allows to increase the biological value of food products. Therefore, the current task today is to create functional products from natural raw materials that are safe for humans, which should be affordable, nutritious and useful. Flaxseed oil is one of the natural raw materials that has great potential in the production of food products of a wide range of applications. As noted above, the possibility of growing flax to obtain seeds and oil will provide consumers with products with fiber and vegetable fats.

Analysis of literary sources allows us to conclude that the number of innovative technologies known today that affect the quality of the resulting products is constantly increasing, and methods for determining the quality of new products are insufficient. However, for the development of the flax industry, it is necessary not only to harmonize the existing regulatory framework, but also to study additional consumer properties, taking into account their impact on the human body, namely hygienic, antiseptic, biological properties, as well as energy and therapeutic value. Since in the future this product will be used not only within the country, but also on the European market.

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Abstract

The monograph highlights the results of scientific research on the comprehensive use of oil flax, presents the general and agrotechnological characteristics of oil flax, problems and prospects for the use of bast and fiber obtained from oil flax stems in industry. The results of research on the use of oil flax seeds and oil in the food industry, as well as methods of oil production, are presented. It is shown that the sown areas of oil flax have increased significantly, which is due to the widespread use of flax seeds in the pharmaceutical industry abroad and in Ukraine to produce biologically active additives. Production and scientific research indicate that oil flax is a promising crop, and it is economically feasible to increase the sown areas. However, unfortunately, the stems of this crop are almost never used in industry. Oil flax straw is mostly burned in the fields, therefore, in modern conditions, the development of new resource– and energy-saving technologies for processing oil flax straw is relevant.

Based on the above, it can be concluded that the issue of integrated use of oil flax will allow to increase the profitability of growing oil flax and will contribute to solving the phenomena in the domestic energy sector and the problem of raw material supply for many industries. Integrated use of oil flax in industry will also contribute to solving the problems associated with the shortage of raw materials obtained from such technical crops as long flax, cotton and hemp.

Keywords: oil flax, straw, bast, fiber, technical textiles, seeds, oil, food industry.

UDC 633.85:631.5(477.7)

Chapter 3.

OPTIMIZATION OF SUNFLOWER CULTIVATION TECHNOLOGIES IN THE SOUTHERN UKRAINE CONDITIONS: CURRENT APPROACHES AND RESULTS

Olesia Revto, Anastasiia Maliarchuk

3.1. Introduction

Global climate change is one of the most pressing issues of the 21st century, extending far beyond scientific discussions. This problem has acquired the status of a complex interdisciplinary task, encompassing a wide range of environmental, economic, and social aspects that are crucial for ensuring the sustainable development of the global community. Climate change manifests in various forms, including an increase in the intensity and frequency of extreme weather events, which cause significant economic losses, destabilize ecosystems, and pose a serious threat to human health and life (Revto & Zolin, 2023, p. 105)[1]. The scientific community (Domaratskyi et al., 2022; Kostiukevych & Voloshyna, 2024) unanimously recognizes that further intensification of climate change could lead to unpredictable and catastrophic consequences if immediate and adequate measures are not taken[2,3].

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1 Revto, O.Y., & Zolin, O.O. (2023). Specificity of growing soybean under conditions of climate change (a review article). Taurian Scientific Herald, (133), 105–112. https://doi.org/10.32782/2226-0099.2023.133.15.

2 Domaratskyi, Ye.O., Dobrovolskyi, A.V., Kozlova, O.P., Dobrovolskyi, P.A., & Lavryshyna, O.Ye. (2022). Ways to optimize water consumption of high-oleic sunflower under climate change. Agrarian Innovations, (10), 34-41. https://doi.org/ 10.32848/agrar.innov.2021.10.6.

3 Kostiukevych, T.K., & Voloshyna, O.V. (2024). Impact of climate change on the formation of corn crop productivity for green fodder in the Central Forest-Steppe of Ukraine. Agrarian Innovations, (25), 31-37. https://doi.org/10.32848/agrar.innov. 2024.25.5.11.

Global climate change is the result of a complex combination of natural and anthropogenic factors. Among the key determinants that shape the current climate dynamics, the following stand out: anthropogenic impact, disruption of the carbon cycle, radiative forcing of the atmosphere, and changes in the Arctic Ocean current system (Revto O.Ya & Domaratskyi Ye.O, 2021, p. 68)[4].

Ukraine's agriculture is the most vulnerable sector of the economy to climate change, as the functioning of crop and livestock sectors, their specialization, and crop yields largely depend on the agro-climatic conditions of the territory, primarily on its heat and moisture availability. Further increases in vegetation period temperatures can significantly impact agricultural productivity and food security as a whole.

The climate change observed on our planet at unprecedented rates in recent decades or even millennia is among the most influential risks that determine global human development (Ahmed et al., 2022)[5].

In Ukraine, particularly in its southern regions, where the agro-industrial complex plays a key role in ensuring food security and economic development, the consequences of climate change are particularly noticeable. Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops in Ukraine, but its cultivation in the southern regions of Ukraine faces a number of challenges, including: instability of climatic conditions characterized by droughts and high temperatures; soil depletion and reduced fertility; and the spread of pests and diseases. These factors negatively affect sunflower yield and seed quality, necessitating the optimization of its cultivation technologies.

Thus, to increase the economic efficiency of sunflower cultivation, the introduction of modern intensive and innovative technologies is necessary.

The aim of our research is to analyze modern approaches to sunflower cultivation in the conditions of Southern Ukraine and evaluate their effectiveness based on the results of conducted studies. The monograph section addresses aspects such as: the selection of optimal hybrids; the application

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4 Revto, O.Ya, & Domaratskyi, Ye.O. (2021). Optimization of the production process of sunflower agrocenoses under arid conditions of the Southern Steppe of Ukraine. Agrarian Innovations, (5), 68-74. https://doi.org/10.32848/agrar.innov.2021.5.11.

5 Ahmed, M., Asim, M., Ahmad, S., Aslam, M. (2022). Climate Change, Agricultural Productivity, and Food Security. In: Ahmed, M. (eds) Global Agricultural Production: Resilience to Climate Change. Springer, Cham. https://doi.org/10.1007/978-3-031-14973-3_2.

of modern soil tillage technologies; the determination of optimal seeding density; and the use of plant growth regulators.

The research results presented in the section demonstrate the possibilities of increasing sunflower yield and seed quality through the introduction of modern technologies and scientifically sound approaches.

Main research objectives:

- analysis of modern sunflower cultivation technologies.
- identification and evaluation of sunflower hybrids best adapted to the conditions of Southern Ukraine.
- optimization of basic soil tillage technologies.
- determination of optimal seeding density.
- evaluation of the effectiveness of growth-regulating preparations.
- development of recommendations for adapting sunflower cultivation technologies to changing climatic conditions.

The scientific novelty of the obtained results lies in the study of the peculiarities of growth, development, and productivity formation of sunflower hybrids when using plant growth regulators and in identifying the dependence of sunflower yield on seed seeding rates and soil tillage methods. The greatest effectiveness of growth-regulating preparations in increasing yield and economic efficiency of sunflower hybrids has been established, and the optimal parameters of methods and depth of basic soil tillage and seeding rates of germinated sunflower seeds for the conditions of Southern Ukraine have been determined, allowing to increase crop yield and reduce water resource consumption.

The obtained experimental data make it possible to develop scientifically sound recommendations for increasing crop productivity.

3.2. Evaluation of the Effectiveness of Growth Regulators Application on Sunflower under Climate Change Conditions in Southern Ukraine

Sunflower (*Helianthus annuus* L.) is one of the key oilseed crops in global agriculture, characterized by high economic profitability. In recent years, fluctuations in global sunflower production have been observed, influenced by weather conditions, economic factors, and geopolitical events.

The demand for sunflower oil is increasing, which stimulates sunflower production in various regions of the world.

Global sunflower production is 52,015 (1000 MT) (Sunflowerseed Explorer, 2025)[6] (PS&D Online updated 03/2025). Visualization of global sunflower production data is presented in Figure 1.

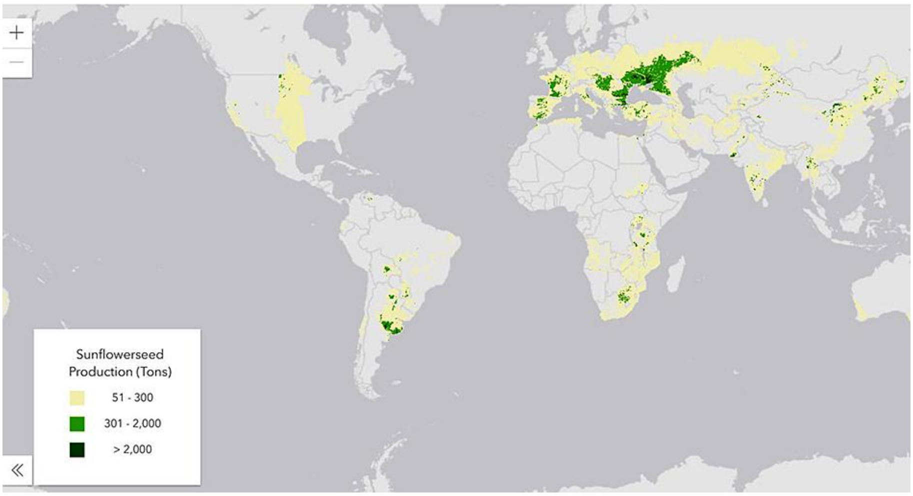

Fig. 1. Sunflowerseed Map Explorer

Source: [6].

In Ukraine, in particular, sunflower has gained the status of a major crop, providing a significant portion of the agricultural sector's income. This leads to a steady increase in demand for high-yielding seeds and stimulates breeding work to create hybrids adapted to various soil and climatic conditions and capable of demonstrating stable yields.

To ensure maximum economic efficiency and minimize production risks, agricultural producers need to carefully select sunflower hybrids that meet the specific conditions of their farms. An important aspect is also the development and implementation of optimal cultivation technologies that consider the characteristics of the selected hybrid and agroecological factors.

6 Sunflowerseed Explorer. (March 2025). International Production Assessment Division (IPAD) – Home Page. https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx? cropid=2224000.

Modern intensive crop cultivation technologies, despite their high efficiency in ensuring yield growth, are often based on the excessive use of mineral fertilizers and pesticides. Uncontrolled use of these agrochemicals leads to a number of negative consequences, including economic inefficiency and serious environmental risks. In this regard, the search for alternative approaches to forming the economically valuable part of the crop is becoming particularly relevant.

One of the promising directions in this context is the introduction of growth-regulating substances. These compounds, even in low concentrations, can significantly affect the physiological processes of plants, increasing their biological productivity potential within the genetically determined range of response. In addition, growth-regulating substances can enhance the adaptive capacity of plants to environmental stress factors, such as drought, extreme temperatures, or soil salinity.

Literature sources indicate that to mitigate negative factors such as excessive anthropogenic pressure, deterioration of water and nutrient regimes, and soil humus status, it is necessary to expand the range of applied agricultural practices. In addition to traditional methods of applying mineral and organic fertilizers, research shows that the use of micronutrients and plant growth regulators is an effective approach. Plant growth regulators (biological products) contribute to an increase in leaf area, activate key physiological processes such as photosynthesis, respiration, nutrient uptake, stimulate the activity of enzyme systems, regulate membrane processes and cell division. In addition, they promote the development of the root system, which ensures an increase in its absorption capacity.

The results of numerous studies confirm the positive effect of growth regulators on morphogenesis, growth, development, and productivity of sunflower. In particular, it has been established that the use of preparations such as "Ceron" and "Architect" contributes to an increase in leaf surface, head diameter, number of seeds, and oil content (Tsyliuryk O. I. et al., 2022, p. 33)[7].

However, the effectiveness of growth regulator application depends on many factors, including sunflower hybrid, soil and climatic conditions, and cultivation technology. Therefore, further research is needed to optimize

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[7] Tsyliuryk, O.I., Rumbakh, M.Y., Izhboldin, O.O., Bondarenko, O.V., Nozdrina, N.L., & Ostapchuk, Y.V. (2022). Efficiency of bioformulations in sunflower fields in the north part of the Steppe Zone of Ukraine. Agrology, 5(1), 27-34. https://doi.org/10.32819/021104.

the use of growth regulators to increase sunflower productivity in the Steppe zone of Ukraine.

Plants are capable of synthesizing their own growth regulators, such as cytokinins, gibberellins, and auxins, which ensure the optimal course of physiological processes and crop formation. However, under the influence of stress factors such as drought, extreme temperatures, wind load, frosts, or phytotoxicity, endogenous hormone synthesis is significantly reduced. This leads to plant weakening, disruption of ontogenesis programs, and increased vulnerability to pathogens and other adverse factors.

To restore physiological balance and optimize growth processes under stress conditions, the use of exogenous phytohormonal preparations is advisable. These preparations contribute to the prolongation of the active photosynthesis period, slowing down the aging processes of the leaf apparatus, and stimulation of growth functions (Domaratskyi Ye. O. et al., 2020)[8].

Changes in climatic conditions require adjustments to existing crop cultivation technologies. In particular, it is necessary to introduce new multifunctional preparations that allow balancing the impact of stress factors. Such preparations, containing mineral compounds and bacterial components, contribute to increasing plant immunity, improving crop quality and structure, and increasing resistance to adverse environmental factors.

The development and deepening of research aimed at developing more advanced and environmentally friendly sunflower cultivation technologies is one of the most relevant and promising areas of modern agricultural science. Studying the mechanisms of growth regulator action, their impact on various aspects of plant growth and development, and developing optimal application schemes are key tasks to ensure sustainable and environmentally safe agriculture.

In the conditions of increasing climate aridization in the Southern Steppe of Ukraine, where insufficient moisture is a limiting factor for agricultural production, the search for effective methods to increase sunflower productivity is of particular relevance.

The aim of the research was to study the impact of various plant growth regulators on the growth, development, and yield of sunflower hybrids under moisture deficiency conditions.

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8 Domaratskyi, Ye.O., Dobrovolskyi, A.V., Bazalii, V.V., Pichura V.I., & Domaratskyi, O.O. (2020). Sunflower: ecological ways to optimize its nutrition. Oldi-plus.

To achieve this goal, the following tasks were defined:

- to identify the patterns of plant growth regulator influence on growth processes, plant development, and sunflower crop formation;
- to conduct a comparative analysis of the influence of growth-regulating substances on sunflower seed productivity;
- to assess the effectiveness of the studied impact factors on the quality indicators of sunflower seeds in the conditions of Southern Ukraine;
- to determine the economic efficiency of growing sunflower hybrids using growth regulators.
- To achieve the set goal, the following research methods were used:
- field method: observation of plant growth and development, weather conditions, biometric records and measurements, yield accounting, study of soil physical properties;
- laboratory method: visual and measurement-weight analysis to observe development phases and determine biometric indicators of plants, their productivity; chemical analysis to determine soil agrochemical indicators;
- analytical methods: formulation of hypotheses, analysis, synthesis, and abstraction in determining the purpose and objectives of the study, summarizing the results, and substantiating conclusions; mathematical and statistical analysis to assess the reliability of the obtained results; calculation and comparative analysis for economic evaluation of the studied elements of sunflower cultivation technology.

The research was conducted on a site where the soil cover is represented by dark chestnut, ultimately slightly solonetzic, heavy loamy soils. The soils are characterized by a well-developed humus profile. According to the granulometric composition, the soils belong to silty heavy loamy soils.

The meteorological conditions of the research period (2019-2021) were characterized by significant variability, which is typical for the steppe zone of Ukraine (Fig. 2 and Fig. 3). One of the characteristic features was the high amplitude of daily air temperature fluctuations, which created additional stress for plants. Summer months were marked by high temperatures, accompanied by prolonged periods of no precipitation and dust storms. Atmospheric precipitation that fell had a shower character, which caused rapid evaporation of moisture from the soil surface.

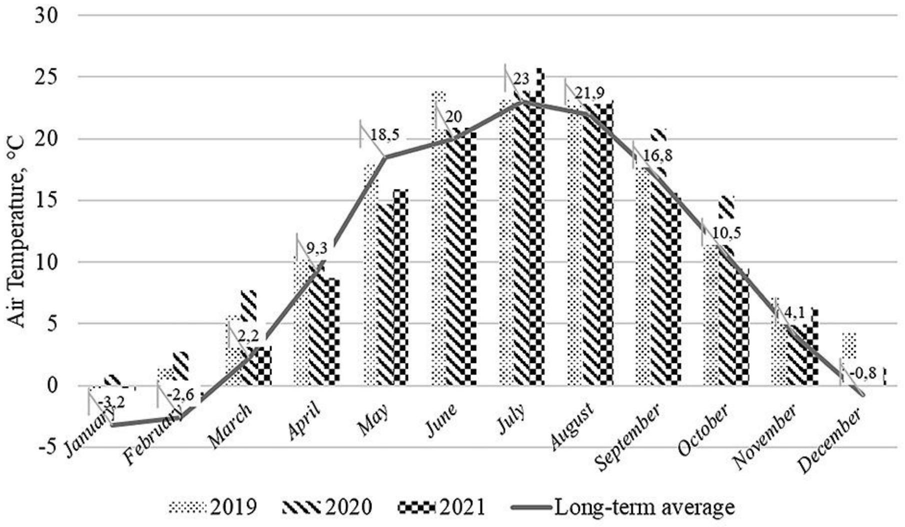

Fig. 2. Air temperature for 2019-2021, °C

Source: results of own scientific research Olesia Revto

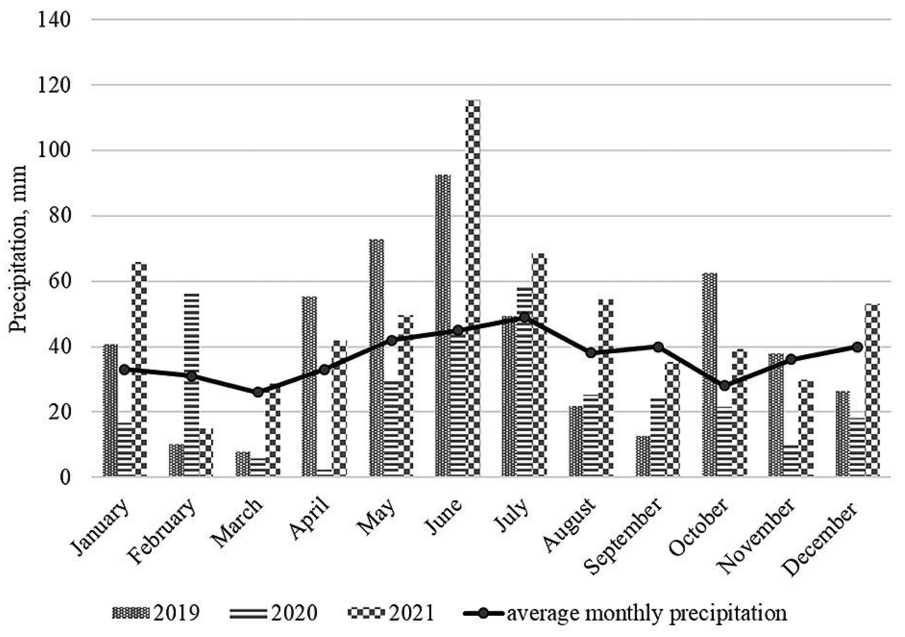

Fig. 3. Weather conditions of the reporting years (precipitation, mm)

Source: results of own scientific research Olesia Revto

The following factors and their variants were studied in field studies:

- Factor A: Sunflower hybrids: Favorit, Dragan, Congress;
- Factor B: Growth regulators: control (water), Bio-gel, Helafit-combi, and Mifosat.

The hybrids that were selected for the study to assess their response to the use of different growth regulators under conditions of insufficient moisture in southern Ukraine differ in morphological, biological, and economic characteristics.

Bio-gel is a multifunctional product that contains a complex of beneficial soil microflora in combination with organic substances from fertile soils. It is used to increase plant stress resistance, increase yields, and restore soil fertility. The product contains natural bacteria from fertile soils, organic humic and fulvic acids, amino acids, and vitamins.

Helafit-combi is a multifunctional stimulator of protective reactions and general non-specific plant resistance. The preparation contains a balanced complex of biologically active substances that ensure its multifunctionality.

Mifosat is a systemic growth regulator characterized by a complex mechanism of action. The preparation contains a balanced complex of stimulants and microelements that regulate growth processes and increase plant resistance to stress factors.

The cultivation technology was generally accepted for non-irrigated conditions of southern Ukraine, with the exception of the factors that were set for study (hybrid composition, plant growth regulators). The predecessor for sunflower was spring barley. Treatment with growth stimulants (Water-control, Bio-gel, Helafit combi, Mifosat) was carried out by spraying plants during the growing season in the 6-8 leaf stage.

It was established that the plant growth regulators Bio-gel, Helafit combi, and Mifosat, with a single spraying of plants during the growing season in the 6-8 leaf stage of the crop, contributed to improving the growth, development of plants, and the formation of sunflower seed yield.

