Ministry of Education and Science of Ukraine
Mykolaiv National Agrarian University

ISSN 2313-092X
E-ISSN 2411-9199
UDC 63

Вісник аграрної науки Причорномор'я

Том 28, № 2

Науковий журнал

Ukrainian Black Sea Region Agrarian Science

Scientific Journal

Volume 28, No. 2

Year of establishment: 1997
Publication frequency: Four times a year

Mykolaiv
2024

DOI: 10.56407/bs.agrarian/2.2024-28(1)

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Миколаївського національного аграрного університету
(протокол № 11 від 11 червня 2024 р.)

Державна реєстрація:
Ідентифікатор медіа R30-04646.
Рішення Національної ради України з питань телебачення і радіомовлення
№ 1177, протокол № 13 (11.04.2024 р.).

Журнал входить до переліку наукових фахових видань України категорії «Б»:
з економічних, технічних, сільськогосподарських, ветеринарних наук за спеціальностями 051 – Економіка, 071 – Облік і оподаткування, 072 – Фінанси, банківська справа та страхування, 073 – Менеджмент, 075 – Маркетинг, 076 – Підприємництво, торгівля та біржова діяльність, 101 – Екологія, 133 – Галузеве машинобудування, 181 – Харчові технології, 183 – Технології захисту навколишнього середовища, 201 – Агрономія, 202 – Захист і карантин рослин, 204 – Технологія виробництва і переробки продукції тваринництва, 205 – Лісове господарство, 207 – Водні біоресурси та аквакультура, 208 – Агроінженерія, 211 – Ветеринарна медицина, 281 – Публічне управління та адміністрування, 292 – Міжнародні економічні відносини
(Наказ Міністерства освіти та науки України від 09 червня 2022 р. № 724)

Журнал представлено у наукометричних базах даних, репозитаріях:
Google Академія, Фахові видання України, Національна бібліотека України імені В. І. Вернадського (НБУВ), Crossref, Polska Bibliografia Naukowa (PBN), Index Copernicus International (ICI), Dimensions, AGRIS, EBSCO, Бібліотека Університету Халла, Бібліотека Лейпцизького університету (UBL), WorldCat, EuroPub, Open Ukrainian Citation Index (OUCI), Zendy Research Library, Asian Science Citation Index

Вісник аграрної науки Причорномор’я : наук. журн. / [редкол.: В. С. Шебанін (голов. ред.) та ін.]. – Миколаїв : Миколаївський національний аграрний університет, 2024. – Т. 28, № 2. – 78 с.

Адреса редакції:
Миколаївський національний аграрний університет
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DOI: 10.56407/bs.agrarian/2.2024-28(1)

Recommended for printing and distribution
via the Internet by the Mykolaiv National Agrarian University
(Minutes No. 11 of June 11, 2024)

State Registration:
Media identifier R30-04646.
Decision of the National Council of Television and Radio Broadcasting of Ukraine
No. 1177, Minutes No. 13, dated 11.04.2024.

The journal is included in the list of professional publications of Ukraine of category "B":
Economic, technical, agricultural, veterinary sciences by specialty 051 – Economics, 071 – Accounting and taxation, 072 – Finance, banking and insurance, 073 – Management, 075 – Marketing, 076 – Business, trade and exchange, 101 – Environmental studies, 133 – Industrial machinery engineering, 181 – Food technology, 183 – Environmental protection technology, 201 – Agronomy, 202 – Plants protection and quarantine, 204 – Livestock production and processing technologies of animal products, 205 – Forestry, 207 – Water bio-resources and aquaculture, 208 – Agricultural engineering, 211 – Veterinary medicine, 281 – Public management and administration, 292 – International economic relations
(Order of the Ministry of Education and Science of Ukraine of August 9, 2022 No. 724)

The journal is presented at scientometric databases, repositories:
Google Scholar, Professional Publications of Ukraine, Vernadsky National Library of Ukraine (VNLU), Crossref, Polish Scientific Bibliography, Index Copernicus International (ICI), Dimensions, AGRIS, EBSCO, University of Hull Library, Leipzig University Library (UBL), WorldCat, EuroPub, Open Ukrainian Citation Index (OUCI), Zendy Research Library, Asian Science Citation Index

Ukrainian Black Sea Region Agrarian Science / Ed. by V. Shebanin (Editor-in-Chief) et al. Mykolaiv: Mykolaiv National Agrarian University, 2024, Vol. 28, No. 2. 78 p.