The use of the studied growth regulators provided better growth activity. Thus, with the use of growth regulators, the plant height was 2-4 cm greater than in the control in the Favorit hybrid, 4-6 cm in Dragan, and 3-6 in Congress. The largest increase in linear plant height of sunflower was observed with the use of the Bio-gel growth regulator.

The number of leaves per plant also increased. And the largest was with the treatment of sunflower plants with the Bio-gel preparation – 24-25 pcs. per 1 plant (Table 1).

Table 1. The Impact of Growth Regulators on Sunflower Plant Height and Leaf Count

No.	Plant Growth Regulators	Plant Height, cm	Leaf Count, pcs
Favorite			
1	Water-control	160	21
2	Bio-gel	164	24
3	Helafit combi	163	22
4	Mifosat	162	23
Dragan			
5	Water-control	162	22
6	Bio-gel	168	24
7	Helafit combi	166	23
8	Mifosat	166	23
Congress			
9	Water-control	164	23
10	Bio-gel	170	25
11	Helafit combi	168	24
12	Mifosat	167	24

Source: results of own scientific research Olesia Revto

The processes of assimilation surface formation by plants are largely determined by their phenotype. But, of course, growing conditions also have a great influence on this indicator.

Determining individual biometric indicators of plants confirmed that they tend to increase under the influence of the studied growth regulators.

Yield is an integral indicator that reflects the effectiveness of agricultural practices, including growth regulators, on the growth, development, and productivity of crops. It is a key criterion for assessing the impact of various factors on sunflower yield formation.

Given that the studied sunflower hybrids belonged to the same maturity group, they were under equal conditions regarding the influence of agricultural factors, which allowed for an objective assessment of the impact of growth regulators.

The results of the conducted studies indicate a positive effect of growth regulators on the growth, development, and productivity of sunflower crops. The use of regulators contributed to the acceleration of growth processes and the formation of a higher level of productivity.

Analysis of the obtained data showed that sunflower seed yield ranged from 16.7 to 24.4 centners per hectare, indicating a significant impact of the studied factors on yield formation (Table 2 and Figure 4).

Table 2. The Impact of Growth Regulators on Sunflower Seed Yield

No.	Plant Growth Regulators	Yield, centners/hectare	Increase (Decrease) in Yield ±, centners/hectare
Favorite			
1	Water-control	16.7	-
2	Bio-gel	19.5	2.8
3	Helafit combi	18.6	1.9
4	Mifosat	18.9	2.2
Dragan			
5	Water-control	20.4	-
6	Bio-gel	23.6	3.2
7	Helafit combi	22.3	1.9
8	Mifosat	22.5	2.1
Congress			
9	Water-control	21.3	-
10	Bio-gel	24.4	3.1
11	Helafit combi	22.9	1.6
12	Mifosat	23.0	1.7

LSD05, centners/hectare: Factor A – 0.51; Factor B – 0.59; Interaction AB – 1.02.

Source: results of own scientific research Olesia Revto

Even a single treatment of plants with growth regulators contributed to a significant increase in yield, which ranged from 1.9 to 2.8 centners per hectare in the Favorite sunflower; in Dragan – from 1.9 to 3.2 centners per hectare, and in Congress – from 1.6 to 3.1 centners per hectare. The highest yield was obtained with the treatment with the Bio-gel regulator, which amounted to 19.5 – 24.4 centners per hectare, with a yield increase of 2.8-3.2 centners per hectare. Treatment of plants with Mifosat and Helafit combi growth regulators was also positive.

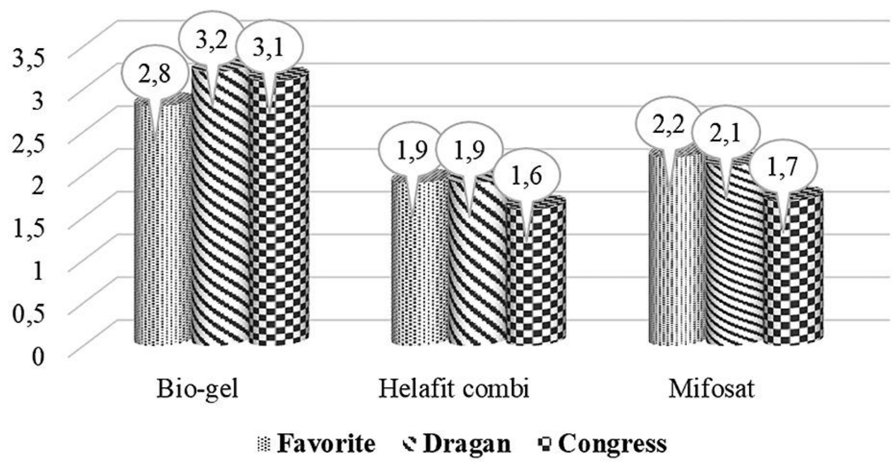

Figure 4. Increase in Sunflower Seed Yield Depending on the Studied Plant Growth Regulators

Source: results of own scientific research Olesia Revto

Measurements of the sunflower head diameter of the studied hybrids, carried out at the stage of physiological maturity (Table 3), showed that all studied plant growth regulators had an impact on its size. However, the most significant effect, as evidenced by the measurement results, was observed with the Bio-gel growth regulator. The head diameter of the Favorite hybrid with this growth regulator treatment was 19.7 cm, the Dragan hybrid – 21.5 cm, and the Congress hybrid – 21.9 cm, which is 9-13% more than the control. The size of the heads was, of course, also determined by the phenotypic characteristics of the hybrid.

Table 3. The Impact of Growth Regulators on Sunflower Head Diameter at the Seed Filling Stage

No.	Plant Growth Regulators	Head Diameter, cm
Favorite		
1	Water-control	18.0
2	Bio-gel	19.7
3	Helafit combi	18.9
4	Mifosat	19.0
Dragan		
5	Water-control	19.0
6	Bio-gel	21.5
7	Helafit combi	20.8
8	Mifosat	21.0
Congress		
9	Water-control	19.4
10	Bio-gel	21.9
11	Helafit combi	21.3
12	Mifosat	21.1

Source: results of own scientific research Olesia Revto

One of the important indicators of sunflower seed quality, which affects the yield, is seed size, characterized by such an indicator as the weight of 1000 seeds.

Regarding the effect of plant growth regulators on the change in the weight of 1000 seeds, all studied preparations to some extent influenced this indicator (Figure 5).

Treatment of the studied crop with a solution of growth regulators contributed to a steady increase in the weight of 1000 seeds in all hybrids. In the variant with water treatment (control), this indicator averaged 59 g. Treatment of crops with Biogel, Helafit combi, and Mifosat provided a weight of 1000 seeds at the level of 60-65 g, while in the control, the average indicator of 1000 seed weight was 57-60 g.

Among the hybrids, Dragan turned out to be the best in terms of seed size, with a weight of 1000 seeds of 60-65 g. As for other hybrids, their indicators were not much worse: in Favorite – 57-62 g, in Congress – 60-64 g.

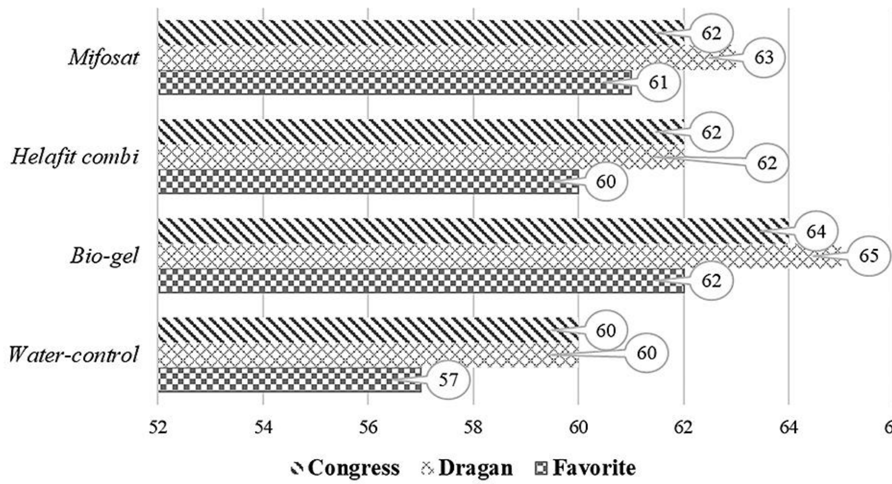

Figure 5. Weight of 1000 Seeds Depending on the Studied Plant Growth Regulators

Source: results of own scientific research Olesia Revto

It has been proven that the use of growth regulators on sunflower crops in the 6-8 leaf stage is an effective agricultural practice. The results of field experiments show that foliar treatment of sunflowers with growth stimulants is an effective tool to improve the production process in agrocenoses, especially in the arid climate of southern Ukraine. This contributes to an increase in seed yield by 11.0-14.2% and an improvement in its qualitative indicators. Among the studied preparations, the Bio-gel growth regulator demonstrated the greatest effectiveness, which confirms its feasibility for use in production conditions.

The obtained results have practical significance for agricultural producers working in similar soil and climatic conditions. Recommendations for growing the Congress hybrid and using the Bio-gel growth regulator will contribute to increasing the productivity and economic efficiency of sunflower cultivation.

3.3. Increasing Sunflower Yield by Optimizing Soil Tillage and Seeding Rate in Arid Conditions of Southern Ukraine

Sunflower is one of Ukraine's strategic agricultural crops, playing a crucial role in the country's economy as a leading export product.

This is due to its high profitability (approximately 220-270%), low labor costs compared to other industrial crops, an unlimited domestic market, and significant export potential. Most natural factors of the Steppe zone (except for low moisture availability) contribute to high sunflower yields across the region, further facilitating its widespread cultivation[9].

According to FAO data, Ukraine accounts for 31% of the world's total sunflower production[10].

In 2023, the total area under sunflower cultivation in Ukraine was approximately 5.03 million hectares, increasing to 5.12 million hectares in 2024, a 1.8% rise compared to the previous year. Sunflower remains the primary spring crop, with cultivation areas significantly exceeding those of corn and other oilseed crops[11].

Sunflower productivity largely depends on the level of cultivation technology. Scientific institutions have developed technologies that include the use of hybrids adapted to specific growing conditions, modern tillage and fertilization systems, optimal plant density, pest and disease control, and adherence to agronomic practices such as timely sowing, crop care, and harvesting. By implementing these technologies, some farms in the arid Steppe region achieve yields of 2.5-3.5 $t{\cdot}ha^{-1}$ and more[12].

One of the main advantages of sunflower cultivation is its consistently high profitability and liquidity. However, the lack of proper planning in crop rotation has led to an excessive share of sunflower in some farms, reaching 25-30% instead of the scientifically recommended 10%. This overuse depletes soil fertility, resulting in declining yields of both sunflower and other rotation crops.

Field studies conducted in the non-irrigated conditions of southern Ukraine on dark chestnut soils have shown that the highest seed yield

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9 Domaratskyi, Ye. O., Dobrovolskyi, A. V., Bazalii, V. V., Pichura V .I., & Domaratskyi, Ye. O. (2020). Sunflower: ecological ways to optimize its nutrition. Oldi-plus..

10 Ukraine suspends exports of some food products (2024). https://www.fao.org/giews/food-prices/food-policies/detail/en/c/1476888.

11 State Statistics Service of Ukraine. (2024). Retrieved from: http://www.ukrstat.gov.ua/.

12 Pysarenko P.V., Malyarchuk A.S., Myshukova L.S., & Malyarchuk V.M. (2020). Sunflower productivity with different methods and depths of basic tillage in crop rotation on irrigation. *Irrigated Agriculture*, 74. 143-147.

(25-30 c·ha^{-1}) is achieved with hybrids planted at a density of 40-50 thousand plants per hectare[13].

In the Right-Bank Steppe of Ukraine, the highest sunflower yield (3.62-3.85 t·ha^{-1}) was obtained with a plant density of 60 thousand plants per hectare (Pinkovskyi & Tanchyk, 2020)[14].

For the Central Polissia region, it is recommended to cultivate sunflower hybrids at a density of 45 thousand plants·ha^{-1} with a seeding rate of 50 thousand/ha. Increasing the density to 60-62 thousand plants·ha^{-1} (seeding rate of 72 thousand/ha) led to a slight (3%) decrease in yield[15].

Field studies conducted in 2018-2019 in the northern Steppe of Ukraine with sunflower hybrids of different maturity groups showed that a mid-maturity hybrid planted at a density of 70 thousand plants·ha^{-1}resulted in a yield increase of 0.14 t·ha^{-1} [16].

In the dry Steppe and semi-desert zones of Kazakhstan, experiments on three different seeding rates revealed that the highest yield in the semi-desert zone was obtained at a seeding rate of 57 thousand seeds·ha^{-1}, while in the Steppe zone, the highest yield was recorded at 65 thousand seeds·ha^{-1} [17].

Thus, sunflower productivity largely depends on the level of implementation of modern cultivation technologies, which take into account regional characteristics, soil tillage methods, seeding rates, and crop management practices. The introduction of scientifically based technologies enables farms to achieve sunflower yields of 2.5-3.5 t·ha^{-1} or more in various regions.

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13 Domaratskiy, Y., Kaplina, A., Kozlova, O., Koval, N., & Dobrovolskyi, A. (2020). Economic justification for the use of biological fungicides and plant growth stimulants for growing sunflower. *Independent journal of management & production* (IJM&P), 11, 2171-2184. DOI:10.14807/ijmp.v11i9.1406

14 Pin'kovskyi H.V., & Tanchyk S.P. (2020). Productivity and economic efficiency of sunflower cultivation depending on sowing dates and plant density in the Right-Bank Steppe of Ukraine. *Agrobiology*, 2. 115–123. doi:10.33245/2310-9270-2020-161-2-115-123.

15 Chyhryn O.V., Voropai Yu.V., & Shashchuk V.A. (2024). Yield of different sunflower hybrids depending on the seeding rate. *Agrarian Innovations*. (24). P. 160-165. https://doi.org/10.32848/agrar.innov.2024.24.23.

16 Andriienko, O., Vasylkovska, K., Andriienko, A., Vasylkovskyi, O., Mostipan, M. & Salo, L. (2020). Response of sunflower hybrids to crop density in the steppe of Ukraine. *Helia*, *43*(72), 99-111. https://doi.org/10.1515/helia-2020-0011

17 Gordeyeva Y., Shelia V., Shestakova N., Amantayev B., Kipshakbayeva G., Shvidchenko V., Aitkhozhin S., Kurishbayev A., & Hoogenboom G. Sunflower (Helianthus annuus) (2024). Yield and Yield Components for Various Agricultural Practices (Sowing Date, Seeding Rate, Fertilization) for Steppe and Dry Steppe Growing Conditions. Agronomy, *14*(1), 36 https://doi.org/10.3390/agronomy14010036.

At the same time, adherence to crop rotation, timely sowing, proper crop care, and efficient harvesting contribute to preserving soil fertility and ensuring the stability of agricultural production.

In this context, it is crucial to study the optimization of sunflower yield through the improvement of soil physical properties, water-air balance, and rational selection of tillage methods and seeding rates. Addressing these issues is essential for the sustainable development of the agro-industrial sector.

The aim of the study was to determine the effectiveness of different tillage methods and depths, as well as optimal seeding rates, for sunflower cultivation in southern Ukraine.

The research was conducted from 2019 to 2021 at the experimental field of the Southern Ukrainian branch of L. Pogorilyy UkrNDIPVT. The field is located in the dry Steppe soil-ecological zone within the Inhulets irrigation system. The relief is flat, and groundwater lies deeper than 10 meters.

During the research, the scientific work was planned in accordance with the set objectives, including field, laboratory-field, and laboratory experiments, as well as a complex of phenological, biometric, and analytical studies.

The early-maturing sunflower hybrid "Karlos 105" (breeder: VNIS LLC) was sown after winter wheat using a wide-row sowing method (row spacing 70 cm) with a Vega-6 seeder (manufacturer: PJSC Elvorti, Kropyvnytskyi). The seeding depth was 5 cm.

The cultivation technology followed standard regional recommendations, except for the studied factors. The experiment included three replications, with a plot size of 1,760 m² and an accounting area of 50 m². Experimental variants were arranged using the split-plot method.

The winter wheat straw was evenly distributed across the field surface. Subsequently, stubble tillage was carried out using a heavy trailed disc harrow (BDVP-6.3) in two mutually perpendicular directions, with a loosening depth of 6-8 cm and 8-10 cm. The experimental variants with different tillage methods and depths were established in the second half of September according to the planned scheme, using a reversible five-bottom plow, a chisel cultivator PCH-2.5 (manufactured by Veles-Agro, Odesa), and disc loosening to a depth of 12-14 cm with the use of heavy disc harrows BDVP-6.3.

At the beginning of the spring fieldwork, harrowing was performed using heavy-toothed harrows. Pre-sowing cultivation, combined with the application of soil herbicides, was carried out on the day of sowing using a KPS-4A steam cultivator in combination with harrows and an OP-2000 sprayer.

In all years of research, sunflower seedlings emerged uniformly and on time. Due to the application of herbicides, pre-emergence and post-emergence harrowing was not required during the study years. However, even slight atmospheric precipitation during the post-sowing period led to the formation of a soil crust, which inhibited sunflower growth and development. Therefore, at the 4-5 true leaf stage, inter-row loosening to a depth of 4-5 cm was performed annually using the USMK-5.4 row-crop cultivator.

The soil of the experimental field was dark chestnut, medium loamy, and coarse-silt loamy in texture. The humus horizon was 38-40 cm deep, with a humus content of 2.15% in the 0-40 cm layer. The minimum moisture capacity in the 0-100 cm soil layer was 21.5%, the wilting point was 9.1%, the content of water-resistant aggregates was 34.1%, the equilibrium bulk density ranged from 1.39 to 1.42 $g \cdot cm^{-3}$, porosity was 49.2%, and water permeability was 1.25 mm/min.

The content of water-soluble salts showed minimal variation across layers. The pH of the water extract was 6.8 in the 0-20 cm layer and 7.2 in the 20-40 cm layer.

The sum of exchangeable bases in the 0-20 cm layer was 21.12 mg-equivalents, while in the 20-40 cm layer, it was 19.35 mg-equivalents. The absorbed bases were represented by Ca and Mg. In the 0-20 cm soil layer, Ca accounted for 80.99%, and Mg for 19.01% of the total absorbed bases, while in the 20-40 cm layer, these values were 80.1% and 19%, respectively.

The research was conducted using widely recognized methodologies and methodological recommendations adopted in Ukraine, based on national standards (DSTU) and other regulatory documents.

The experimental scheme included three soil tillage methods:

- plowing to a depth of 30-32 cm;
- chisel tillage to a depth of 30-32 cm;
- disking to a depth of 12-14 cm.

The seeding rates tested were:

- 30 thousand $seeds \cdot ha^{-1}$;

- 40 thousand seeds·ha^{-1};
- 50 thousand seeds·ha^{-1}.

The arrangement of experimental variants was systematic.

In the tables and text, the least significant difference (LSD) was presented at the 5% significance level.

The soil tillage depth was measured from the edge of the untreated furrow to its bottom using a furrow gauge, with at least fifty measurements taken on each plot. After determining the average depth for each experimental plot, the uniformity coefficient of tillage was calculated and evaluated on a five-point scale[18].

Soil moisture content at a depth of 0-100 cm was determined before sowing and after sunflower harvesting using the thermostat-weight method. Total water consumption was assessed using the water balance method, while the water use coefficient was calculated as the ratio of total water consumption to seed yield.

Chemical treatments of crops were conducted mechanically using an OP-2000 sprayer in combination with an MTZ-82 tractor.

Sunflower harvesting and yield assessment were performed by threshing the entire accounting area of plants for all experimental variants, adjusting to a standard moisture content of 8%, and recalculating the yield per hectare[19].

Statistical processing, generalization, and analysis of experimental results from field and laboratory studies, as well as various observations and measurements, were carried out using modern dispersion and correlation analysis methods on a PC.

The economic efficiency of sunflower cultivation was calculated using standard methodologies and determined based on technological maps and prices as of the fourth quarter of 2021[20,21].

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18 Soil quality. Soil fertility indicators: DSTU 4362:2004. (2006). Kyiv: Derzhspozhyvstandart of Ukraine.

19 Oilseeds. Determination of moisture and volatile matter content DSTU ISO 665:2008. (2008). Kyiv. Derzhspozhyvstandart Ukrainy.

20 Pyvovar V.S., Nuzhdin Ye.M., & Kysliachenko M.F. (2010). Methodical provisions and norms of productivity and fuel consumption for soil cultivation. Kyiv. NDI Ukragropromproductivity.

21 Pyvovar V.S., Nuzhdin Ye.M., & Kysliachenko M.F. (2010). Methodical provisions and norms of productivity and fuel consumption for sowing, planting and crop care. Kyiv. Ukragropromproductivity. 192 p.

The assessment of total water consumption and water expenditure per unit of production, depending on the soil tillage method and depth while considering atmospheric precipitation, revealed that the tillage method did not significantly affect water expenditure. However, the depth of loosening had a considerable impact.

The key factors in reducing total water consumption and increasing the efficiency of precipitation and soil moisture reserves, apart from introducing modern high-yielding varieties and hybrids, included agronomic measures such as primary soil tillage, a rational fertilization system, and optimizing plant density.

Moisture availability conditions varied between 2019 and 2021 in terms of soil moisture reserves and the amount of precipitation during the growing season. The years were classified as follows based on moisture deficit: 2019 and 2021 – moderately wet; 2020 – average.

Under rainfed conditions, total water consumption for agricultural crops during the growing season is formed by productive soil moisture reserves and effective precipitation. Observations conducted during 2019-2021 showed that total water consumption for sunflower crops varied depending on the soil tillage method and depth but remained within the margin of error for different seeding rates of viable seeds.

The results showed that in arid conditions, sunflower's total water consumption varied depending on the tillage method. On average, the total water consumption ranged from 3128 to 3318 $m{\cdot}ha^{-3}$. The highest moisture consumption was recorded in the plowing variant (30-32 cm), while the lowest was in the disking variant (12-14 cm).

An analysis of the components of the water balance revealed that the proportion of utilized moisture reserves in the active soil layer varied slightly depending on the tillage method and depth, ranging from 25.9% to 31.0%, while the contribution of precipitation ranged from 69.0% to 74.1% (Table 4).

Table 4. Total water consumption and its balance for 2019-2021

Indicators	**Soil tillage and depth**		
	plowing 30-32 cm	**chisel tillage 30-32 cm**	**disking 12-14 cm**
Initial soil moisture reserves, $m \cdot ha^{-3}$	2919	2905	2848
Final soil moisture reserves, $m \cdot ha^{-3}$	1889	1960	1948
Used moisture, $m \cdot ha^{-3}$	1030	945	860
Precipitation, $m \cdot ha^{-3}$	2355	2355	2355
Total water consumption, $m \cdot ha^{-3}$	3318	3233	3128

Source: results of own scientific research Anastasiia Maliarchuk

The water use coefficient is an essential indicator that complements the assessment of the impact of agronomic practices on sunflower's water use efficiency alongside total water consumption. This coefficient reflects the amount of water consumed by the plant to produce one ton of sunflower seeds, along with the corresponding amount of aboveground biomass. It is significantly influenced by the biological characteristics of the variety or hybrid, the seeding rate per hectare, agronomic practices, and the weather conditions during the growing season.

The ratio of total water consumption to sunflower yield was used to determine the water use coefficient of the crops, depending on the soil tillage method, depth, and seeding rate per hectare. Both factors had a significant impact on the water use efficiency of sunflower crops (Figure 6).

Analysis of water-use efficiency revealed that increasing the seeding rate reduced the water consumption coefficient. For example, increasing the seeding rate from 30 to 40 thousand $plants \cdot ha^{-1}$ reduced the water consumption coefficient by 316 $m \cdot t^{-3}$ in the plowing variant, by 322 $m \cdot t^{-3}$ in the chisel tillage variant, and by 350 $m \cdot t^{-3}$ in the disking variant.

The key criterion for evaluating any crop cultivation practice is its productivity. Studying the impact of different soil tillage methods, depths, and seeding rates on sunflower productivity allows us to conclude that replacing plowing at 30-32 cm with chisel tillage (30-32 cm) or shallow disking (12-14 cm) in years with low soil moisture reserves at sowing and a lack of effective precipitation during the growing season led to a decrease in yield.

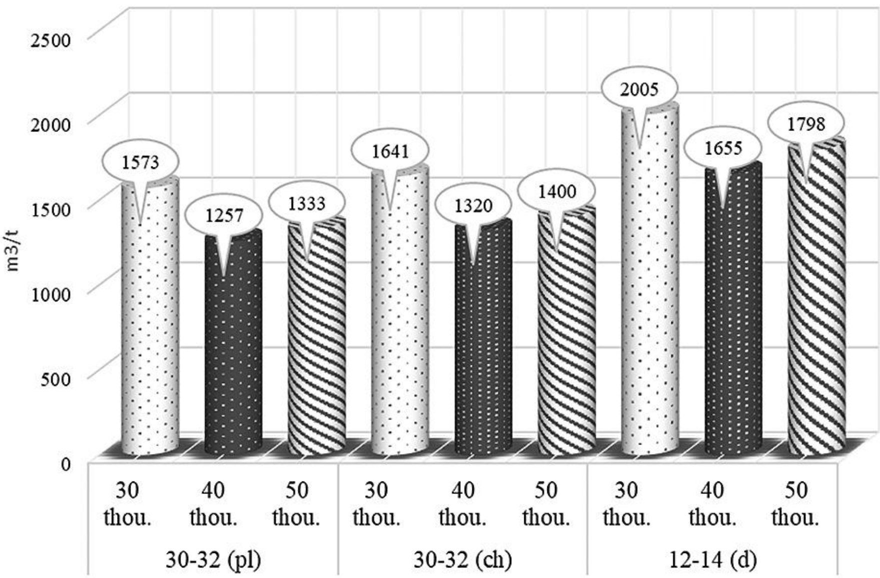

Figure 6. Sunflower water use coefficient, m·t^{-3} of dry biomass (average for 2019-2021)

Source: results of own scientific research Anastasiia Maliarchuk

Research conducted from 2019 to 2021 to assess the effectiveness of various sunflower cultivation technologies confirmed that all studied factors had a significant influence on yield formation.

Yield analysis showed significant differences between the experimental variants. The highest yield was obtained with plowing at 30-32 cm (2.64 t·ha^{-1}) and chisel tillage at 30-32 cm (2.45 t·ha^{-1}). The lowest yield (1.56-1.89 t·ha^{-1}) was recorded in the disking variant (12-14 cm), depending on the seeding rate (Table 5).

Table 5. Sunflower yield under different main tillage and seeding rates (average for 2019-2021), $t \cdot ha^{-1}$

Soil tillage and depth (factor A)	Seeding Rate, thousand seeds·ha^{-1} (factor B)		
	30	40	50
30-32 (pl)	2,11	2,64	2,49
30-32 (ch)	1,97	2,45	2,31
12-14 (d)	1,56	1,89	1,74

For partial differences: $LSD_{0.05}$ A = 0.16 $t \cdot ha^{-1}$; B = 0.21 $t \cdot ha^{-1}$
For main differences: $LSD_{0.05}$ A = 0.09 $t \cdot ha^{-1}$; B = 0.12 $t \cdot ha^{-1}$

Source: results of own scientific research Anastasiia Maliarchuk

Seeding rates per hectare had a significant effect on yield formation. Over the three-year study period, the highest sunflower yield (2.64 $t \cdot ha^{-1}$) was achieved with a seeding rate of 40 thousand seeds·ha^{-1} under moldboard plowing at a depth of 30-32 cm. Increasing the seeding rate to 50 thousand seeds·ha^{-1} led to a yield reduction, ranging from 1.74 to 2.49 $t \cdot ha^{-1}$ depending on the tillage method and depth, which represents a decrease of 5.7-34.1%. The lowest yields (1.56-2.11 $t \cdot ha^{-1}$) were observed across all tillage methods when the seeding rate was set at 30 thousand viable seeds per hectare.

The effectiveness of seeding rates also depended on soil moisture levels. Under drier conditions, their influence was relatively weak, but as soil moisture increased, their impact on yield improved.

An analysis of annual yield data showed that sunflower yield was highest in 2021, reaching 1.74 $t \cdot ha^{-1}$ under disk tillage at a depth of 12-14 cm with a seeding rate of 30,000 seeds·ha^{-1}. In contrast, during the less favorable hydrothermal conditions of 2020, yield decreased to 1.44 $t \cdot ha^{-1}$ under the same cultivation conditions.

3.4. Analysis of the Economic and Energy Efficiency of Optimized Sunflower Cultivation Technologies in the Southern Regions of Ukraine

At the current stage of agrarian production development, the key task of scientific research is to develop and implement technologies for growing crops that ensure a high level of yield and product quality at minimal costs and maximum profitability. Intensive agricultural technologies should demonstrate high economic efficiency, as this indicator determines their competitiveness in market conditions and attractiveness to agricultural producers.

The intensification of sunflower production is a key factor in increasing its economic and energy efficiency. Optimizing the cost per unit of production (seeds) and achieving maximum yield per unit area are of significant scientific and practical importance.

The economic efficiency of sunflower production and processing depends on a complex of interrelated natural-economic, technological, and scientific-technical factors.

In this study, to calculate the economic efficiency of using plant growth regulators in the cultivation of sunflower hybrids (Favorite, Dragan, Congress), exchange prices for seeds and market prices for agricultural resources were used.

The economic efficiency of using various growth regulators in the cultivation of sunflower hybrids is shown in Table 6.

Table 6. Economic Efficiency of Using Plant Growth Regulators in Sunflower Cultivation

No.	Plant Growth Regulators	Yield, $t \cdot ha^{-1}$	Product Value, $USD \cdot ha^{-1}$	Production Costs, $USD \cdot ha^{-1}$	Cost Price per $USD \cdot ha^{-1}$	Net Profit, $USD \cdot ha^{-1}$	Profitability Level,%
Favorite							
1	Water-control	1.67	571.23	433.76	260.24	137.55	32
2	Bio-gel	1.95	666.92	438.63	224.95	228.37	52
3	Helafit combi	1.86	636.22	434.97	233.84	201.21	46
4	Mifosat	1.89	646.48	435.21	230.34	211.20	48
Dragan							
5	Water-control	2.04	697.79	436.70	214.12	261.09	60
6	Bio-gel	2.36	807.24	441.93	187.32	365.27	82
7	Helafit combi	2.23	762.74	438.03	196.46	324.71	74
8	Mifosat	2.25	770.02	438.23	194.77	331.39	76

No.	**Plant Growth Regulators**	**Yield, t·ha^{-1}**	**Product Value, USD·ha^{-1}**	**Production Costs, USD·ha^{-1}**	**Cost Price per USD·ha^{-1}**	**Net Profit, USD·ha^{-1}**	**Profitability Level,%**
Congress							
9	Water-control	2.13	728.57	437.42	205.39	291.09	67
10	Bio-gel	2.44	834.69	442.74	181.45	391.87	89
11	Helafit combi	2.29	783.30	438.51	191.51	344.71	79
12	Mifosat	2.30	786.72	438.59	190.75	348.09	79

Source: results of own scientific research Olesia Revto

By analyzing the indicators of gross product value in the cultivation of sunflower hybrids in the southern regions of Ukraine, it has been proven that the studied growth regulators significantly affected this indicator.

The gross product value of over 805 USD·ha^{-1} was observed when growing the studied Dragan and Congress hybrids and treating them with the Bio-gel growth regulator. The lowest values of this indicator (571 USD·ha^{-1}) were observed when growing the Favorite hybrid without the use of plant growth regulators.

Among the studied hybrids, the highest gross product value of 835 USD·ha^{-1} was obtained when growing the Congress hybrid.

The application of the Bio-gel growth regulator contributed to an increase in the gross product value per unit area, on average, to 770 USD·ha^{-1}. In the variant with Helafit Combi treatment, this indicator decreased by 5.5%, and with Mifosat treatment – by 4.6%. Overall, the treatment of crops with plant growth regulators, compared to the control plots, ensured an increase in gross yield by 7-14.4%.

According to the analysis of technological maps for growing Favorite, Dragan, and Congress sunflower hybrids in the experimental plots, production costs did not significantly change depending on the use of Bio-gel, Helafit Combi, and Mifosat growth regulators.

A tendency for this economic indicator to increase in proportion to the increase in yield was established, which is due to some increase in the cost of harvesting additional yield, its transportation, cleaning, and drying, as well as in areas with the application of plant growth regulators.

Calculations have shown that the lowest cost price per 1 ton of sunflower seeds, at the level of 181 USD, was in the variant with the Congress hybrid and crop treatment with the Bio-gel growth regulator. The highest value (at the level of 260 USD·t^{-1}) was formed in the variant with the Favorite hybrid and without the use of plant growth regulators.

The maximum net profit of 392 USD was obtained in the variant with the Congress hybrid and the application of the Bio-gel growth regulator.

Among the studied hybrids, Congress also had advantages in terms of forming the largest conditional net profit. Thus, in the variant with this hybrid, this indicator averaged 344 USD·ha^{-1}, while in the variants with Favorite and Dragan hybrids, it decreased to 195-321 USD·ha^{-1}, or by 6.8-43.4%.

The use of all plant growth regulators without exception led to a significant increase in net profit in the cultivation of sunflower hybrids. In the control variant, the minimum values of the studied indicator were noted – at the level of 230 USD·ha^{-1}. The highest net profit was in the variant with the application of Bio-gel, where it increased to 329 USD·ha^{-1}, which is 1.4 times more than the control variant.

The fluctuations in the profitability level in specific experimental variants were determined by the analysis of the above-mentioned initial economic indicators.

The highest profitability (89%) was formed when growing the Congress hybrid in the experimental plots and applying the Bio-gel growth regulator.

In the treated variants with growth regulators, a steady increase in the profitability level of sunflower cultivation was noted. Thus, in the variants with the application of Bio-gel, the studied economic indicator increased to 74.3%, Helafit Combi – to 66.0%, Mifosat – 67.7%. Therefore, plant growth regulators contributed to the formation of maximum profitability, which exceeded the untreated variant (control) by 21.3, 13.0, and 14.7 percentage points, respectively. It should be emphasized that the treatment of sunflowers with the Bio-gel regulator was more effective, and the profitability exceeded the variants with the application of Helafit Combi and Mifosat by 8.3 and 6.6 percentage points.

Economic indicators are also influenced by soil tillage methods and depth, seed sowing rates, fertilization, the use of production mechanization, and the use of a plant protection system against pests, weeds, and diseases.

Economic efficiency for 2019-2021 was calculated by us at the prices of the fourth quarter of 2021. The cost of 1 ton of sunflower seeds was taken as 644.00 USD.

It was established that the factors studied directly affected the indicators of economic efficiency (Table 7). Thus, calculations of economic efficiency in sunflower cultivation show that at a seeding rate of 40 thousand germinated seeds per hectare, the highest level of profitability and profitability was ensured in most cases, regardless of the tillage method.

Table 7. Economic Efficiency of Sunflower Cultivation with Different Methods and Depths of Primary Tillage and Seeding Rates of Germinated Seeds, 2019-2021

Method and Depth of Primary Tillage	Seeding Rate of Germinated Seeds, thousand/ha	Total Costs, USD·ha^{-1}	Gross Product Value, USD·ha^{-1}	Profit, USD·ha^{-1}	Cost Price per 1 ton of Grain, USD	Profitability Level,%
Plowing 30-32 (o)	30	591	1359	768	280	130
	40	605	1700	1096	229	181
	50	601	1604	1003	241	167
Chisel Tillage 30-32 (o)	30	575	1269	694	292	121
	40	594	1578	984	242	166
	50	595	1488	893	258	150
Disk Tillage 12-14 (d)	30	549	1005	456	352	83
	40	569	1217	648	301	114
	50	577	1121	544	331	94

Source: results of own scientific research Anastasiia Maliarchuk

Calculations of the economic efficiency of sunflower cultivation show that the highest conditional net profit – 1096 USD on average over the years of research – was obtained in the variant with a seeding rate of 40 thousand/ha with plowing to a depth of 30-32 cm. The product value for this indicator was 1700 USD with total costs of 605 USD and a cost price of 229 USD per 1 ton of seeds, with a profitability level of 181%.

With an increase in the seeding rate from 40 thousand germinated seeds to 50 thousand, the size of the conditional net profit decreased, as there were no yield increases. Thus, with plowing to a depth of 30-32 cm and a seeding rate of 50 thousand/ha, the conditional net profit was 1003 USD, with chisel loosening – 893 USD, and with disking – 544 USD.

Analyzing the cost price per 1 ton of seeds, it should be noted that the highest (352 USD) was in the variant with a seeding rate of 30 thousand germinated seeds per hectare with disk tillage to a depth of 12-14 cm, since the lowest yield indicators were observed in this variant.

The highest costs for sunflower cultivation were in the variant of plowing to 30-32 cm and a seeding rate of 40 thousand germinated seeds – 605 USD, and the lowest – 549 USD, or 9.3% less – with disk primary tillage and a seeding rate of 30 thousand/ha.

It should be noted that sunflower cultivation was profitable in all experimental variants. Analyzing the indicators of profitability levels, it should be noted that the use of disk primary tillage did not allow to obtain such high profits as in other variants.

Thus, the calculation of economic efficiency proves that sunflower cultivation with a seeding rate of 40 thousand germinated seeds per hectare and plowing to a depth of 30-32 cm is the most appropriate and economically advantageous.

The main advantage of the energy assessment of crop cultivation technologies is that its use makes it possible to compare the costs of agricultural measures with the results of crop production in single indicators. Therefore, energy analysis can be used for a deeper and more comprehensive substantiation of the technological process, which should further serve as the basis for establishing purchase prices for various types of products, their changes by zones and crops, as well as for substantiating profitability rates in agriculture.

Energy analysis consists of assessing the costs of all types of agricultural resources and live labor, which are converted into GJ using standard equivalents and compared with the energy gain of the grown products, also converted into $GJ \cdot ha^{-1}$.

The energy balance components for sunflower hybrid cultivation in the southern regions of Ukraine were calculated using energy analysis. This analysis was carried out using technological maps that were developed for all variants of the field experiment to determine technological costs for seed yield formation with subsequent calculations of energy input from the yield, gross energy gain indicators, energy efficiency coefficients, and energy intensity of the obtained products.

The gross energy input from the seed yield was determined by fluctuations in seed yield under the influence of the studied factors – hybrid composition (factor A) and plant growth regulators (factor B).

Among sunflower hybrids, the largest energy output per unit area was provided by the cultivation of the Congress hybrid, where the studied indicator was 41.27 GJ·ha^{-1} (Table 8).

Table 8. Energy Efficiency of Sunflower Hybrid Cultivation Depending on Growth Regulation

No.	Plant Growth Regulators	Energy Expenditure, GJ·ha^{-1}	Energy Input, GJ·ha^{-1}	Energy Gain, GJ·ha^{-1}	Energy Coefficient	Product Energy Intensity, GJ·ha^{-1}
Favorite						
1	Water-control	21.96	30.10	8.14	1.37	13.1
2	Bio-gel	22.00	35.15	13.15	1.60	11.3
3	Helafit combi	21.99	33.52	11.53	1.52	11.8
4	Mifosat	22.00	34.06	12.07	1.55	11.6
Dragan						
5	Water-control	21.99	36.77	14.78	1.67	10.8
6	Bio-gel	22.03	42.54	20.50	1.93	9.3
7	Helafit combi	22.02	40.19	18.17	1.82	9.9
8	Mifosat	22.03	40.55	18.53	1.84	9.8
Congress						
9	Water-control	21.99	38.39	16.40	1.75	10.3
10	Bio-gel	22.04	43.98	21.94	2.00	9.0
11	Helafit combi	22.03	41.27	19.24	1.87	9.6
12	Mifosat	22.03	41.45	19.42	1.88	9.6

Source: results of own scientific research Olesia Revto

The application of Bio-gel, Helafit combi, and Mifosat growth regulators contributed to an increase in energy input from sunflower seed yield from 35.09 to 38.33-40.56 $GJ \cdot ha^{-1}$. Comparison of the studied preparations shows the maximum effectiveness of Bio-gel.

According to calculations, it has been proven that gross energy costs for sunflower seed production changed slightly under the influence of the studied factors, which is due to a small difference between individual technological operations and resource costs for individual variants of the cultivation technology.

In contrast to the indicators of energy costs for the cultivation technology, the energy gain significantly fluctuated according to the studied factors and variants, which is explained by differences in gross energy input indicators and, conversely, the stability of energy costs.

The maximum energy gain of 21.94 $GJ \cdot ha^{-1}$ was in the variant with the Congress hybrid and the application of the Bio-gel growth regulator.

The use of plant growth regulators on sunflowers led to a significant increase in energy gain in the cultivation of all hybrids. Thus, in the control variant (water), this indicator was 13.1 $GJ \cdot ha^{-1}$, and with the use of growth regulators, it increased to 16.31-18.53 $GJ \cdot ha^{-1}$, or by 24.5-41.5%. The Bio-gel growth regulator was the most effective in terms of energy gain formation from 1 hectare of sown area than the use of Helafit combi and Mifosat preparations.

The energy efficiency coefficient is a reflection of the ratio of energy input from sunflower seed yield and energy costs for the cultivation technology and resource provision. This indicator most fully allows conclusions about the energy efficiency of the studied factors, especially in terms of the possibility of saving technological costs. In our study, the maximum level of the energy efficiency coefficient (2.0) was in the variant with the Congress hybrid and the application of the Bio-gel growth regulator.

Treatment of sunflower crops with complex growth regulators contributed to a steady decrease in energy intensity. Thus, in the control variant, the studied indicator was 11.4 $GJ \cdot t^{-1}$, and with the application of Bio-gel, Helafit combi, and Mifosat preparations, its decrease to 9.9, 10.4, and 10.3 $GJ \cdot t^{-1}$, respectively, was noted.