Publishing Address:
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
Tel.: +38(0512) 70-93-54
E-mail: info@bsagriculture.com.ua
https://bsagriculture.com.ua/en

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UDC: 633.1.631.1
DOI: 10.56407/bs.agrarian/2.2024.09

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Aspects of legume growth in Ukraine

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Abstract. The cultivation of legumes in Ukraine is key for agriculture and the economy, as they are strategic crops for food security, export potential and sustainable development of the agricultural sector. The study aimed to examine the current state of legume cultivation in Ukraine and identify the main aspects that determine their production. Gross harvest, yields, planted areas, export dynamics and prices of such legumes as soybeans, chickpeas, beans and peas for 2015-2023 were analysed to address the set aim. The results of the study showed the stability and potential growth of legume production in Ukraine. Despite changes in the level of soybean exports, production and processing from year to year, there is a general upward trend. In 2023, soybean exports reached a record high of 3.6 million tonnes, a significant increase from the lowest level in 2021, when only 1.4 million tonnes were exported. As for peas, chickpeas and beans, their production in Ukraine reflected fluctuating trends. Pea production peaked in 2018 at 755 thousand tonnes, chickpea production reached its highest level in 2021 (93.4 thousand

Article's History:
Received: 26.01.2024
Revised: 13.04.2024
Accepted: 11.06.2024

Suggested Citation:
Drobitko, A., Kachanova, T., Markova, N., Manushkina T., & Tarabrina, A.-M. (2024). Aspects of legume growth in Ukraine. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 9-20. doi: 10.56407/bs.agrarian/2.2024.09.

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tonnes), and beans in 2020 (65 thousand tonnes). In the period from 2021 to 2023, prices for legumes in Ukraine showed steady growth, with chickpeas at 21.6 thousand UAH/t, beans at 33-35 thousand UAH/t, and peas at 8.1 thousand UAH/t. The price dynamics of soybeans also showed an increase to the level of 17.2-17.4 thousand UAH/t. The strategic directions identified in the study point to the need to invest in research, technological progress and infrastructure to ensure sustainability in legume production

Keywords: exports; acreage; yield; soy; chickpea; agricultural production

INTRODUCTION

Legumes are an important component of the agricultural sector in many countries, and their cultivation is essential for the sustainable development of agriculture and the economy. The cultivation of legumes improves soil fertility, diversifies production, reduces environmental impacts and ensures food safety. In Ukraine, the cultivation of legumes creates new opportunities for exports and the development of the agricultural sector, contributing to the country's integration into global markets and ensuring economic stability.

Legumes are attracting considerable attention from researchers in agriculture and the food industry. These crops play a key role in the food, feed and agricultural-ecological sectors of Ukrainian agriculture. However, the area under legumes is insufficient, which may be a limiting factor for further development of legumes and utilisation of their full potential. Therefore, according to V. Mazur *et al*. (2021), when expanding sown areas, it is necessary to choose the right varieties, addressing current environmental conditions and biological characteristics of plants. The main criteria for choosing varieties are their yield, resistance to stress, height and other technological characteristics. In this context, it is necessary to address the creation of highly productive varieties of legumes, optimisation of the structure of sown areas and the development and implementation of scientific and innovative cultivation technologies based on the efficient use of life factors such as light, heat, moisture and nutrients, which will contribute to the maximum synthesis of organic matter and protein, as noted by N. Leschuk *et al*. (2022). In addition, in the context of climate change, it will be important to develop a unified agricultural policy to produce legumes.

Growing legumes requires a flexible approach to international competition to ensure food and environmental security for the modern globalised economy. These crops are important in the grain and fodder balance of Ukraine. According to I. Kulyk (2019), the reduction of raw material export and the development of advanced processing is strategically important for Ukraine. This will meet the needs of intensive livestock production with high-protein feed, create new jobs, increase tax revenues, and ensure the country's food and environmental security. Many scientists emphasise the unique properties of legumes, which open wide opportunities in the processing industry – from various food products to the production of feed, medicines and cosmetics. Therefore, Y.A. Yigezu *et al*. (2021), B. Dessalegn *et al*. (2022) and A. Singh *et al*. (2023) argue that there is a need for the strategic development of agricultural technologies focused on global trends in the cultivation and fertilisation of these crops.