The results of the conducted studies clearly demonstrate that the economic efficiency of sunflower cultivation in the southern regions of Ukraine significantly depends on a complex of agricultural factors, among which the key ones are the hybrid, growth regulation, method and depth of soil tillage, as well as the seed sowing rate.

The results of the conducted studies in non-irrigated conditions of southern Ukraine on dark chestnut soil indicate the high adaptability and productivity of the Congress sunflower hybrid. It has been established that this hybrid provides a stable yield at the level of over 2.0 t·ha^{-1}, which is accompanied by economic efficiency expressed by net profit in the range of 282-362 USD·ha^{-1} and a profitability level of 67-89%.

The analysis of economic indicators for 2019-2021 revealed that the most profitable and cost-effective is the variant of sunflower cultivation with a seeding rate of 40 thousand germinated seeds per hectare and plowing to a depth of 30-32 cm. This variant provided the highest conditional net profit (1096 USD·ha^{-1}) and profitability level (181%), which indicates its high economic feasibility.

Increasing the seeding rate to 50 thousand seeds·ha^{-1} did not lead to a proportional increase in yield, but rather caused a decrease in conditional net profit. This emphasizes the importance of optimizing the seeding rate for rational resource use and increasing the economic efficiency of production.

Disk tillage turned out to be less effective compared to plowing and chisel tillage, which is confirmed by lower profitability and profitability indicators.

It has been established that the cost price per 1 ton of sunflower seeds also varies depending on agricultural practices, and it was the highest in the variant with disk tillage and the lowest seeding rate.

Therefore, the research results provide clear recommendations for agricultural producers on the choice of optimal agricultural practices for sunflower cultivation in the southern regions of Ukraine. The implementation of these recommendations will increase the economic efficiency of production, ensure stable and high profits, and contribute to the sustainable development of agriculture in the region.

Conclusions. The results of studies conducted in non-irrigated conditions of southern Ukraine on dark chestnut soil demonstrated the high adaptability and productivity of the Congress sunflower hybrid. It was established that this hybrid is characterized by a stable yield at the level of over 2.0 t·ha^{-1}. The economic efficiency of growing the Congress hybrid is confirmed by obtaining a net profit in the range of 282-362 USD·ha^{-1} and a profitability level of 67-89%.

It has been proven that the use of growth regulators on sunflower crops in the 6-8 leaf stage is an effective agricultural practice. The results of field experiments show that foliar treatment of sunflowers with growth stimulants is an effective tool to improve the production process in agrocenoses, especially in the arid climate of southern Ukraine. This contributes to an increase in seed yield by 11.0-14.2% and an improvement in its qualitative indicators. Among the studied preparations, the Bio-gel growth regulator demonstrated the greatest effectiveness, which confirms its feasibility for use in production conditions.

Also, sunflower productivity largely depends on the methods and depth of primary tillage and seeding rates of germinated seeds per hectare. Thus, in the conditions of southern Ukraine when growing sunflowers on dark chestnut soils in order to create a favorable soil water regime and satisfactory crop condition, it is advisable to plow to a depth of 30-32 cm and sow with a seeding rate of 40 thousand germinated seeds per hectare, which contributes to the rational use of resources and an increase in yield to 2.64 t·ha^{-1} and a profitability level of 181%.

The obtained results have practical significance for agricultural producers working in similar soil and climatic conditions. Recommendations for growing the Congress hybrid and using the Bio-gel growth regulator will contribute to increasing the productivity and economic efficiency of sunflower cultivation.

The recommendation to plow to a depth of 30-32 cm on dark chestnut soils is key to creating a favorable water regime. This is especially important in arid climates, where soil moisture conservation is critical for sunflower growth and development. This tillage depth promotes better moisture penetration into the soil and improves aeration, which positively affects the root system of plants.

The recommendation to sow 40 thousand germinated seeds per hectare allows achieving optimal crop density. This ensures rational use of resources such as moisture and nutrients, and promotes the formation of an optimal feeding area for each plant. Proper crop density also helps reduce competition between plants, which contributes to increased yields.

Thus, a comprehensive approach to sunflower cultivation, which includes the use of a high-yielding hybrid, the application of growth stimulants, and the optimization of agricultural practices, is a key factor in achieving high and stable yields in the arid climate of southern Ukraine. The implementation of these recommendations in production will not only increase the profitability of sunflower cultivation but also contribute to the sustainable development of agriculture in the region.

3.5. References

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Abstract

The monograph section is devoted to the study of modern approaches to sunflower cultivation in the conditions of Southern Ukraine, where climate change and weather instability create significant challenges for the agricultural sector. The work analyzes the impact of various factors, such as hybrid selection, soil tillage technologies, seeding density, and the use of growth regulators, on sunflower yield and seed quality.

During the experiments, field, quantitative-weight, visual, laboratory, calculation-comparative, and mathematical-statistical methods were used, employing generally accepted methodologies and guidelines.

The main focus is on evaluating the effectiveness of growth regulators application, particularly "Bio-gel," "Helafit-combi," and "Mifosat," on sunflower crops. Studies have shown that these preparations contribute to improving plant growth, development, and productivity, as well as increasing their resistance to stress factors. In particular, the use of the "Bio-gel" regula-

tor demonstrated the greatest efficiency, ensuring a significant increase in yield and improvement in seed quality.

Recommendations for growing the Congress hybrid and using the Bio-gel growth regulator will contribute to increasing the productivity and economic efficiency of sunflower cultivation.

In addition, the monograph section addresses the optimization of soil tillage and sunflower seeding rates in the arid conditions of Southern Ukraine. Studies have shown that the correct choice of tillage method and depth, as well as optimal seeding density, are important factors for ensuring high yields and efficient use of soil moisture. In the conditions of Southern Ukraine, when growing sunflower on dark chestnut soils, it is advisable to plow to a depth of 30-32 cm and sow with a seeding rate of 40 thousand germinated seeds per hectare, which contributes to the rational use of resources and an increase in yield to 2.64 $t \cdot ha^{-1}$ and a profitability level of 181%.

In the arid climate of Southern Ukraine, achieving high and stable sunflower yields requires an integrated approach. This approach includes the use of high-yielding hybrids, the application of growth stimulants, and the optimization of agricultural practices.

Keywords: sunflower, climate change, Southern Ukraine, plant growth regulators, Bio-gel, Helafit-combi, Mifosat, hybrid, basic soil tillage, plowing, chisel tillage, disking, seed seeding rate, crop water consumption, yield, economic efficiency, energy efficiency.

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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·ha^{-2} to 40,000-50,000 m·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·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·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·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·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·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·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*	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
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, $t \cdot ha^{-1}$		Energy input with yield, $GJ \cdot ha^{-1}$	Incoming PAR, $GJ \cdot ha^{-1}$	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:

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

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

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:

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

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

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:

$$Y = 0{,}0001 \cdot x^2 - 0{,}2189 \cdot x + 166{,}92 \qquad (3)$$

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

where, Y – Water consumption coefficient of onion, m³/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 m³/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 m^3/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 $UAH \cdot ha^{-1}$), the optimal option was 950 thousand $plants \cdot ha^{-1}$ (75.27 $t \cdot ha^{-1}$, 143% profitability).

An increase in planting density from 550 to 950 thousand $plants \cdot ha^{-1}$ contributes to higher yield, net profit, and profitability. The lowest labor costs per ton of production were recorded at 950 thousand $plants \cdot ha^{-1}$ (12.4 person-hours). The lowest production cost per ton (4111 UAH) was also observed at 950 thousand $plants \cdot ha^{-1}$ and 80-85% MMHC. The most effective pre-irrigation moisture level is 80-85% MMHC, as it ensures the highest yield (75.27 $t \cdot ha^{-1}$), maximum net profit (443,247 $UAH \cdot ha^{-1}$), and profitability (143%). The optimal planting density is 950 thousand $plants \cdot ha^{-1}$, which allows reducing labor costs and production costs while achieving maximum economic benefits. The lowest efficiency was observed at 550 thousand $plants \cdot ha^{-1}$ 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 $plants \cdot ha^{-1}$, 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 $plants \cdot ha^{-1}$. With an increase in plant density from 550 to 950 thousand $plants \cdot ha^{-1}$, 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$\cdot$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$\cdot$ha^{-1}, with the maximum value recorded at 950,000 plants$\cdot$ha^{-1} (649,600 UAH$\cdot$ha^{-1}). At 70-75% MMHC (gross production value: 448,300-697,100 UAH$\cdot$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$\cdot$ha^{-1}), the largest increase occurred at 950,000 plants$\cdot$ha^{-1} (752,700 UAH$\cdot$ha^{-1}), which is the highest value among all options.

Increasing the plant density from 550,000 to 950,000 plants$\cdot$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$\cdot$ha^{-1}) was achieved at 80-85% MMHC and 950,000 plants$\cdot$ha^{-1}, confirming the effectiveness of this combination. Increasing the planting density from 550,000 to 950,000 plants$\cdot$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$\cdot$ha^{-1}) was recorded at 80-85% MMHC and a density of 950,000 plants$\cdot$ha^{-1}.

To achieve the highest product value, it is recommended to optimize planting density at 950,000 plants$\cdot$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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17. Vitanov, O. D., Zelendin, Y. D., & Chefonova, N. V. (2024). *Onion bulb: Effective agro-techniques* (O. D. Vitanov, Ed.). *Agrarian Science.* https://doi.org/10.31073/978-966-540-617-4

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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.

Chapter 5.

THE IMPACT OF WEED INFESTATION ON THE INITIAL GROWTH AND DEVELOPMENT OF MAIZE GROWN FOR GRAIN

Jolanta Puczel

5.1. Introduction

5.1.1. Trends in the development of maize cultivation

Corn is one of the most important crops. Corn is grown for: seed, grain for consumption, grain for feed, whole plant silage, LKS silage, CCM silage, distillery substrate, biogas substrate, sweet corn[1,2].

Corn (Zea mays L.) is one of the most popular, profitable, and promising agricultural crops both worldwide and in Poland. It is one of the oldest plants cultivated since prehistoric times (4,500 years ago), originating in North America and well known to the world's oldest civilisations, including the Mayan and Aztec Indian tribes[3].

Both the yield and energy efficiency confirm the unquestionable usefulness of this species for the production of biomass for heating plants, combined heat and power plants, and agricultural biogas plants. The addition of corn silage significantly increases the energy efficiency of biogas plants, thus increasing the profitability of biogas production. Corn, as a fermenta-

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1 Anishin L. 2015. Corn yield depends on the level of crop care. Agricultural Resources. Institute of Genetics and Microbiology of the Ukrainian Academy of Agrarian Sciences [online]. [Accessed 02.03.2015]. Available online: http://agrosev.narod.ru/page149itemid2685number87.htm, pp. 4.

2 Bulgakov V., Shpokas L., Petkavichius S. 2006. Research on the harvesting of maize for grain. (The investigation of long stem maize threshing process). MOTROL No. 8, pp. 58-68.

3 Pikuła D. 2014. Fertilisation of maize grown for grain. Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy. Notebook 37 (11): pp. 99–109

tion stimulator, can also significantly facilitate the utilisation of manure and sewage sludge. Ethanol obtained from corn grain can be used as an additive to petrol in its pure form, or as ETEB (ethyl tert-butyl ether), and can also be burned directly in the production of electricity[4].

The harvesting of maize grain should commence once the appropriate degree of maturity and absolute moisture content has been achieved. A high degree of maturity promotes better grain separation from the cobs and lower absolute moisture content. Drying grain with an initial moisture content of 30-40% to a moisture content of several percent, suitable for storage, is an energy-intensive process. Therefore, it is very important to use varieties with the appropriate ripening time, suitable for local soil and climatic conditions[5].

The agrotechnical conditions for growing maize for grain are particularly important. To obtain 1 tonne of grain, the following fertiliser doses are required: nitrogen 24 to30 kg, phosphorus 10 to12 kg, and potassium 25 to 30 kg. The soil pH should be between 5 and 8, with 6.5 considered optimal. The recommended doses of calcium fertilisers depend on the acidity of the soil and the type of lime used, and range from 300 to 500 $kg \cdot ha^{-1}$ for oxide lime or 5,000 to 10,000 $kg \cdot ha^{-1}$ for defecation lime applied under the preceding crop or directly under the crop[6].

In its maize cultivation guide, the team provides detailed information on: pre-sowing cultivation, sowing date, nutritional requirements of maize, regulation of soil abundance in assimilable phosphorus and potassium, nitrogen fertilization, organic fertilization, magnesium and sulfur fertilization, prophylactic use of microelements, herbicide protection, pests, diseases, grain harvesting, and silage harvesting. Proper plant planting per hectare is of great importance, which, depending on the width of the inter-rows, ranges from 40 to 90 thousand $pieces \cdot ha^{-1}$. Many researchers focus on growing corn for grain without herbicides. They highlighted the role of maize cultivation in soil fertilization. Thanks to leaving a large amount of crop residues and roots in the field (estimated at about 14 tons per hectare of organic waste) after mineralization, which accumulates up to 52.5 kg of nitro-

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4 Kaszkowiak E., Kaszkowiak J. 2013 Yield and bioethanol productivity from maize in light soil conditions. University of Technology and Life Sciences in Bydgoszcz. Chemical Engineering and Equipment No. 2/2013; p. 56

5 Shpaar D. (ed.) 2012. Corn: cultivation, harvesting, storage and use. Publisher: I. D. "Zerno" Ukraine. Edition 4. ISBN 978-966-1560-02-3, pp. 464.

6 Euralis Semences 2017. Corn cultivation guide. Euralis Creating seeds and trust team, [online]. [Accessed 12 December 2017]. Available online: http://www.euralis.pl, pp. 32.

gen, 12.8 kg of phosphorus, and 79.1 kg of potassium in the soil per 1 hectare, which makes it a good site for cereal crops. At the same time, attention should be paid to the IT needs in the management of agricultural production, the Sea Seft system of decision support in the selection of maize variety[7].

The corn cultivation guide developed by the team[6], covering all technological operations and literature on corn production technology modelling, is of great cognitive value[8].

In recent years, there has been significant progress in maize grain cultivation technology. This concerns both the introduction of new varieties and the improvement of all technological operations, with particular attention to energy consumption, treatment costs, grain damage during combine harvesting (which is least at 15-18% grain moisture content), and environmentally friendly agricultural production. Trends in improving maize cultivation technology mainly involve simplifying individual treatments and eliminating chemical treatments.

5.2. Literature review

Agrotechnical requirements for field cultivation of grain maize mainly concern machine performance indicators, operating indicators, organisational principles, and environmental restrictions[9,1011,12,13,14,15]. The basic parame-

7 Zaliwski A. S. 2009. Decision support system for corn variety selection (Zea Soft). Studies and Reports of the National Institute of Ground Water Research and Information, No. 16, pp. 83–96, PDF [online]. [Accessed 12 December 2017]. Available online: http://www.dss.iung.pulawy.pl/Documents/ipr/DSSasInfoSource.html

8 Hołaj J., Zaliwski A. S. 2008. Modelling the technology of maize production grown on CCM. Agricultural Engineering. No. 2(100), pp. 43-49.

9 Anishin L. 2015. Corn yield depends on the level of crop care. Agricultural Resources. Institute of Genetics and Microbiology of the Ukrainian Academy of Agrarian Sciences [online]. [Accessed 02.03.2015]. Available online: http://agrosev.narod.ru/page149itemid2685number87.htm, pp. 4.

10 Euralis Semences 2017. Corn cultivation guide. Euralis Creating seeds and trust team, [online]. [Accessed 12.12.2017}. Available online: http://www.euralis.pl, pp. 32.

11 Gangun V.V. 2017. Productivity of corn for grain in different crop rotations of the left-bank forest-steppe of Ukraine. Bulletin of the Belarusian State Agricultural Academy. ISSN 1997-1044. No. 2, pp. 92–95

12 Habuštova O., Sehnal F. 2007. Four-year field study of the impact of BT maize on arthropod communities. Kosmos Problems of Biological Sciences. Volume 56. No. 3-4 (276-277), pp. 275-284.

13 Hołaj J., Zaliwski A. S. 2008. Modelling the production technology of maize grown on CCM. Agricultural Engineering. № 2(100), pp. 43-49.

ters in maize cultivation are: row spacing (currently used are 67,5 cm and 75 cm), seed spacing in the row (25 to 50 cm, depending on the variety), working width of machines (4, 6, and 12-row seeders, 1, 2, 3, 4, and 6-row harvesting machines). The number of rows worked by fertilisation, plant protection, and harvesting machines should be a multiple of the number of sowing sections of precision seeders.

Akhtyrtsov M. M., Vakulenko I., N. conducted research on the impact of weed infestation in corn plantations on grain yield, depending on cultivation method and herbicide used. They found that tillage with a Wil-Rich disc harrow to a depth of 10-12 cm is less efficient than winter ploughing, deep cultivation, and disc levelling when herbicides are used in summer, due to weed infestation and grain yield[16].

Biskupski A. et al. conducted research on the impact of intercropping and simplified cultivation on maize grain yield. In their summary, they state that "maize grain yield in simplified and zero cultivation was lower than in traditional cultivation". In addition, the use of simplifications led to higher weed infestation in the plantation than in traditional cultivation[17].

Piskier T., Sekutowski T. R. 2016, in search of new technologies, conducted research on the assessment of sowing quality. The assessment was based on the use of a modern seed drill, which ensured very good sowing quality at a working speed of 14 $km \cdot h^{-1}$. The second seed drill selected for the trials was a commonly used maize seed drill, which ensures good sowing quality at a working speed of 7-8 $km \cdot h^{-1}$. The experiment showed that when

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[14] Gołębiowska H. 2013. Influence of herbicides on yielding and selected indexes of spatial structure of maize canopy depending on tillage systems. Fragmenta Agronomica. No. 30(3), pp. 64-69.

[15] Innocent Malunga, Joyce J. Lelei, Wilkson Makumba. 2017. Effect of Mineral Nitrogen and Legume Intercrops on Maize (*Zea Mays* L.) Nitrogen Uptake, Nutrient Use Efficiency and Yields in Chitedze and Zambia, Malawi. Sustainable Agriculture Research. Canadian Centre of Science and Education. p-ISSN 1927-050X, e-ISSN 1927-0518. Vol. 7, No. 1, pp. 64-79.

[16] Akhtyrtsov M. M., Vakulenko I., N. 2012. The effect of corn weed infestation on grain yield depending on the method of primary soil cultivation and herbicide application system. (Weeds effect on A maize grain yield in A relation to A primary cultivation and A herbicide treatment). Scientific Library CyberLeninka: State Scientific Institution Krasnodar Research Institute of Agriculture of the Russian Academy of Agricultural Sciences, Krasnodar, Russia. Scientific Library CyberLeninka: http://cyberleninka.ru/article/n/vliyanie-zasorennosti-poseva-kukuruzy-na-urozhaynost-zerna-v-zavisimosti-ot-sposoba-osnovnoy-obrabotki-pochvy-i-sistemy-primeneniya#ixzz3nP2eVs00

[17] Biskupski A., Sekutowski T. R., Włodek S., Smagacz J., Owsiak Z. 2014. The effect of intercrops and differentiated tillage on maize yielding. (The effect of intercrops and differentiated tillage on maize yield). Ecological Engineering. Vol. 38, pp. 7–16.

sowing at 14 km·h^{-1}, there were no gaps and double planting occurred in approximately 0.6% of cases. In the second technology, almost 3% of double plants and 3.9% of gaps were observed. The authors' research showed that maize yield is primarily influenced by the evenness of plant distribution within the row and the total number of poorly sown seeds, especially those sown too densely or double-sown[18].

Gaworski M. believes that sowing in the so-called "magic triangle" results in higher grain yields and an increase in the quality of the harvested mass. The implementation of this sowing method increases corn yields by 10% and has a positive impact on the natural environment by reducing soil erosion, water evaporation, and earlier crop closure, as well as reducing weed growth[19].

Kadłubiec W. and Kuriata R. point out in their publication that the size of maize grain yield is influenced by the relationships among individual traits, their mutual correlations, and the generational relationships between parents and offspring[20].

Landi P. et al. concluded on the basis of their own research that there is a relationship between grain yield, plant height, and the setting of the first cob[21].

Shehata A. H. proved in his work that there is a correlation between the weight of cobs and the weight of grain[22] obtained from cobs and the thickness of cobs. Sowiński J conducted a two-year study on the impact of weeding and sowing methods on the yield of maize and soybeans in coordinated cultivation. The research proved that the share of maize in the total yield depended on the sowing method and the method of plantation maintenance. The use of herbicides in coordinated cultivation resulted in a higher share

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[18] Piskier T., Sekutowski T.R. 2016 . Maize in precision sowing [online]. [Accessed 22 January 2018]. Available online: http://www.wilan.com.pl/?p=1857

[19] Gaworski M. 2018. Modern maize sowing [online]. [Accessed on 22 January 2018]. Available online: http://agro-technika.pl/archiwa/nowoczesny-siew-kukurydzy/

[20] Kadłubiec W., Kuriata R. 2004. Multipe analyses of traits determining grain yield of inbred lines and hybrids $F_1$of maize. Bulletin of the Institute of Plant Breeding and Acclimatisation No. 231, pp. 419-423.

[21] Landi P., Camussi A., Verdiego C. 1986. Combining ability of early inbred lines as evaluated under conditions of double cropping. Maydica No. 31 (4), pp. 369-377.

[22] Shehata A. H. 1974. Association among metric attributes in varietal populations of maize in relation to their future improvement. Egyptian Journal of Genetics and Cytology, No. 3 (2), pp. 296-297.

of maize than in mechanical maintenance. Mechanical maintenance also contributed to a reduction in the total soybean yield[23].

A higher proportion of maize and soybeans in pure sowing was observed with chemical weed control methods. The research also showed that the maize yield in intercropping with soybeans was significantly lower than in pure sowing[24].

Research shows that the yield obtained from intercropping with legumes exceeded the yield of maize in pure sowing.

Księżak J. et al. evaluated the yield of maize grown in an organic system, depending on cultivation method and organic fertiliser dose.

Two years of research proved that higher rainfall in July, two applications of a brush harrow and a mulcher resulted in higher yields, while the lack of weed control measures in maize treated with 20 $t \cdot ha^{-1}$ of organic fertiliser resulted in yields that were 19% lower than those fertilised with a dose of 40 $t \cdot ha^{-1}$. These differences were significantly smaller, ranging from 7% to 11% on sites where mechanical cultivation was used. It was also found that with an increase in organic fertilisation from 20 to 40 $t \cdot ha^{-1}$, there was a significant increase in the proportion of cobs in the maize plant and, consequently, in the grain yield[25].

Evans S.P et al. state that maize is a slow-growing species in the early stages of growth and is most sensitive to weed infestation, which occurs in the field from emergence to 8-10 leaves[26].

Both organic and mineral fertiliser doses affect the size of the maize yield, as proven by an experiment conducted by[27], who determined the effect

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23 Sowiński J . 2010. The effect of weed control and sowing method on the yield of maize and fodder soybean in a coordinate system. The effect of weed control and sowing method on yield of maize and soybean intercropping. Scientific Journals of the Wrocław University of Environmental and Life Sciences № 578, pp. 23-33.

24 Eskandari H., Ghanbari A. 2009. Intercropping of maize (Zea mays) and cowpea (Vigna sinensis) as whole-crop fodder: effect of different planting patterns on total dry matter production and maize fodder quality. Not. Bot. Hort. Agrobot. Cluj., 37 (2), 152–155.

25 Księżak J., Staniak M., Bojarczuk J., 2011. Assessment of maize yield grown using organic farming methods depending on the method of cultivation and the dose of organic fertiliser. Journal of Research and Applications in Agricultural Engineering, Vol. 56, No. 3, pp. 227-231.

26 Evans S.P ., Knezevic S.Z., Lindquist J.L, Shapiro C.A., 2003. Nitrogen application influences the critical period weed control in corn. Weed Sci. 51, pp. 408-417.

27 Bury M., Stankowski S., Hury G., Dawidowski A., Opatowicz N., Sobolewska M., Kowalewska R., Bashutska U., 2015. The effect of sulphur fertilisation on the growth and yield of fodder maize. Науковий вісник НЛТУ України.-Issue 25.10. – pp. 149–156. – Access mode: http://nbuv.gov.ua/UJRN/nvnltu_2015_25.10_27

of sulphur fertilisation on the growth and grain yield of feed maize. Summarising their research, they concluded that the combined use of mineral fertilisation with nitrogen and sulphur in the form of industrial calcium sulphate clearly increased yields of fresh and dry matter, as well as grain yield.

Piechota T. et al. present the results of research on the impact of strip tillage and weed control methods on weed infestation in maize grown as a secondary crop. They focused on traditional cultivation, deep strip cultivation, shallow strip cultivation, and weed control methods (control, mechanical, and chemical). Weed biomass after strip tillage was lower compared to traditional cultivation. The amount of biomass on mechanically and chemically weeded plots differed slightly. The universal tool used for strip tillage and inter-row cultivation ensured high weed control effectiveness in maize[28]. Bojarszczuk J. et al. conducted research on weed infestation in maize plantations grown in combination with selected plant species. They conclude that the combined cultivation of maize with other plant species significantly reduced weed infestation[29]. Researchers devote a lot of attention to the costs and expenses of maize production[30,31,32,33,34]. Other issues are also of great importance, such as: maize variety[35], morphological properties[36]

[28] Piechota T., Zbytek Z., Kowalski M. 2017. Effect of strip tillage and weeding method on weed infestation pf silage maize planted after winter cover crop. The impact of strip tillage and weed control methods on weed infestation of maize grown as a secondary crop. Journal of Research and Applications in Agricultural Engineering, Vol. 62(4), pp. 90–93.

[29] Bojarszczuk J., Staniak M., Książak J. 2013. Assessment of weed infestation of winter cereals cultivated in pure sowing and undersown with serradella (Ornithopus sativus L.) in an organic system. Woda-Środowisko-Obszary Wiejskie. ISSN 1642-8145. Vol. 13. No. 2(42), pp. 5–16

[30] Kornarzyński K., Gładyszewska B. 2017. Evaluation of the Moisture Change Ability of Selected Crop Seeds. Agricultural Engineering. Vol. 21. No. 1(161).

[31] Kwaśniewski D., Kuboń M., Małaga-Toboła U., Tabor S. 2016. Costs of mechanical services in organic farms. Journal of Research and Applications in Agricultural Engineering, Vol. 61(4), pp. 23-27.

[32] Muzalewski A. 2008. Principles of agricultural machinery selection. 2nd revised edition. Institute of Agricultural Engineering, Mechanisation and Electrification in Warsaw. ISBN 978-83-89806-21-5, pp. 92

[33] Puczel J. 2015. Technology of corn cultivation for grain. Scientific Conference "Environmentally Friendly Agriculture". Conference materials. University of Agribusiness in Łomża, 21-22 May 2015. Part I – Abstracts, pp. 14–16. Part II – Posters, p. 61.

[34] Şeflek A.Y. 2017. Determining the physico-mechanical characteristics of maize stalks for designing harvesters. The Journal of Animal & Plant Sciences. ISSN 1018-7081.

[35] Kieloch R. 2016. The importance of variety in the light of selected aspects of weed control in cereals. Wieś Jutra, Nauka Doradztwo Praktyka, April-June № 2(187), pp. 10–12.

cultivation and care of plantations[37]. Research on the impact of weed infestation on plant yield has also been conducted by researchers, including:[38], who studied the impact of compaction and varied tillage on secondary weed infestation and winter rapeseed yield, and Staniak et al.[39], who assessed weed infestation in oat-pea mixtures grown on an organic farm. However, research on this topic should be considered fragmentary and not provide a basis for generalisations across variety, environment, climate, agrotechnology, ecology, etc.

5.3. Origin of the topic and research problem

5.3.1. Origin of the topic

A review of scientific and research work carried out by universities and national and foreign institutes, as well as research results available in the literature, shows that the issue of maize cultivation for grain is a topical one, and that scientific and research work can be divided into three groups, among others. The first group includes issues that have been sufficiently resolved, such as agricultural issues related to agrotechnical requirements, soil cultivation, mineral and organic fertilisation, and plant protection. The second group includes topics related to the selection of varieties for soil and climatic conditions, seed sowing principles, plantation maintenance, grain harvesting methods, monoculture and crop rotation principles, the use of crops as feed grains, post-harvest residues as organic fertiliser, and biomass for biogas production, etc. The third group covers topics that are little known or have not been addressed. These include the organisational principles of maize cultivation on farms of various sizes, with tractors of different power ratings and machines with different technical and operational characteristics, new production technologies, new machines and technological pro-

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36 Lavrinenko Yu.A., Marchenko T.Yu., Nuzhna M. V. 2017. Morpho-physiological and heterosis models of corn hybrids of maturity groups FAO 180-390 for irrigation conditions. Bulletin of the Belarusian State Agricultural Academy. Gorki, No. 3, pp. 67-70.

37 Przybył J., Mioduszewska N. 2012. Strip Tillage. Agricultural Technical Review, No. 1, pp. 32-35.

38 Orzech K., Marks M., Stępień A. 2014. Effect of soil packing and diversified tillage on secondary weed infestation and the yield of winter rape. Fragmenta Agronomica. Vol. 31. No. 1, pp. 53-63.

39 Staniak M., Bojarszczuk J., Książak J. 2014. Assessment of weed infestation of oats-pea mixtures grown in organic farming conditions. Research and Applications in Agricultural Engineering. Vol. 59. No. 4, p. 87.

cesses taking into account, above all, issues of environmentally friendly agricultural production that is technically safe and does not pose a threat to human health, with low energy consumption, low production costs, and high rates of technical and technological progress. Issues related to the technological principles of maize cultivation, in particular the technological operations of sowing seeds and harvesting grain for feed, should be considered a particularly important research topic. Agricultural producers expect scientifically based recommendations for maize cultivation regarding yield quantity and quality, the area of the plantation, and the technology used in tractors and machinery. The effectiveness of maize cultivation technology is mainly influenced by plant growth conditions and the technological operation of sowing seeds and harvesting grain. Important factors affecting plant growth include the degree of weed infestation in the plantation during the emergence period and the distance between seeds in a row (number of plants per hectare). In both cases, there are no clear recommendations. There are also no recommendations on selecting machinery for farms of different sizes.

5.3.2. Research problem

Taking into account current needs in research on grain maize cultivation and recommendations for agricultural producers and service providers, the research problem was formulated as follows:

1. Determining the impact of plant varieties, the timing of herbicide spraying, and weed infestation on the yield of maize grown for grain.

Working hypothesis and its brief justification

The working hypothesis was that there is a close relationship between the variety of maize used, the timing of herbicide treatment, weed infestation of the plantation, and the yield of maize grown for grain. Previous studies, both national and conducted at the Variety Evaluation Experimental Station in Krzyżewo, confirm the existence of such relationships. Therefore, rigorous research is needed to confirm the existence of these relationships and to formulate practical recommendations for farms.

The Podlaskie Province is characterised by extensive maize cultivation for grain and silage. There is a wide range of farm sizes, from several dozen to several hundred hectares. Maize plantations vary in size, but cultivation is carried out in a similar manner, using similar technological operations.

5.4. Objective and scope of the research

5.4.1. Purpose of the research

The aim of the laboratory and field research was to determine the impact of the corn variety used and the plantation's weed infestation on corn yield in the initial phase of plant growth.

5.4.2. Scope of the research

The scope of laboratory and field research included: preparing a description of the farm, setting up experiments using the split-block-split-plot method (number of varieties – 3, number of combinations – 5, number of strips – 2) using 10 corn varieties.

5.5. Research methodology

5.5.1. Place, object, and subject of the research

The laboratory and field research was conducted at the Experimental Variety Assessment Station in Krzyżewo. The research used maize varieties intended for grain cultivation with the following early maturity values: Lokata – FAO 220, Tonacja – FAO 230, Smolitop – FAO 230, Juhas – FAO 240, Konkurent –FAO 240, SY Gibuti – FAO 240, Touran – FAO 240, Ricardinio – FAO 240, ES Convent – FAO 250, ES Opoka – FAO 240. Three varieties were selected for detailed testing, namely: SY Gibuti – FAO 240, Opoka – FAO 240, Smolitop – FAO 230. The soil was cultivated using basic and pre-sowing cultivation tools, sowing was carried out using a precision seeder with a pneumatic system for collecting seeds from the tank and row sowing with adjustable seed spacing in the row, using row spacing of 0,75 m, in accordance with the spacing of agricultural tractor wheels of 150 cm (the tractor wheels cover two rows of plants while driving). Maintenance work was carried out using a hoe and a field sprayer in accordance with current needs.

The characteristics of the farm of the Experimental Variety Assessment Station in Krzyżewo are given in Appendix 1. The agrotechnical conditions of the experiment are given in Appendix 2.

5.5.2. Laboratory and field testing methodology

Characteristics of the varieties involved in the experiments

OPOKA – a three-line hybrid (TC) variety, registered in 2016. Early maturity, on the border between early and medium-early varieties. FAO 240. Total dry matter yield and cob yield at the level of the early group standard. Average yield structure. Quite high total fresh mass yield, low susceptibility to lodging. Characterised by good *in vitro* digestibility of stems, leaves, and cobs. Suitable for silage production throughout the country."

SMOLITOP – "three-line variety (TC). Entered in the National Register in 2010. Variety intended for grain cultivation, medium early. FAO 230-240. Compared to the medium-early group standard, the grain yield is medium to high. The plants are of medium height. Quite good vigour in the early stages of vegetation, with slower drying of leaves during grain ripening. Good plant health. The variety is characterised by low susceptibility to stalk fusarium and smut, and low lodging tendency. The cob structure is medium. Smolitop is suitable for grain production areas and CCM across the country.

SY GIBUTI – "a double-line (SC) maize variety registered in 2016. It is intended for silage production. It is a medium-early variety with FAO 240. The cobs mature relatively earlier than the vegetative parts of the plants. The overall dry matter yield and fresh matter yield are quite high, and the dry matter yield of the cobs is very high. The yield structure is quite good. The plants are of medium height. The yield of nutritional units is high. The energy concentration index is average. Plant vigour in the initial phase of vegetation is quite good. The variety's resistance to cob smut is high, and to stalk smut is average.

Characteristics of the experiment

Experiments with maize grown for grain were conducted using a Planter II precision seeder in the experimental field of the Variety Assessment Experimental Station in Krzyżewo, using the split-block-split-plot method. They were conducted as three-factor experiments. The research factors were the tested variety, the timing of herbicide application, and the degree of weed infestation. The cobs were harvested manually and shelled using a SAMPO 130 plot combine harvester. Table 1 presents the experimental parameters for sowing and harvesting.

Table 1. Parameters of the sowing and harvesting experiments.

Parameters	Sowing	Harvest
Plot length (m)	12	11
Plot width (m)	3	1.5
Number of rows	4	2
Distance between rows (cm)	75	75
Plant spacing in row (cm)	16	16
Width of path between strips (m)	2	2
Protective strip (cm)	50	50

Source: own study based on the Methodology for Testing the Economic Value of Varieties

The experiments were set up in three strips. The first strip was a control, while the second and third strips had the following combinations: weed infestation:

Combination 1 – 6 weeds per m^2

Combination 2 – 11 weeds per m^2

Combination 3 – 16 weeds per m^2

Combination 4 – 22 weeds per m^2

Combination 5 – 33 weeds per m^2

Combination 6 – 55 weeds per m^2.

Weed control was carried out according to the following scheme:

1 strip: weed control – first spraying after setting up the experiment, second in case of secondary weed infestation up to the 8-10 leaf stage,

2nd strip: weed control in the 4-6 leaf stage on the control,

3rd strip: weed control in the 8-10 leaf stage on the control.

Table 2 below presents the plan for the experiment setup in the experimental field.

55 pcs·m^{-2} → 700 pcs of oats + 300 pcs of rapeseed (per 18 m^2)

33 pcs·m^{-2} →400 pcs of oats + 200 pcs of rapeseed (per 18 m^2)

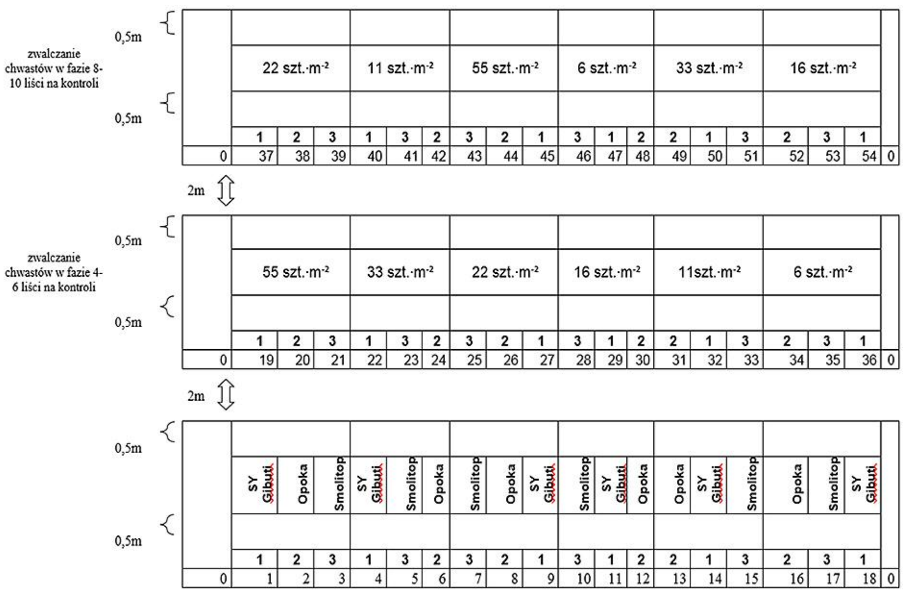
22 pcs·m^{-2} → 270 pcs of oats + 130 pcs of rapeseed (per 18 m^2)

16 pcs·m^{-2} → 200 pcs of oats + 100 pcs of rapeseed (per 18 m^2)

11 pcs·m^{-2} → 130 pcs of oats + 70 pcs of rapeseed (per 18 m^2)

6 pcs·m^{-2} → 70 pcs of oats + 30 pcs of rapeseed (per 18 m^2)

Table 2. Plan of the experiment conducted in the experimental field



Source: own study

The following observations and measurements were carried out throughout the growing season:

Assessment of emergence (9°)

This assessment is performed on a 9-point scale, where 9 represents the most favourable condition (full emergence), and 1 represents the least favourable condition (10-15% of plants missing from the plot). This assessment is visual and is performed approximately 3 weeks after sowing.

Number of weeds per m² (pcs)

In order to create provocative conditions, six combinations of weeds (spring rapeseed and oats) were sown in the second and third strips in fixed proportions:

Combination 1 – 6 weeds per m^2

Combination 2 – 11 weeds per m^2

Combination 3 – 16 weeds per m^2

Combination 4 – 22 weeds per m^2

Combination 5 – 33 weeds per m^2

Combination 6 – 55 weeds per m^2

Just before spraying the second strip, when the maize in the control group had reached the 4-6 leaf stage, and on the third strip, when the maize in the control group had reached the 8-10 leaf stage, the number of weeds per m^2 was determined. The condition and degree of weed infestation were determined using the frame method.

Plant height and cob placement height (cm)

Another observation was to measure the height of the maize plants and the height of the cob. These measurements were taken 2 weeks after the emergence of the first leaves on 20 consecutive plants, and the average was calculated. The maize was measured from the ground to the top of the tassel at plant height, while the height of the first (upper) cob was measured from the ground to the base of the branch holding the cob on the stalk.

Stalk diameter before harvest (mm)

Before harvesting, the stems' diameters were measured. The measurement was made with a calliper on 10 stems just below the base of the cob.

Cob structure (% grain content in the cob)

Cob structure is one of the measures that indicates the suitability of hybrids for cultivation for corn cob meal (CCM) and the percentage of grain in relation to the cob core in the cob weight. This trait was determined using the following formula:

$$\text{grain share in cob weight} = \frac{a}{b} \cdot 100\% \tag{1}$$

where:
a – grain yield, $t{\cdot}ha^{-1}$
b – yield of proper cobs without covering leaves, $t{\cdot}ha^{-1}$.

Grain yield ($t{\cdot}ha^{-1}$).

From each plot designated for harvesting, the cobs were handpicked, counted, weighed, and threshed using a threshing machine. The grain yield was first converted to $t{\cdot}ha^{-1}$ at 14% moisture content.

Grain moisture content at harvest (%).

The moisture content of maize grain is not measured with automatic moisture meters; it is determined solely by drying methods, either classic or simplified.

The moisture content of the grains of the tested maize varieties was determined using the simplified drying method**.** From the thoroughly mixed threshed grain, two samples of 100 g s of grain, without major impurities (pieces of cobs and leaves), were taken from each plot and placed in appropriately sized, tared containers. The grain was dried at 105 °C for 36 hours. After drying and cooling, the samples were weighed**.**

Moisture content was calculated using the following formula:

$$W_x = \frac{a-b}{a-c} \cdot 100\% \quad (2)$$

where:
a – weight of the container with the sample before drying, g
b – mass of the container with the sample after drying, g
c – mass of the container, g

Statistical analyses

The experimental data came from a field experiment with three factors (A – variety, B – spraying date, C – weed infestation), which were arranged in a split-block-split-plot (strip-split-plot) design. Analysis of variance (ANOVA) was used in accordance with the mathematical model of the experimental design:

$$Y_{ijkl} = m + A_i + R_j + e_{ij}^{(1)} + B_k + e_{jk}^{(2)} + AB_{ik} + e_{ijk}^{(3)} + C_l + AC_{il} + BC_{kl} + ABC_{ikl} + e_{ijkl}^{(4)} \quad (3)$$

where:
Y_{ijkl} is the value of the tested feature for the i-th level of factor A, the k-th level of factor B, the l-th level of factor C in the j-th repetition; m – general mean; R_j – repetition; AB_{ik}, AC_{il}, BC_{kl}, ABC_{ikl} – interactions of main effects; $e_{ij}^{(1)}$, $e_{jk}^{(2)}$, $e_{ijk}^{(3)}$, $e_{ijkl}^{(4)}$ – random effects.