To ensure maximum productivity with minimal environmental impact, it is important to study and implement modern agricultural technologies, such as agricultural operations, irrigation systems, fertilisers and plant protection. O. Krupchan & V. Korol (2022) emphasise the need to ensure high-quality standards for legume products, which affects their perception of the world market. At the same time, there is a need to support small and medium-sized farms, which typically grow legumes, to ensure their sustainable development and market competitiveness. E. Lagerquist *et al*. (2024) note that this may include providing access to financial resources, support for the introduction of new technologies, training and advice on cultivation and farm management. In addition, the need to adopt environmentally friendly approaches to growing legumes is key to preserving natural resources and ensuring sustainable development of the agricultural sector. W.F. Abobatta *et al*. (2022) and S. Kodgire *et al*. (2022) emphasise that such measures will not only preserve the environment but will also contribute to ensuring productivity and crop quality, which are important aspects of modern production.

In the context of the analysis of data from various authors, it is worth noting that there is a gap in the collection and analysis of data on production, available acreage and yields of legumes in Ukraine. Information on the exact volumes and dynamics of their cultivation is important for effective agricultural policy planning, development of agricultural technologies and food security. The lack of such data makes it difficult to analyse trends in legume production, identify problem areas and develop strategies to address them. Therefore, the study aimed to collect and systematise the data on the cultivation of legumes in Ukraine and identify key aspects of their production. To achieve this goal, the following tasks were set: to analyse the current state of legume cultivation, evaluate existing methods of cultivation, and identify strategic directions for increasing the sustainability and development of Ukrainian agricultural production in the field of legume cultivation.

MATERIALS AND METHODS

The theoretical segment of the study addressed achievements in the field of agrarian development and the field of research on the problems of transformations in agricultural production and its sale. In addition, the study used statistics from the United Nations (2024) and Food and Agriculture Organization (n.d.), the official statistical body of the European Union – Eurostat (2023) and Statista (2024) websites, which provide access to statistics from various sectors. The research materials were analysed using the method of comparison and grouping, as well as the abstract and logical method, which was aimed at studying the current state, problems and prospects of growing legumes in Ukraine.

The study used a range of methods: generalisation – when working with literary sources to systematise and summarise information, the dactylic method – to study the patterns, state and prospects of growing legumes in Ukraine, grouping – to study the totality of data and their logical combination, statistical methods – to quantify data and analyse them statistically. The production of legumes in the modern Ukrainian agricultural sector was addressed to analyse statistical data on cultivation volumes, yields and areas, according to the State Statistics Service of Ukraine (n.d.). The data on exports of legumes obtained from the Ministry of Agrarian Policy and Food of Ukraine (2024) were also included. The use of these data was justified by their completeness and reliability, as they are officially collected and confirmed by government agencies.

The following indicators were analysed to determine the state and prospects of growing legumes in Ukraine: dynamics of gross harvest, yields and sown areas of such crops as soybeans, chickpeas, peas and beans, dynamics of changes in the price of legumes on the market, as well as indicators of their production, processing and exports for the period 2015-2023. In addition, the main agrotechnical methods for growing these crops and the existing market and legal requirements for the quality of their products in Ukraine are identified. A SWOT analysis was conducted to identify the strengths and weaknesses of the legume sector and to identify existing opportunities and threats to substantiate strategic directions for increasing the sustainability and development of Ukrainian agricultural production. The obtained research results were processed for reliability by applying the multivariate method of MANOVA analysis of variance using Microsoft Excel software and the Statistica 10 software package. Differences in the results obtained are possible at a significance level of $P \leq 0.05$ according to the Student's criterion.

RESULTS

The Food and Agriculture Organization (n.d.) (FAO) recognises legumes as key food crops that play an important role in meeting the ever-growing food needs of the global population. Beans, chickpeas, peas, soybeans and lentils are the most common legumes in the world. At the same time, legumes used for harvesting green fruits (such as green peas and green beans) are more often classified as vegetable crops.