The scheme of the variance analysis table for the discussed three-factor experiment set up in a split-block-split-plot design in accordance with model (1) is presented in Table 3 [Trętowski, Wójcik 1988; Luszniewicz, Słaby 2001]. The significance of differences between means was tested using Fisher's NIR at α=0.05.

Table 3. Analysis of variance scheme for the split-block-split-plot design

Source of variation	Number of degrees of freedom	Sum of squares	Variance	*F*
Replications	r-1 = 1	*var R*		
Variation (A)	a-1 = 2	*var A*	s^2_A	F_A
Error (1)	(r-1)(a-1) = 2	*var* E_1		

Source of variation	**Number of degrees of freedom**	**Sum of squares**	**Variance**	***F***
Spraying date (B)	b-1 = 2	*var B*	s^2_B	F_B
Error (2)	(r-1)(b-1) = 2	*var* E_2		
AxB	(a-1)(b-1) = 4	*var AB*	s^2_{AB}	F_{AB}
Error (3)	(r-1)(a-1)(b-1) = 4	*var* E_3		
Weed infestation (C)	c-1 = 5	*var C*	s^2_C	F_C
AxC	(a-1)(c-1) = 10	*var AC*	s^2_{AC}	F_{AC}
BxC	(b-1)(c-1) = 10	*var BC*	s^2_{BC}	F_{BC}
AxBxC	(a-1)(b-1)(c-1) = 20	*var ABC*	s^2_{ABC}	F_{ABC}
Error(4)	*ab(r-1)(c-1) = 45*	*var* E_4		
Total	rabc-1 = 107			

Source: own study based on Trentowski, Wójcik [1988]

In the next stage of the analysis, regression models were used to assess the relationship between weed infestation and yield. In the first phase, simple regression was used to determine the linear model of the relationship and its statistical significance. The analyses were performed separately for each spraying date (4-6 leaves, 8-10 leaves) and in general terms. When no statistically significant linear relationship was observed, a possible curvilinear relationship was assessed using Levenberg-Marquardt estimation.

5.6. Course and results of the research

5.6.1. Course and results of laboratory and field studies

The characteristics of the meteorological conditions during the corn growing seasons in 2015 and 2016 were presented based on data from the Experimental Variety Assessment Station in Krzyżewo (Tables 4 and 5) for two climate elements: average monthly air temperature and total precipitation. The data were compared with the 55-year period (1961-2016).

Table 4. Distribution of precipitation from April to October in 2015-2016

		Precipitation [mm]						
		April	**May**	**June**	**July**	**August**	**September**	**October**
2015								
decades	I	11.5	20.2	0.5	4.7	1.2	18.5	0
	II	6.5	23.5	4.5	25.9	0.0	3.0	12.2
	III	12.6	26.2	28.4	24.0	3.9	1.0	14.1
∑		30.6	69.9	33.4	54.6	5.1	22.5	26.3
2016								
decades	I	0.0	5.4	15.8	25.4	42.6	9.4	45.2
	II	2.3	29.2	36.7	47.6	9.3	0.0	4.5
	III	10.5	6.9	0.0	14.0	15.7	5.9	60.5
∑		12.8	41.5	52.5	87.0	67.6	15.3	110.2
1961-2016								
$\bar{x}$		34.9	59.1	63.7	77.4	70.5	48.9	43.1

Source: meteorological data from SDOO in Krzyżewo

The early start of vegetation in 2015, recorded on 9 March, enabled good field preparation for sowing the experiment. May 2015, with an average monthly temperature of 12.3°C, was significantly cooler than the long-term average. Low temperatures delayed emergence and led to poor post-emergence plant development. The plants were weakened by a deficiency of many nutrients, the availability of which was limited by the thermal conditions prevailing during that month. The very cool May caused weeds to dominate over maize (in lanes 2 and 3, where no herbicide protection was applied after sowing). The weeds overgrew the young maize seedlings, shading them and blocking nutrient uptake, and slowed down their initial development.

Table 5. Distribution of average monthly temperatures from April to October in 2015-2016

Month	Average air temperature [°C]								
	Year				Year 2016				$\bar{x}$ from the 1961-2016 multi-year period
	decade			∑/3	decades			∑/3	
	I	II	III		I	II	III		
April	4.9	8.0	7.1	7.9	9.1	10.4	6.1	8.5	7.9
May	11.6	11.8	13.3	12.3	14.0	12.2	17.9	13.5	13.7
June	17.2	16.0	16.2	16.4	16.1	16.4	21.1	17.8	16.8
July	20.3	17.7	18.5	18.8	18.3	18.3	21.1	19.3	18.9
August	22.9	20.9	19.7	21.1	19.3	15.9	19.0	18.1	18.0
September	15.5	16.9	12.8	15.1	17.9	14.0	10.4	14.1	13.0
October	8.0	6.5	5.6	6.7	9.1	4.6	5.6	6.4	7.4

Source: SDOO meteorological data in Krzyżewo

A significant increase in temperature in the second and third decades of June, accompanied by moderate rainfall, contributed to an increase in vegetative mass and an overall improvement in plant condition. July was characterised by significantly higher temperatures compared to June. A particularly large increase in temperature was recorded in the first decade of the month (max 34,6 °C). August, like July, turned out to be the warmest month of the year. It was characterised by a high daily average air temperature (21,1°C), which was 3,1 °C higher than the long-term average. Light rainfall (5,2 mm) also accelerated grain ripening. High air temperatures in September and uneven rainfall distribution (the highest rainfall was recorded in the first 10 days of the month, 18,5 mm) had a positive effect on corn grain drying. The first ten days of October, with a maximum air temperature of 23,1°C and no rainfall, allowed for harvesting.

In 2016, vegetation resumed only on 3 April, which was 25 days later than in 2015. However, the late vegetation onset did not delay the optimal sowing date for maize, which occurred on 4 May. The average temperature in April was 8,3 °C and exceeded the long-term average (7,9°C), allowing the experiment to be sown in soil at the appropriate temperature.

Favourable temperature and humidity conditions in May positively affected plant emergence and initial growth. Corn varieties sown in rows 2 and 3, which were not treated with herbicides after sowing, were not completely dominated by weeds, as was the case in 2015. June 2016 was 1 °C warmer than the long-term average and 1,4 °C warmer than in 2015. Favourable temperature and precipitation patterns through the end of August created ideal conditions for growth, biomass production, and the development of plump cobs. Light rainfall in September, with an average air temperature 1,1 °C above the long-term average, accelerated ripening and thus reduced the promising harvest. In turn, a wet October with an average monthly rainfall of 110.2 mm, which was 67 mm higher than the long-term average, and a temperature 1 °C lower than the long-term average, caused an almost month-long break in threshing. The harvest began at the end of the second decade of October.

To summarise the meteorological conditions during the corn-growing seasons in 2015 and 2016, they were varied. The year 2016 proved to be more favourable than the previous year. The distribution of temperatures and precipitation in 2016 enabled proper initial plant development and subsequent vegetative growth, as well as proper cob formation and grain filling.

Research results

Both biotic and abiotic environmental factors, the genotypic characteristics of maize varieties, the use of appropriate agrotechnology, and the current yield potential of new varieties determine the achievable yield. An analysis of the experimental results shows a significant difference in the impact of weed infestation and herbicide application timing on the growth, development, and grain yield of maize varieties.

Grain yield and moisture content

Based on two years of research, it can be concluded that the grain yields of maize varieties in the years in question differed significantly, as shown in Tables 6 and 7. In 2015, grain yield ranged from 0.9 to 6.2 $t \cdot ha^{-1}$, while in 2016, varieties yielded between 3.2 and 7.7 $t \cdot ha^{-1}$.

The varieties tested in the control in 2015 achieved a lower grain yield than in 2016.

Table 6. Grain yield converted to 14% H_2O in 2015 ($t \cdot ha^{-1}$)

Variety	Control	Maize development stage in the control	Combinations ($pcs \cdot m^{-2}$)					
			6	11	16	22	33	55
SY Djibouti	5.9	4-6 leaves	**3.6**	2.9	2.9	2.6	1.3	**1.1**
		8-10 leaves	**2.5**	1.8	1.3	1.2	1.1	**0.9**
Opoka	5.2	4-6 leaves	**3.9**	2.9	2.1	2.0	2.2	**2.0**
		8-10 leaves	**2.2**	2.2	1.9	1.2	1.2	**0.9**
Smolitop	6.2	4-6 leaves	**4.2**	3.6	2.8	2.5	2.2	**1.8**
		8-10 leaves	**2.5**	2.0	1.7	1.5	**1.3**	1.3

Red indicates maximum values, green indicates minimum values
Source: own research

Table 7. Grain yield converted to 14% H_2O in 2016 ($t \cdot ha^{-1}$)

Variety	Control	Maize development stage in the control	Combinations ($pcs \cdot m^{-2}$)					
			6	11	16	22	33	55
SY Djibouti	7.7	4-6 leaves	7.4	**7.6**	7.3	**6.7**	7.5	7.4
		8-10 leaves	**6.2**	**4.2**	5.3	6.2	4.8	4.5
Opoka	5.9	4-6 leaves	**6.1**	6.1	5.9	5.7	5.7	**5.5**
		8-10 leaves	**4.6**	4.6	4.2	4.5	3.6	**3.2**
Smolitop	6.8	4-6 leaves	6.8	**6.9**	6.7	6.3	**6.1**	6.5
		8-10 leaves	**5.7**	**3.7**	4.5	4.4	4.3	4.4

Maximum values are marked in red, minimum values in green
Source: own research

The greatest yield difference between the years in question was observed in the SY Gibuti variety, whose yield in 2015 was 1.8 $t \cdot ha^{-1}$ lower than in 2016. The yield difference between 2015 and 2016 for the other two varieties was smaller, at 0.6–0.7 $t \cdot ha^{-1}$.

The combinations used in the years studied (2015 and 2016) proved that increased weed infestation and delayed weed control resulted in a significant decrease in grain yield. The greatest yield difference was observed between the control and the maximum weed infestation for each of the three varieties tested. The decrease in yield between the different combinations was not as drastic as between the control and the maximum weed infestation. Greater differences were observed in the timing of herbicide application. Delayed herbicide application (8-10 leaves) significantly reduced maize grain yield, as shown in Tables 6 and 7.

In the case of grain moisture determined immediately after harvest, it can be seen that as weed infestation increases, so does the moisture content of maize grain. The difference in grain moisture between the control and combinations in 2015 was higher than in 2016, as shown in Tables 8 and 9. The grain moisture content of the varieties in question ranged from 28% to 38% in 2015 and from 29% to 35% in 2016.

Table 8. Grain moisture content at harvest in 2015 (%)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	**11**	**16**	**22**	**33**	**55**
SY Djibouti	28	4-6 leaves	**34**	34	34	34	**38**	38
		8-10 leaves	**34**	34	**36**	34	34	36
Opoka	26	4-6 leaves	**28**	30	**32**	32	30	30
		8-10 leaves	**26**	**28**	28	28	28	28
Smolitop	24	4-6 leaves	**28**	28	28	**30**	28	28
		8-10 leaves	**28**	28	**30**	28	28	28

Maximum values are marked in red, minimum values in green
Source: own research

Table 9. Grain moisture content during harvest in 2016 (%)

Variety	Control	Maize development stage in the control	Combinations ($pcs \cdot m^{-2}$)					
			6	**11**	**16**	**22**	**33**	**55**
SY Djibouti	31	4-6 leaves	32	32	33	**34**	**31**	32
		8-10 leaves	34	**32**	34	33	**35**	35
Opoka	33	4-6 leaves	**32**	**31**	32	32	32	32
		8-10 leaves	35	35	35	**33**	**36**	35
Smolitop	29	4-6 leaves	**30**	30	**29**	29	30	29
		8-10 leaves	**31**	31	**33**	31	32	31

Maximum values are marked in red, minimum values in green
Source: own research

Evaluation of emergence

The results of the plant emergence assessment in 2015 and 2016 are presented in Tables 10 and 11. Analysis of the data contained therein showed that in both 2015 and 2016, full emergence was achieved in the control group, where weed control was carried out immediately after sowing. As weed infestation increases and the spraying date is delayed, the germination capacity of maize seeds deteriorates, resulting in poorer emergence.

Table 10. Assessment of emergence in 2015 (9°)

Variety	Control	Maize development stage in the control	Combinations ($pcs \cdot m^{-2}$)					
			6	**11**	**16**	**22**	**33**	**55**
SY Djibouti	8	**4-6 leaves**	8	7	7	8	7	6
		8-10 leaves	7	8	7	7	6	4
Opoka	9	**4-6 leaves**	7	6	6	6	5	5
		8-10 leaves	8	6	7	7	6	5
Smolitop	9	**4-6 leaves**	8	7	6	7	5	4
		8-10 leaves	7	7	7	7	6	6

Source: own research

Table 11. Assessment of emergence in 2016 (9°)

Variety	Control	Maize development stage at control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	9	4-6 leaves	9	8	8	7	7	7
		8-10 leaves	7	8	7	7	7	6
Opoka	9	4-6 leaves	8	7	7	7	7	6
		8-10 leaves	8	8	7	7	7	6
Smolitop	9	4-6 leaves	8	8	7	7	6	6
		8-10 leaves	8	8	7	7	6	6

Source: own research

Number of weeds

The results of calculations of the number of weeds per 1 m² in 2015 and 2016 are presented in Tables 12 and 13. Analysis of the data contained in the tables shows that the number of weeds per m² depends not only on the combinations used, but also on the previous crop.

Table 12. Number of weeds per m^2 in 2015 (pcs.)

Variety	Maize development stage in the control	Combinations (pcs·m^{-2})					
		6	11	16	22	33	55
SY Djibouti	4-6 leaves	57	118	128	137	224	282
	8-10 leaves	76	114	142	163	149	199
Opoka	4-6 leaves	74	115	96	150	190	276
	8-10 leaves	90	100	125	170	176	171
Smolitop	4-6 leaves	68	99	136	162	181	259
	8-10 leaves	88	105	110	176	135	237

Source: own research

Table 13. Number of weeds per m^2 in 2016 (number)

Variety	Maize development stage at control	Combinations (pcs·m^{-2})					
		6	11	16	22	33	55
SY Djibouti	4-6 leaves	21	46	46	36	83	86
	8-10 leaves	14	80	40	63	40	55
Opoka	4-6 leaves	15	32	35	69	96	131
	8-10 leaves	25	162	32	75	65	64
Smolitop	4-6 leaves	33	28	26	42	85	150
	8-10 leaves	33	84	35	55	36	140

Source: own research

The supply of weed seeds in the soil significantly exceeded the amount of weeds sown. Table 6.9 shows that in 2015, when spring rapeseed was the previous crop for the maize experiment, the number of weeds was significantly higher than in the experiment after winter wheat.

Plant height and cob placement height

Both plant height and cob placement height varied in the years under discussion. The decisive factor influencing plant height was the thermal and humidity conditions prevailing throughout the entire maize development period, as shown in Tables 14 and 15. The maize varieties in the control group in 2016, when climatic conditions were more favourable than in 2015, were 10 cm taller in the Smolitop variety and up to 22 cm taller in the Opoka variety. Taking into account the combinations used and the timing of herbicide application, it was noted that plant height decreased with increasing weed infestation and delayed herbicide application. A similar relationship was found when measuring the height of the cobs, Tables 16 and 17.

Table 14. Plant height in 2015 (cm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	277	**4-6 leaves**	**255**	225	205	205	165	**155**
		8-10 leaves	**180**	175	147	150	155	**125**
Opoka	256	**4-6 leaves**	**250**	208	205	190	147	**135**
		8-10 leaves	**164**	155	163	155	**127**	147
Smolitop	266	**4-6 leaves**	**230**	205	200	165	145	**140**
		8-10 leaves	**160**	144	139	140	120	**110**

Maximum values are marked in red, minimum values in green
Source: own research

Table 15. Plant height in 2016 (cm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	283	**4-6 leaves**	288	285	283	280	275	260
		8-10 leaves	248	210	235	225	230	210
Opoka	278	**4-6 leaves**	260	293	270	280	277	278
		8-10 leaves	235	195	225	245	195	173
Smolitop	276	**4-6 leaves**	265	270	270	270	260	260
		8-10 leaves	158	198	230	210	210	145

Source: own research

Table 16. Flask immersion depth in 2015 (cm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	139	4-6 leaves	**115**	100	60	75	55	**47**
		8-10 leaves	**80**	67	58	60	60	**42**
Opoka	131	4-6 leaves	**130**	60	75	65	52	**50**
		8-10 leaves	**78**	70	65	57	47	**42**
Smolitop	138	4-6 leaves	**105**	90	75	36	39	**35**
		8-10 leaves	**70**	50	50	47	47	**45**

Maximum values are marked in red, minimum values in green
Source: own research

Table 17. Height of the flask in 2016 (cm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	133	4-6 leaves	138	128	133	140	120	128
		8-10 leaves	100	83	108	99	98	90
Opoka	129	4-6 leaves	138	143	133	128	122	133
		8-10 leaves	100	80	104	108	78	80
Smolitop	125	4-6 leaves	125	130	133	125	100	113
		8-10 leaves	93	80	88	90	88	55

Source: own research

Stem diameter before harvesting

Before harvesting, the stem diameters were measured in Tables 18 and 19. The measurement was performed using a calliper on 10 stems just below the cob base. After compiling the results, it was observed that in 2015, both in the control and in the individual combinations, the stem diameter was larger compared to 2016. On average, the difference was 4 mm. Differences in stem thickness may result from plant height in the years in question. The taller the plant, the smaller the stem diameter.

Table 18. Stem diameter before harvest in 2015 (mm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	16	4-6 leaves	**17**	15	15	14	**13**	13
		8-10 leaves	**16**	14	**12**	13	12	12
Opoka	18	4-6 leaves	**16**	14	14	15	14	**13**
		8-10 leaves	**16**	15	13	13	12	**10**
Smolitop	18	4-6 leaves	**18**	13	14	15	**11**	11
		8-10 leaves	**14**	**10**	12	11	13	13

Maximum values are marked in red, minimum values in green
Source: own research

Table 19. Stem diameter before harvest in 2016 (mm)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	12	4-6 leaves	14	14	14	**11**	**16**	13
		8-10 leaves	11	**10**	12	11	10	11
Opoka	14	4-6 leaves	14	**17**	12	15	**11**	16
		8-10 leaves	**12**	10	12	12	11	**9**
Smolitop	14	4-6 leaves	15	**11**	13	**17**	14	14
		8-10 leaves	**11**	11	**9**	10	11	9

Maximum values are marked in red, minimum values in green
Source: own research

Structure of the cobs

The experiments show that the percentage structure of the cobs differed between the years in question for individual varieties and across combinations. The results presented in Tables 20 and 21 show that in 2015 the cob structure was significantly lower than in 2016, especially in combinations 5 and 6 (33 pcs.·m^{-2} and 55 pcs.·m^{-2}). It can be concluded that the unfavourable temperature and humidity conditions in May 2015 and the increased weed infestation had an impact on the subsequent development of maize, resulting in poor-quality cobs with a significantly lower percentage of grain in relation to the cob core. The SY Gibuti variety reacted the most, with a cob structure of 77% in 2015 in the control, 45% in the second strip, where protection was carried out in the 4-6 leaf stage, and 68% in the third strip, where weeds were controlled in the 8-10 leaf stage.

In 2016, the cob structure across all the varieties discussed was similar, ranging from 73% to 77%. The favourable temperature and rainfall conditions in 2016 during the initial growth period of maize and the lack of weed dominance over the crop created favourable conditions for the production of properly developed, well-formed, and well-filled cobs.

Table 20. Cob structure in 2015 (%)

Variety	Control	Maize development phase in the control	Combinations (pcs·m^{-2})					
			6	**11**	**16**	**22**	**33**	**55**
SY Djibouti	77	**4-6 leaves**	**76**	72	74	71	71	**45**
		8-10 leaves	**78**	71	**65**	74	67	68
Opoka	75	**4-6 leaves**	**73**	72	72	70	71	**65**
		8-10 leaves	**85**	73	70	71	70	**68**
Smolitop	77	**4-6 leaves**	**77**	75	72	72	**71**	71
		8-10 leaves	**75**	73	**72**	72	72	74

Maximum values are marked in red, minimum values in green
Source: own research

Table 21. Structure of cobs in 2016 (%)

Variety	Control	Maize development stage in the control	Combinations (pcs·m^{-2})					
			6	11	16	22	33	55
SY Djibouti	77	4-6 leaves	**76**	**77**	76	77	76	76
		8-10 leaves	**76**	76	**77**	77	76	77
Opoka	74	4-6 leaves	**75**	74	74	74	**73**	74
		8-10 leaves	**75**	73	75	**74**	74	73
Smolitop	75	4-6 leaves	76	76	76	**77**	**75**	76
		8-10 leaves	75	**76**	75	76	75	76

Maximum values are marked in red, minimum values in green
Source: own research

Table 22 shows the significance of the influence of three factors: A – variety, B – spraying date, C – weed infestation, and their interactions (AB, AC, BC, ABC) on the 8 characteristics studied. The most significant differentiating factor was weed infestation. This factor had a highly significant ($p<0.01$) influence on all characteristics except moisture content. The interaction between the spraying date and the level of weed infestation (combination BC) significantly affected the yield and plant height (with $p<0.05$) and highly significantly affected emergence, the number of weeds, and the height of the cob. The main effect of variety (factor A) significantly differentiated only plant height, and the spraying date (factor B) significantly affected only emergence. The interaction of these factors (AB) significantly affected yield and stalk diameter. The other effects did not significantly affect the traits studied.