Ukrainian agribusinesses are showing an active interest in growing legumes, including soybeans, peas, chickpeas and beans, which demonstrates their popularity among agricultural producers. It is worth noting that growing legumes in Ukraine is a complex and multifaceted process that includes a range of agronomic practices that contribute to the successful cultivation of these crops. This process begins with the selection of the right variety, which is based on the individual requirements of the climate and soil conditions of the region, as well as yield and disease and pest resistance. Soil preparation before sowing is an important step, which includes tilling the soil and applying the necessary fertiliser. Legumes are sown at the optimum sowing density and seeding depth to ensure healthy growth and development of the plants. Crop care involves various activities such as weed control, fertilisation, watering and protection against pests and diseases. Plants are cared for throughout the growing season to ensure maximum yield and product quality. The final stage is harvesting, which requires care and precision to maintain grain quality. After harvesting, the crops are stored and further processed for use in various industries, such as the food industry, feed production and others. All these aspects of agricultural technology together contribute to the successful cultivation of legumes in Ukraine, ensuring high yields and product quality, as well as contributing to the sustainable development of the agricultural sector (Dankevych *et al.*, 2022).

According to many scientists, modern legume cultivation technologies in Ukraine are constantly evolving and include several innovative approaches that help to increase yields, reduce costs and improve product quality. Some of these include developing legume varieties that are suitable for different soil types and using modern genetic technologies to develop new hybrids and varieties of legumes that have improved properties such as resistance to stress, diseases and pests, and higher yields. The use of agricultural informatics and modern data collection and analysis technologies, such as remote sensing, agricultural drones and sensor technology, allows farmers to obtain detailed information about the condition of fields and plants, which helps them make more informed decisions on agricultural management. The use of precision farming technologies, such as GPS systems and autopilot tractors, reduces fuel and fertiliser costs and improves the accuracy of agricultural operations. Development of biological farming, including the use of biological methods of pest and disease control, green fertilisers and biological control agents, which help to preserve soil fertility and reduce environmental impact. These modern technologies help Ukrainian farmers increase the efficiency of legume cultivation, reduce environmental impact and increase the profitability of agricultural production (Kravchenko *et al.*, 2019; Leschuk *et al.*, 2022).

According to the State Statistics Service of Ukraine (n.d.), the gross harvest of cereals and legumes from 2015 to 2023 experienced significant fluctuations. Thus, the highest gross harvest was recorded in 2019 (751 million tonnes), and the lowest in 2021 (566 million tonnes). Peas, chickpeas and beans show a general downward trend in gross harvest during the period under review. Soybeans, on the other hand, were growing steadily. Significant fluctuations in the gross harvest of each crop can be attributed to factors such as weather conditions, pests and diseases, changes in agricultural technology and practices, as well as pandemics and full-scale war (Fig. 1).

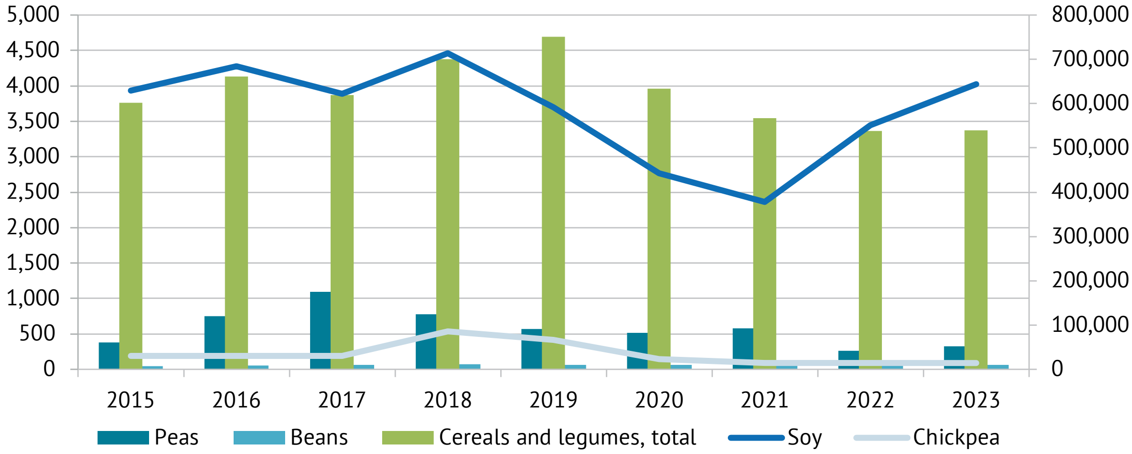

Figure 1. *Gross harvest of legumes in Ukraine, thousand tonnes*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