Table 23 shows how the average values of individual factors were compiled:

A – VARIETY,

B – SPRAYING DATE,

C – WEEDING and their interactions (AB, AC, BC, ABC).

$NIR_{0.05}$ – Smallest Significant Difference at a significance level *of* $\alpha=0.05$

Table 24 shows the average maize yields for the tested varieties for factor C.

Table 22. *F* statistics of the split-block-split-plot analysis of variance

Source of variation	Number of degrees of freedom (df)	*F* statistic							
		Yield	Moisture	Emergence	Number of weeds	Plant height	Ear placement height	Stalk diameter	Cob structure
Replications	r-1 = 1								
Variety (A)	a-1 = 2	1.37	2.17	0.90	0.31	**32.05***	13.14	9.07	0.57
Error (1)	(r-1)(a-1) = 2								
Spraying date (B)	b-1 = 2	4.51	1.88	**84.59**	5.57	6.80	3.22	3.70	0.94
Error (2)	(r-1)(b-1) = 2								
AxB	(a-1)(b-1) = 4	**7.52**	1.85	3.52	0.86	2.20	3.72	**26.53**	2.37
Error (3)	(r-1)(a-1)(b-1) = 4								
Weed infestation (C)	c-1 = 5	**10.61**	1.70	**28.39**	**20.06**	**6.49**	**8.42**	**3.75**	**2.84**
AxC	(a-1)(c-1) = 10	0.31	0.78	1.03	0.71	0.32	0.29	0.81	0.67
BxC	(b-1)(c-1) = 10	**3.21**	1.20	**7.88**	**7.69**	**2.24**	**3.26**	1.11	1.43
AxBxC	(a-1)(b-1)(c-1) = 20	0.52	0.59	1.16	0.48	0.30	0.40	1.26	0.66
Error(4)	ab(r-1)(c-1) = 45								
Total	rabc-1 = 107								

Source: own study

Table 23. Table diagram with average values

<table>
<tr><td rowspan="4">Factor C</td><td colspan="9">Factor A</td><td colspan="3" rowspan="3">Average BC</td><td rowspan="4">Average C</td></tr>
<tr><td colspan="3">SY Djibouti</td><td colspan="3">Opoka</td><td colspan="3">Smolitop</td></tr>
<tr><td colspan="9">Factor B</td></tr>
<tr><td>Control</td><td>4-6 leaf</td><td>8-10 leaves</td><td>Control</td><td>4-6 leaves</td><td>8-10 leaves</td><td>Control</td><td>4-6 leaves</td><td>8-10 leaves</td><td>Control</td><td>4-6 leaves</td><td>8-10 leaves</td></tr>
<tr><td>6</td><td colspan="9" rowspan="6">ABC</td><td colspan="3" rowspan="6">BC</td><td rowspan="6">C</td></tr>
<tr><td>11</td></tr>
<tr><td>16</td></tr>
<tr><td>22</td></tr>
<tr><td>33</td></tr>
<tr><td>55</td></tr>
<tr><td></td><td colspan="9">Average AC</td><td colspan="3">Average B</td><td rowspan="2"></td></tr>
<tr><td>6</td><td colspan="3" rowspan="6">AC</td><td colspan="3" rowspan="6">AC</td><td colspan="3" rowspan="6">AC</td><td>B</td><td>B</td><td>B</td></tr>
<tr><td>11</td><td colspan="4" rowspan="2">$NIR_{0.05}$</td></tr>
<tr><td>16</td></tr>
<tr><td>22</td><td colspan="2">A</td><td colspan="2">AB</td></tr>
<tr><td>33</td><td colspan="2">B</td><td colspan="2">AC</td></tr>
<tr><td>55</td><td colspan="2">C</td><td colspan="2">BC</td></tr>
<tr><td>Average AB</td><td>AB</td><td>AB</td><td>AB</td><td>ABA</td><td>AB</td><td>AB</td><td>AB</td><td>AB</td><td>AB</td><td colspan="2"></td><td colspan="2">ABC</td></tr>
<tr><td>Average A</td><td colspan="3">A</td><td colspan="3">A</td><td colspan="3">A</td><td colspan="4"></td></tr>
</table>

Source: own study

Table 24. Yields of maize varieties

Factor C	Factor A: *SY Djibouti* – Factor B: *Control*	*SY Djibouti* – *4-6 leaf*	*SY Djibouti* – *8-10 leaves*	*Opoka* – *Control*	*Opoka* – *4-6 leaves*	*Opoka* – *8-10 leaves*	*Smolitop* – *Control*	*Smolitop* – *4-6 leaves*	*Smolitop* – *8-10 leaves*	Average BC – *Control*	Average BC – *4-6 leaves*	Average BC – *8-10 leaves*	Average C
6	6.80	5.50	4.35	5.55	5.00	3.40	6.50	5.50	4.10	6.28	5.33	3.95	5.19
11	6.80	5.25	3.00	5.55	4.50	3.40	6.50	5.25	2.85	6.28	5.00	3.08	4.79
16	6.80	5.10	3.30	5.55	4.00	3.05	6.50	4.75	3.10	6.28	4.62	3.15	4.68
22	6.80	4.65	3.70	5.55	3.85	2.85	6.50	4.40	2.95	6.28	4.30	3.17	4.58
33	6.80	4.40	2.95	5.55	3.95	2.40	6.50	4.15	2.80	6.28	4.17	2.72	4.39
55	6.80	4.25	2.70	5.55	3.75	2.05	6.50	4.15	2.85	6.28	4.05	2.53	4.29
Average AB	6.80	4.86	3.33	5.55	4.18	2.86	6.50	4.70	3.11				

Factor C	Average AC – *SY Djibouti*	Average AC – *Opoka*	Average AC – *Smolitop*
6	5.55	4.65	5.37
11	5.02	4.48	4.87
16	5.07	4.20	4.78
22	5.05	4.08	4.62
33	4.72	3.97	4.48
55	4.58	3.78	4.50
Average A	5.00	4.19	4.77

Average B – *Control*	Average B – *4-6 leaves*	Average B – *8-10 leaves*
6.28	4.58	3.10

$NIR_{0.05}$			
A	ns	*AB*	0.315
B	ns	*AC*	ns
C	0.343	*BC*	0.343
		ABC	ns

ns – no significant differences
Source: own study

Table 25 shows the impact of moisture on weed infestation.

Table 25. Moisture content for the tested maize varieties

Factor C	Factor A: *SY Gibuti*			Factor A: *Opoka*			Factor A: *Smolitop*			Average BC			Average C
Factor B	*Control*	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	29.50	33.00	34	29.50	30.00	30.50	26.50	29.00	29.50	28.50	30.67	31.33	30.17
11	29.50	33.00	33.00	29.50	30.50	31.50	26.50	29.00	29.50	28.50	30.83	31.33	30.22
16	29.50	33.50	35.00	29.50	32.00	31.50	26.50	28.50	31.50	28.50	31.33	32.67	30.83
22	29.50	34.00	33.50	29.50	32.00	30.50	26.50	29.50	29.50	28.50	31.83	31.17	30.50
33	29.50	34.50	34.50	29.50	31.00	32.00	26.50	29.00	30.00	28.50	31.50	32.17	30.72
55	29.50	35.00	35.50	29.50	31.00	31.50	26.50	28.50	29.50	28.50	31.50	32.17	30.72
	Average AC									Average B			
6	32.17			30.00			28.33			28.50	31.28	31.81	
11	31.83			30.50			28.33			$NIR_{0.05}$			
16	32.67			31.00			28.83						
22	32.33			30.67			28.50			*A*	ns	*AB*	ns
33	32.83			30.83			28.50			*B*	ns	*AC*	ns
55	33.33			30.67			28.17			*C*	ns	*BC*	ns
Average AB	29.50	33.83	34.25	29.50	31.08	31.25	26.50	28.92	29.92			*ABC*	ns
Average A	32.53			30.61			28.44						

ns – no significant differences
Source: own study

Table 26 presents the results of the analysis of plant emergence.

Table 26. Plant emergence for individual maize varieties

Factor C	Factor A: *SY Gibuti* – Factor B: *Control*	*SY Gibuti* – *4-6 leaf*	*SY Gibuti* – *8-10 leaves*	*Opoka* – *Control*	*Opoka* – *4-6 leaves*	*Opoka* – *8-10 leaves*	*Smolitop* – *Control*	*Smolitop* – *4-6 leaves*	*Smolitop* – *8-10 leaves*	Average BC – *Control*	Average BC – *4-6 leaves*	Average BC – *8-10 leaves*	Average C
6	8.50	8.50	7.00	9.00	7.50	8.00	9.00	8:00	7.50	8.83	8.00	7.50	8.11
11	8.50	7.50	8.00	9.00	6.50	7.00	9.00	7.50	7.50	8.83	7.17	7.50	7.83
16	8.50	7.50	7.00	9.00	6.50	7.00	9.00	6.50	7.00	8.83	6.83	7.00	7.56
22	8.50	7.50	7.00	9.00	6.50	7.00	9.00	7.00	7.00	8.83	7.00	7.00	7.61
33	8.50	7.00	6.50	9.00	6.00	6.50	9.00	5.50	6.00	8.83	6.17	6.33	7.11
55	8.50	6.50	5.00	9.00	5.50	5.50	9.00	5.00	6.00	8.83	5.67	5.50	6.67
Average AB	8.50	7.42	6.75	9.00	6.42	6.83	9.00	6.58	6.83				
Average A	7.56			7.42			7.47						
Average B										8.83	6.81	6.81	

Factor C	Average AC – *SY Gibuti*	Average AC – *Opoka*	Average AC – *Smolitop*
6	8.00	8.17	8.17
11	8.00	7.50	8.00
16	7.67	7.50	7.50
22	7.67	7.50	7.67
33	7.33	7.17	6.83
55	6.67	6.67	6.67

$NIR_{0.05}$			
A	ns	*AB*	ns
B	0.775	*AC*	ns
C	0.339	*BC*	0.339
		ABC	ns

ns – no significant differences
Source: own study

Table 27 presents data on weed infestation for individual maize varieties.

Table 27. Number of weeds for the tested maize varieties

Factor C	Factor A: *SY Gibuti*			*Opoka*			*Smolitop*			Average BC			Average C
	Factor B: *Control*	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	0.00	39.00	45.00	0.00	44.50	57.50	0.00	50.50	60.50	0.00	44.67	54.33	33.00
11	0.00	82.00	97.00	0.00	73.50	131.00	0.00	63.50	94.50	0.00	73.00	107.50	60.17
16	0.00	87.00	91.00	0.00	65.50	78.50	0.00	81.00	72.50	0.00	77.83	80.67	52.83
22	0.00	86.50	113.00	0.00	109.50	122.50	0.00	102.00	115.50	0.00	99.33	117.00	72.11
33	0.00	153.50	94.50	0.00	143.00	120.50	0.00	133.00	85.50	0.00	143.17	100.17	81.11
55	0.00	184.00	127.00	0.00	203.50	117.50	0.00	204.50	188.50	0.00	197.33	144.33	113.89

	Average AC: *SY Gibuti*	*Opoka*	*Smolitop*
6	28.00	34.00	37.00
11	59.67	68.17	52.67
16	59.33	48.00	51.17
22	66.50	77.33	72.50
33	82.67	87.83	72.83
55	103.67	107.00	131.00

	SY Gibuti			*Opoka*			*Smolitop*		
Average AB	0.00	105.33	94.58	0.00	106.58	104.58	0.00	105.75	102.83
Average A	66.64			70.39			69.53		

Average B: Control	4-6 leaves	8-10 leaves
0.00	105.89	100.67

NIR0.05			
A	ns	*AB*	ns
B	ns	*AC*	ns
C	21.489	*BC*	21,489
		ABC	ns

ns – no significant differences
Source: own study

Table 28 presents data on plant height for individual maize varieties.

Table 28. Plant height for the tested maize varieties

Factor C	Factor A: SY Gibuti			Opoka			Smolitop			Average BC			Average C
	Factor B: *Control*	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	280.00	271.50	214.00	267.00	255.00	199.50	271.00	247.50	159.00	272.67	258.00	190.83	240.50
11	280.00	255.00	192.50	267.00	250.50	175.00	271.00	237.50	171.00	272.67	247.67	179.50	233.28
16	280.00	244.00	191.00	267.00	237.50	194.00	271.00	235.00	184.50	272.67	238.83	189.83	233.78
22	280.00	242.50	187.50	267.00	235.00	200.00	271.00	217.50	175.00	272.67	231.67	187.50	230.61
33	280.00	220.00	192.50	267.00	212.00	161.00	271.00	202.50	165.00	272.67	211.50	172.83	219.00
55	280.00	207.50	167.50	267.00	206.50	160.00	271.00	200.00	127.50	272.67	204.67	151.67	209.67

	Average AC: SY Gibuti	Opoka	Smolitop
6	255.17	240.50	225.83
11	242.50	230.83	226.50
16	238.33	232.83	230.17
22	236.67	234.00	221.17
33	230.83	213.33	212.83
55	218.33	211.17	199.50

	SY Gibuti: Control	4-6	8-10	Opoka: Control	4-6	8-10	Smolitop: Control	4-6	8-10
Average AB	280.00	240.08	190.83	267.00	232.75	181.58	271.00	223.33	163.67
Average A	236.97			227.11			219.33		

Average B	Control	4-6 leaves	8-10 leaves
	272.67	232.06	178.69

$NIR_{0.05}$			
A	9,502	*AB*	ns
B	ns	*AC*	ns
C	15,508	*BC*	15,508
		ABC	ns

ns – no significant differences
Source: own study

Table 29 presents data on the height of corn cobs.

Table 29. Height of corn cobs

Factor C	Factor A									Average BC			Average C
	SY Djibouti			*Opoka*			*Smolitop*						
	Factor B												
	Control	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	136.00	126.50	90	130	134.00	89.00	131.50	115.00	81.50	132.50	125.17	86.83	114.83
11	136.00	114.00	75.00	130.00	101.50	75.00	131.50	110.00	65.00	132.50	108.50	71.67	104.22
16	136.00	96.50	83.00	130.00	104.00	84.50	131.50	104.00	69.00	132.50	101.50	78.83	104.28
22	136.00	107.50	79.50	130.00	96.50	82.50	131.50	80.50	68.50	132.50	94.83	76.83	101.39
33	136.00	87.50	79.00	130.00	87.00	62.50	131.50	69.50	67.50	132.50	81.33	69.67	94.50
55	136.00	87.50	66.00	130.00	91.50	61.00	131.50	74.00	50.00	132.50	84.33	59.00	91.94
	Average AC									Average B			
6	117.50			117.67			109.33			132.50	99.28	73.81	
11	108.33			102.17			102.17			NIR$_{0.05}$			
16	105.17			106.17			101.50						
22	107.67			103.00			93.50			*A*	ns	*AB*	ns
33	100.83			93.17			89.50			*B*	ns	*AC*	ns
55	96.50			94.17			85.17			*C*	9.803	*BC*	9.803
Average AB	136.00	103.25	78.75	130.00	102.42	75.75	131.50	92.17	66.92			*ABC*	ns
Average A	106.00			102.72			96.86						

ns – no significant differences
Source: own study

Table 30 shows the diameter of maize stalks before harvest.

Table 30. Plant stalk diameter before harvest

Factor C	Factor A: *SY Djibouti*			*Opoka*			*Smolitop*			Average BC			Average C
Factor B	*Control*	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	14.00	15.50	13.50	16.00	15:00	14:00	16:00	16:50	12:50	15:33	15:67	13.33	14.78
11	14.00	14.50	12:00	16:00	15:50	12:50	16:00	12:00	10:50	15:33	14:00	11.67	13.67
16	14.00	14.50	12.00	16:00	13:00	12:50	16:00	13.50	10:50	15:33	13.67	11.67	13.56
22	14.00	12.50	12:00	4:00 p.m.	3:00	12:50	16:00	16:00	10:50	15:33	14:50	11.67	13.83
33	14.00	14.50	11.00	16:00	12:50	11:50	16:00	12:50	12:00	15:33	13:17	11:50	13:33
55	14.00	13:00	11:50	16:00	14:50	9:50	16:00	12:50	11:00	15:33	13.33	10.67	13.11

Factor C	Average AC: SY Djibouti	Opoka	Smolitop
6	14.33	15.00	15.00
11	13.50	14.67	12.83
16	13.50	13.83	13.33
22	12.83	14.50	14.17
33	13.17	13.33	13.50
55	12.83	13.33	13.17

	SY Djibouti Control	4-6 leaf	8-10 leaves	Opoka Control	4-6 leaves	8-10 leaves	Smolitop Control	4-6 leaves	8-10 leaves
Average AB	14.00	14.08	12.00	16.00	14.25	12.08	16:00	13.83	11.17
Average A	13.36			14.11			13.67		

Average B: Control	4-6 leaves	8-10 leaves
15:33	14.06	11.75

NIR$_{0.05}$			
A	ns	*AB*	0.592
B	ns	*AC*	ns
C	1.044	*BC*	ns
		ABC	ns

ns – no significant differences
Source: own study

Table 31 presents values concerning the structure of corn cobs.

Table 31. Structure of corn cobs

Factor C	Factor A: SY Djibouti			Opoka			Smolitop			Average BC			Average C
	Factor B: *Control*	*4-6 leaf*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	*Control*	*4-6 leaves*	*8-10 leaves*	
6	77.00	76.00	77.00	74.50	74.00	80.00	76.00	76.50	75.00	75.83	75.50	77.33	76.22
11	77.00	74.50	73.50	74.50	73.00	73.00	76.00	75.50	74.50	75.83	74.33	73.67	74.61
16	77.00	75.00	71.00	74.50	73.00	72.50	76.00	74.00	73.50	75.83	74.00	72.33	74.06
22	77.00	74.00	75.50	74.50	72.00	72.50	76.00	74.50	74.00	75.83	73.50	74.00	74.44
33	77.00	73.50	71.50	74.50	72.00	72.00	76.00	73.00	73.50	75.83	72.83	72.33	73.67
55	77.00	60.50	72.50	74.50	69.50	70.50	76.00	73.50	75.00	75.83	67.83	72.67	72.11

	Average AC: SY Djibouti	Opoka	Smolitop
6	76.67	76.17	75.83
11	75.00	73.50	75.33
16	74.33	73.33	74.50
22	75.50	73.00	74.83
33	74.00	72.83	74.17
55	70.00	71.50	74.83

	SY Djibouti: Control	4-6 leaf	8-10 leaves	Opoka: Control	4-6 leaves	8-10 leaves	Smolitop: Control	4-6 leaves	8-10 leaves
Average AB	77.00	72.25	73.50	74.50	72.25	73.42	76.00	74.50	74.25
Average A	74.25			73.39			74.92		

Average B: Control	4-6 leaves	8-10 leaves
75.83	73.00	73.72

$NIR_{0.05}$			
A	ns	*AB*	ns
B	ns	*AC*	ns
C	2.774	*BC*	ns
		ABC	ns

ns – no significant differences
Source: own study

5.6.2. Regression models

Regression analysis was used to assess the interdependence between the degree of weed infestation and yield. In the first phase, simple regression was used to estimate the linear dependence model and assess its statistical significance. The analyses were performed separately for each spraying date (4-6 leaves, 8-10 leaves) and in general terms. The results of these analyses are presented in Table 32 and graphically in Figures 1, 2, and 3.

Table 32. Simple regression analysis in the assessment of the relationship between weed infestation and yield.

N=6	SY Gibuti		Opoka		Smolitop	
	Parameter	t-Student	Parameter	t-Student	Parameter	t-Student
4-6 leaf						
Free word	**5,470**	**34.674**	**4,654**	**18,131**	**5,345**	**21,656**
Regression coefficient	**-0.026**	**-4.702**	-0.020	-2.263	**-0.027**	**-3.167**
Standard error of estimation	0.219		0.356		0.342	
R^2	0.85		0.56		0.71	
8-10 leaf						
Free expression	**3.891**	**11.060**	**3,565**	**34,936**	**3,478**	**10,450**
Regression coefficient	-0.023	-1.923	**-0.030**	**-8.393**	-0.016	-1.348
Standard error of estimation	0.487		0.141		0.461	
R^2	0.48		0.95		0.31	
Total						
Free expression	**5.387**	**40,674**	**4,590**	**43,944**	**5,108**	**30,083**
Regression coefficient	**-0.016**	**-3.569**	**-0.017**	**-4.587**	-0.014	-2.416
Standard error of estimation	0.183		0.145		0.235	
R^2	0.76		0.84		0.59	

Note: statistical significance is indicated in bold.
Source: own study

The analyses confirmed a linear relationship, which indicated that as the degree of weed infestation increased, the average yield decreased, which meant that the models of this relationship were as follows:

$$y = a - bx \tag{4}$$

where: y is the dependent variable (here, yield), a is the constant term, b is the regression coefficient, and x is the value of the independent variable (here, weed infestation).