The analysis of yields shows that for peas it varies from 22.4 hwt/ha in 2015 to 25.7 hwt/ha in 2023. Bean yields range from 13.5 hwt/ha in 2015 to 15.9 c/ha in 2022. The highest yield of beans was recorded in 2018 – 17.7 hwt/ha. It is worth noting that chickpea yields have been increasing over the years, and in 2023, they reached 25.4 centners per ha, up from 6.49 in 2016. Soybean yields ranged from 19.7 hwt/ha in 2017 to 25.8 hwt/ha in 2018 and 2023. In a comparison between crops, pea and soy yields are higher than beans. In general, it is worth noting that there is a general tendency to increase the yield of legumes over the years, especially in the case of soybeans (Fig. 2). The study determined that the sown area of legumes tends to decrease during the study period. From 2015 to 2023, the total area under legumes decreased from 14,739 thousand ha to 12,357.2 thousand ha. Considering the sown areas for each legume crop by year, it is possible to state that the sown areas changed significantly. For peas, they ranged from 423 thousand ha in 2018 to 139.3 thousand ha in 2023. Bean acreage ranged from 36 thousand ha in 2015 and 2016 to 42 thousand ha in 2019 and 2020. The area under Chickpea also reached its lowest point in 2023, amounting to 5.3 thousand ha. However, soybean acreage is growing over time, from 1,323.2 thousand ha in 2020 to 1,780 thousand ha in 2023. The general trend is that soybeans have seen the largest increase in area (Table 1).

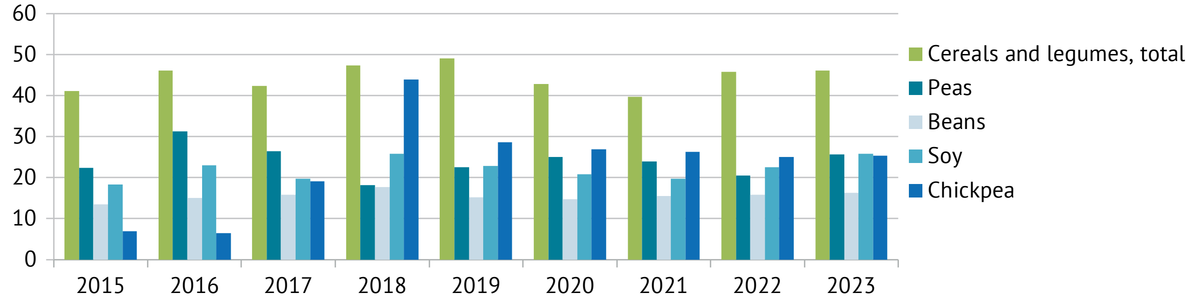

Figure 2. *Yield of legumes in Ukraine, hwt/ha*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

Table 1. *Sown areas under legumes in Ukraine, thousand ha*

Year	Cereals and legumes, total	Peas	Beans	Soy	Chickpea
2015	14,739	173	36	2,158	7
2016	14,401	237	36	1,869	7.3
2017	14,607	412	41	1,994	13.7
2018	14,848	423	40	1,709	35
2019	15,318	258	42	1,609	31
2020	14,759.1	237.7	42	1,323.2	20
2021	10,203.2	242.8	41	1,183.4	9.1
2022	12,171.1	131.3	37.5	1,558.9	8
2023	12,357.2	139.3	37	1,780	5.3

Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

When analysing the dynamics of soybean exports, production and processing data over the years, certain fluctuations can be noted. The highest exports were recorded in 2023 (3.6 million tonnes), and the lowest in 2021 (1.4 million tonnes). The highest volume of soybean production was set in 2018 (4.5 million tonnes), and the lowest – in 2020 (2.8 million tonnes). Soybean processing volumes also fluctuated over the years, with the highest value in 2023 (1.6 million tonnes) and the lowest in 2016 (1 million tonnes). Although exports, production and processing volumes of soybeans may fluctuate from year to year, they have been increasing over the period of observation. This may indicate an increase in demand for soybeans, both as an export commodity and for domestic consumption or processing in Ukraine (Fig. 3).