At the 4-6 leaf stage, the analyses confirmed a significant linear relationship between the degree of weed infestation and yield in the case of the Gibuti and Smolitop varieties, at the 8-10 leaf stage only in the case of the Opoka variety, and in general terms in the case of the Gibuti and Opoka varieties, with a fairly good fit of the models to the empirical data. In statistically significant models, the *R2 coefficient ranged from 71 to* 95.

In cases where no statistically significant linear relationship was confirmed, the arrangement of points suggested a possible curvilinear relationship in the form of a second-degree polynomial. This was the case for the Opoka variety at the 4-6 leaf stage and for the Smolitop variety in general. In each of these cases, the model was as follows:

$$y= a - bx + cx^2 \tag{5}$$

where: y is the dependent variable (here, yield), a is a constant, b and c are regression coefficients, and x is the value of the independent variable (here, weed infestation).

Using Levenberg-Marquardt estimation, a statistically significant curvilinear relationship was confirmed in both cases. For the Opoka variety in the 4-6 leaf stage, the model had the form with $R^2 = 0.84$:

$$y= 5.2922 - 0.0818x + 0.0010x^2 \tag{6}$$

and for the Smolitop variety in general terms with $R^2 = 0.92$:

$$y= 5.5786 - 0.0598x + 0.0007x^2 \tag{7}$$

Graphs showing the regression relationships between maize grain yield and the degree of weed infestation in the 4-6 and 8-10 leaf stages and overall for the SY Gibuti, Opoka and Smolitop varieties are shown in Figures 1, 2 and 3.

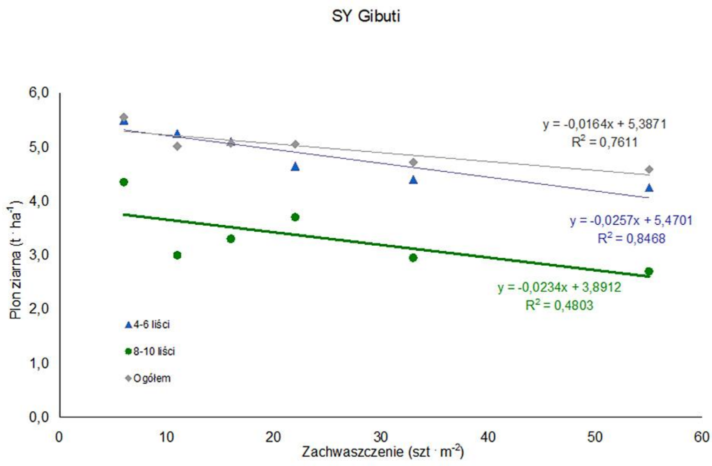


Fig. 1. Graph showing the regression relationship between maize grain yield and the degree of weed infestation in the plantation in the 4-6, 8-10 leaf stages, and overall for the SY Gibuti variety

Source: own study

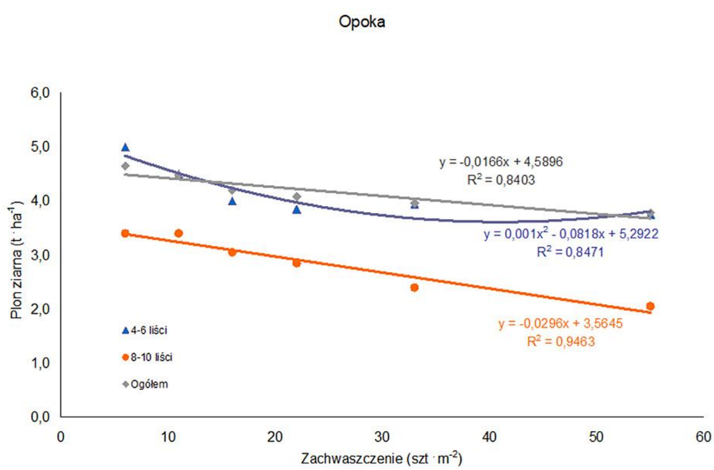


Fig. 2. Regression chart of maize grain yield depending on the degree of weed infestation of the plantation in the 4-6, 8-10 leaf stages, and overall for the Opoka variety

Source: own study

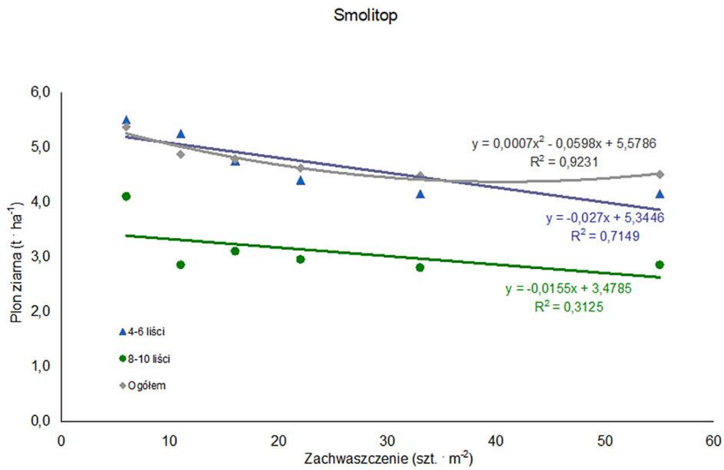


Fig. 3. Regression chart of maize grain yield depending on the degree of weed infestation of the plantation in the 4-6, 8-10 leaf stages and overall for the Smolitop variety

Source: own study

5.6.3. Summary of research results

Comparing the results of our own experiments with those of other researchers reveals both similarities and discrepancies. In both cases, the results were greatly influenced by factors such as soil and climatic conditions of the experiments, corn variety, soil fertility, and agricultural practices. In all the crops studied, weed infestation reduced yield, especially during emergence and the early stages of plant development. However, there is no clarity as to the level of weed infestation that significantly reduces yield.

Yield also depends on the maize variety cultivated and, as the study showed, decreases with increasing weed infestation, linearly in one case and non-linearly in the other.

Weed control before emergence increases the cost of chemical treatment. On the other hand, weed control after emergence worsens emergence quality and, as a result, reduces grain yield. It has also been found that as weed infestation increases, the percentage of grain in the cob decreases. Delaying weed control leads to a significant reduction in maize grain yield. Delaying the application of herbicides results in weaker initial plant development and, as a result, lower plant height before harvest, smaller stalk diameter, and a large proportion of non-productive cobs, which is reflected in the yield and moisture content of the grain. Delaying weed control by about two weeks significantly delays plant development and corn grain ripening. Experience has shown that herbicides must be applied immediately after sowing, as applying herbicides in the 4-6 leaf stage results in a grain yield reduction of about 3 $t \cdot ha^{-1}$, while in the 8-10 leaf stage the yield decrease was approximately twice as high, ranging from 4.5 to 6 $t \cdot ha^{-1}$.

As shown by a review of both domestic and foreign literature, universities and scientific research institutes are conducting extensive research on new varieties of maize grown for grain, as well as on technological operations, especially grain harvesting. The research problem formulated corresponded to current scientific and practical needs, and its solution provided a basis for further research in this field.

Laboratory and field research within the planned scope enables computational and statistical assessments of the impact of basic factors on indicators such as plant yield in grain maize cultivation. It is important to note that the impact of weed infestation on plant yield can be characterised by a linear relationship (SY Gibuti and Smolitop maize varieties) or a non-linear relationship, i.e. a second-degree polynomial (Opoka maize variety). The yields of these varieties on control plots in 2015 were as follows: Smolitop 6.2; SY Gibuti 5.9; and Opoka 5.2 $t \cdot ha^{-1}$, while in 2016 they were: SY Gibuti 7.7; Smolitop 6.8; and Opoka 5.9 $t \cdot ha^{-1}$. The average for the two years was as follows: SY Gibuti 6.8; Smolitop 6.28; Opoka 5.55 $t \cdot ha^{-1}$.

The impact of post-emergence weed infestation on yield, depending on the date of herbicide treatment, in the form of lower grain yield, was as follows: SY Gibuti from 5.50 to 2.95 $t \cdot ha^{-1}$, Smolitop from 5.50 to 2.85 $t \cdot ha^{-1}$, Opoka from 5.00 to 2.05 $t \cdot ha^{-1}$. The smallest decrease in yield due to weed infestation was observed in the SY Gibuti variety, the average in the Smolitop variety and the largest in the Opoka maize variety.

The scope of the research allowed us to expand our knowledge in this area and obtain additional information of scientific and practical value, enabling us to formulate recommendations for agricultural practice.

5.7. Findings and conclusions

1. Comparing the yields of the tested grain maize varieties with a similar ripening period from the control plots, it can be concluded that the highest average yield in 2015 and 2016 was 6.80 $t \cdot ha^{-1}$ was obtained for

the SY Gibuti variety (FAO 240), a lower yield of 6.28 $t \cdot ha^{-1}$ for the Smolitop variety (FAO 230) and the lowest yield of 5.55 $t \cdot ha^{-1}$ for the Opoka variety (FAO 240).

2. The degree of weed infestation of the plantation in the initial phase of plant growth significantly affects post-emergence plant growth and plant parameters during the growing season and at harvest, as well as maize grain yield.
3. The decrease in maize grain yield depending on the degree of post-emergence weed infestation was linear (for the two varieties SY Gibuti and Smolitop), while for the Opoka variety it was non-linear.
4. Delaying post-emergence herbicide weed control results in a significant reduction in maize grain yield and deterioration of its technological parameters (degree of maturity and grain moisture content at harvest). The use of herbicides at the 4-6 leaf stage reduces grain yield by about 3 $t \cdot ha^{-1}$, whereas at the 8-10 leaf stage, the reduction ranges from 4.5 to 6 $t \cdot ha^{-1}$.

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5.9. Appendices

Appendix 1. Characteristics of the agricultural holding in Krzyżewo

The Experimental Station for Variety Evaluation in Krzyżewo is one of 16 regional branches of the executive agency, the Research Centre for Cultivar Testing (COBORU) headquartered in Słupia Wielka. The Station operates directly for the benefit of agricultural practice through the coordination and conduct of research in post-registration varietal and agricultural experimentation.

The main tasks of the Experimental Station for Variety Evaluation in Krzyżewo include:

- implementation of the research and experimental plan of the Research Centre, established annually;
- conducting experiments and documenting them in accordance with the methodologies developed and binding at the Research Centre;
- coordination of post-registration varietal experimentation within the voivodeship in which the station is located;
- preparation of lists of varieties recommended for cultivation in the voivodeship, based on the results of experiments carried out under the Post-Registration Variety Testing (PDO) system;
- dissemination of knowledge on varieties of cultivated crops;
- provision of experimental services at a high level of agricultural culture;
- maintaining financial and tax accounting;
- performing activities in the field of labour law in relation to employees of the Station.

The holding of the Experimental Station for Variety Evaluation discussed in this study is located within the territory of the Sokoły municipality, in Wysokie Mazowieckie County, in the Podlaskie Voivodeship. The location is shown in Figure 1, while the characteristics of the soils occurring in the holding are presented in Table 1.

Currently, the SDOO Krzyżewo holding covers 209 ha. The soil quality in the holding is presented in Table 1. Experiments are established primarily on soils of classes III and IV. The fields are drained, with a humus layer up to 30 cm thick and an organic matter content exceeding 2%. The area is characterised by a climate typical of north-eastern Poland, where conditions for agricultural production are less favourable than in other regions of the country.

Geographical location: φ = 53°01′, λ = 22°46′, H = 135 m a.s.l.

Appendix 2. Agrotechnical conditions for conducting experiments

Maize does not have excessive soil requirements. It can be grown on both lighter and heavier soils, except in wet, cold, sandy, or compact soils. The experiments were conducted on a very good rye complex, class IVa, with black soil in 2015 and brown soil in 2016. The previous crop in 2015 was spring rapeseed, and in 2016 it was winter wheat.

After harvesting the previous crop, a full set of post-harvest and pre-winter treatments was carried out. To accelerate the decomposition of post-harvest residues, post-harvest cultivation was carried out using the following equipment: KOS 3U739/4 stubble cultivator with a working width of 3 m and a Lamborghini 105 tractor, to a depth of 10 cm. Pre-winter cultivation consisted of winter ploughing, which was carried out using the following equipment: URSUS 1614 tractor + IBIS 120XL 4-furrow reversible mounted plough in the third decade of October to a depth of30 cm and left in sharp furrows. Ploughing was carried out perpendicular to the direction of sowing. Spring tillage and maintenance treatments depended on the start of vegetation. In 2015, vegetation resumed at the beginning of March, enabling earlier sowing of mineral fertilisers and the start of pre-sowing cultivation. The later vegetation onset in spring 2016 delayed the start of spring tillage and maintenance treatments. In both 2015 and 2016, spring tillage began with harrowing to level the field and prevent evaporation, using the following combination: MF 255 tractor + Unia harrow, followed by the application of mineral fertilisers using the following equipment: URSUS C360 tractor + 1200L AMAZONE mounted fertiliser spreader. Mineral fertiliser doses were determined based on the current soil content of individual components. Pre-sowing cultivation using the following combination: URSUS 1614 tractor + Kombi 5.1 BH passive cultivator covered the previously sown fertilisers. The next step was to use the following combination: URSUS 1614 tractor + KG 3000 Super active cultivator to loosen and level the soil more deeply before sowing the trial crops. After measuring the outlines of the experiment, corn was sown using a combination consisting of a KUBOTA M6060 tractor + Planter II precision seeder. Immediately after setting up the experiments, weed seeds were sown in the second and third strips to create provocative conditions. The weeds were sown using a set consisting of |a URSUS C330 tractor + SPZ-1.5 grain plot seeder. In the first strip, Lumax 537.5 SL herbicide was applied at a rate of 3.5 dm3· ha^{-1} to protect the strip from weeds. All herbicide treatments were performed using a KUBOTA M6060 tractor + Heros ORZ600/15/H mounted sprayer. After harvesting the cobs, threshing was performed using a Sampo 130 plot combine harvester.

The agrotechnical treatments carried out in the field in 2015 and 2016, along with the application dates and fertiliser doses used, are presented in Table 1.

Table 1. Agrotechnical and field conditions for conducting experiments with maize used for grain.

Specification	Years of experiments	
	2015	2016
Sowing date	30.04	4 May
Harvest date	12 October	17 October
Mineral fertilisation		
N $kg \cdot ha^{-1}$	134	167
$P_2O_5 kg \cdot ha^{-1}$	80	80
K_2 O $kg \cdot ha^{-1}$	120	120
Herbicides dose	Lumax 375.5 SE–3.5 $dm^3 \cdot ha^{-1}$ Elumis 105 OD–1.25 $dm^3 \cdot ha^{-1}$	Lumax 375.5 SE–3.5 $dm^3 \cdot ha^{-1}$ Elumis 105 OD–1.25 $dm^3 \cdot ha^{-1}$
Cultivation treatments		
Ploughing	24 August	29 August
Ploughing	30 October	25 October
Harrowing	27 March	04.04
Mineral fertilisation	14 April; 30 April;	20 April; 23 April; 14 June
Passive cultivator	14	20.04
Active cultivator	30 April	23
Herbicide spraying	30 April; 5 June; 10 June	04.05; 03.06; 09.06

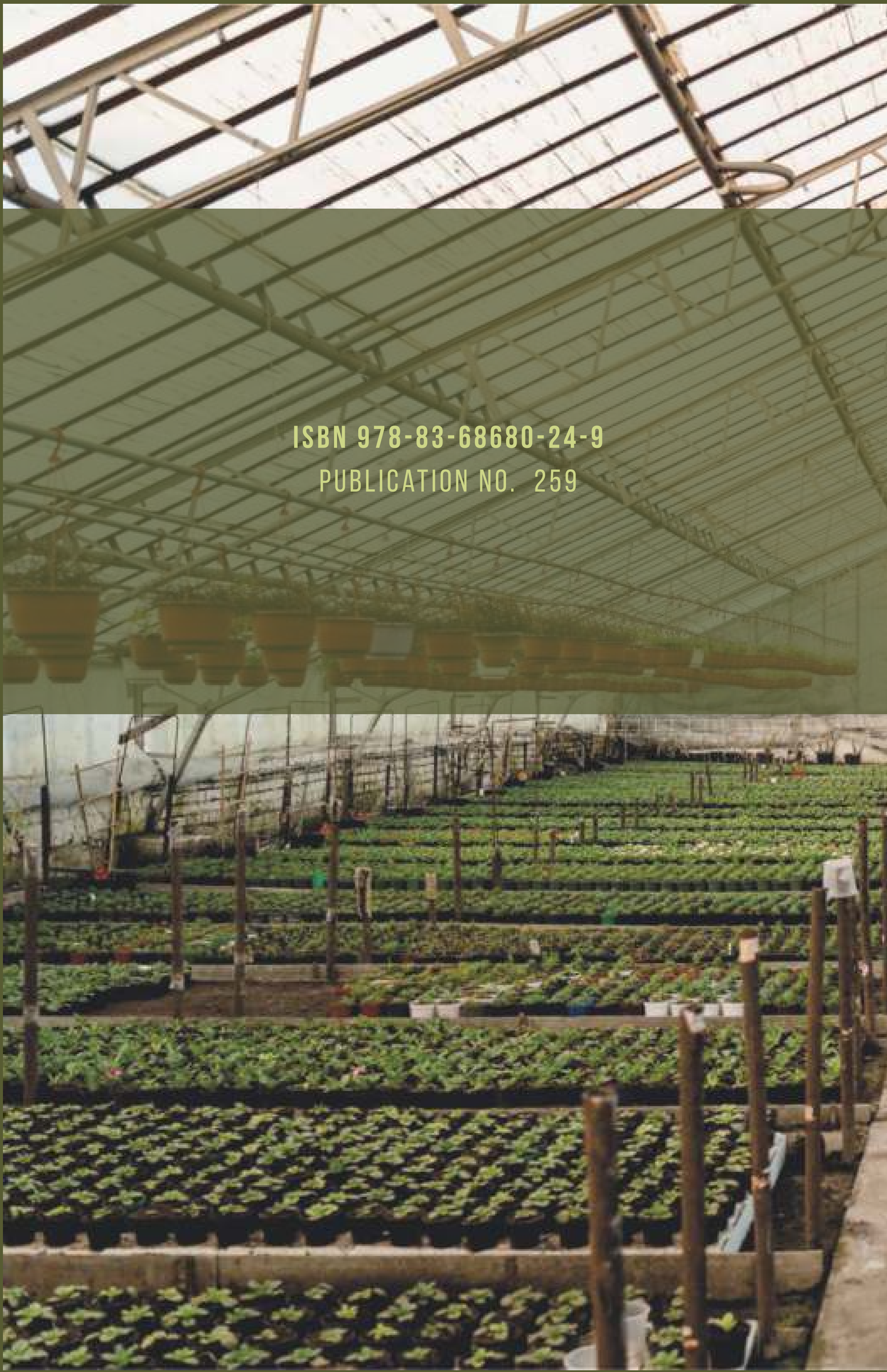
Source: own study based on SDOO Krzyżewo data

Abstract

The aim of the laboratory and field research was to determine the impact of the corn variety used and the plantation's weed infestation on corn yield in the initial phase of plant growth. The laboratory and field studies within the planned scope enable computational and statistical assessments of the impact of key factors on indicators such as maize grain yield. It is important to note that the impact of weed infestation on plant yield can be characterised by a linear relationship (SY Gibuti and Smolitop maize varieties) or a non-linear relationship (Opoka maize variety), i.e., a second-degree polynomial. The yields of these varieties on control plots in 2015 were as follows: Smolitop 6.2; SY Gibuti 5.9; and Opoka 5.2 $t \cdot ha^{-1}$, while in 2016 they were: SY Gibuti 7.7; Smolitop 6.8; and Opoka 5.9 $t \cdot ha^{-1}$. The average for the two years was as follows: SY Gibuti 6.8; Smolitop 6.28; Opoka 5.55 $t \cdot ha^{-1}$.

The impact of post-emergence weed infestation on yield, depending on the date of herbicide treatment, in the form of lower grain yield, was as follows: SY Gibuti from 5.50 to 2.95 $t \cdot ha^{-1}$, Smolitop from 5.50 to 2.85 $t \cdot ha^{-1}$, Opoka from 5.00 to 2.05 $t \cdot ha^{-1}$. The smallest decrease in yield due to weed infestation was observed in the SY Gibuti variety, the average in the Smolitop variety, and the largest in the Opoka maize variety.

Keywords: grain maize, weed infestation, experiment, yield, growth



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