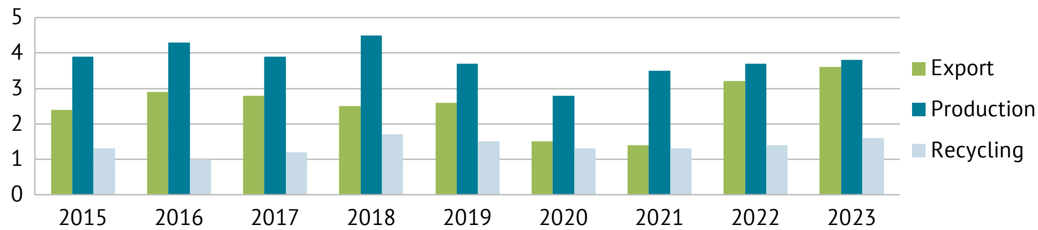

Figure 3. *Production, exports and processing of Ukrainian soybeans, million tonnes*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

In the period 2015-2023, the production of peas, chickpeas and beans in Ukraine showed growth and decline, ranging from small volumes to impressive figures. Thus, in 2018, there was a significant increase in pea production – 755 thousand tonnes, while chickpeas and beans had lower volumes compared to previous years – 535.6 thousand tonnes and 70 thousand tonnes, respectively. In 2020, pea production declined to 142.2 thousand tonnes, but in the following years, pea production recovered and increased to 344.2 thousand tonnes in 2022 and 270 thousand tonnes in 2023, although it remained lower than in previous years.

Chickpea production also experienced a decline in 2020, falling to 142.2 thousand tonnes. However, in

2021, chickpea production increased again, reaching 93.4 thousand tonnes, but declining to 38 thousand tonnes in 2023. Bean production in 2020 totalled 80 thousand tonnes, which is stable compared to previous years. However, in 2021, bean production decreased to 65 thousand tonnes, and in 2022 and 2023 it continued to decline to 60 thousand tonnes and 40 thousand tonnes, respectively. The analysis described the dynamics of the production of these important crops in Ukraine (Fig. 4).

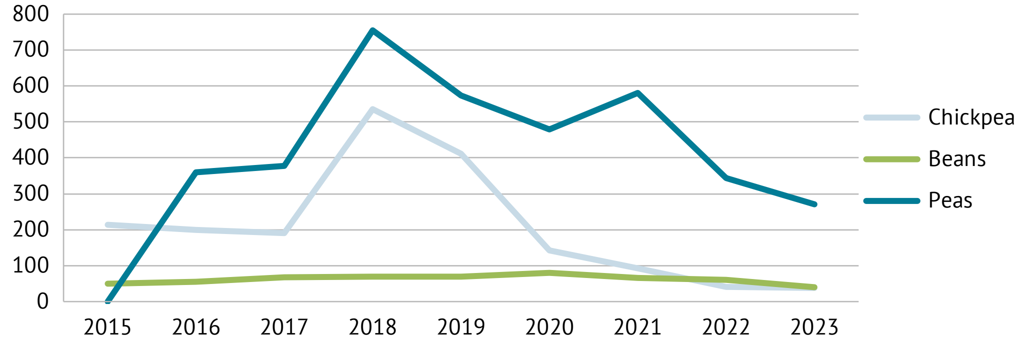

Figure 4. *Production of Ukrainian peas, chickpeas and beans, thousand tonnes*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

Analysing the export data, it is possible to argue that the overall trend of pea exports to Ukraine is declining. After stable exports in 2015-2018, pea exports declined sharply in 2019 and continued to decline until 2023, reaching 132 thousand tonnes, although there were some fluctuations in this process. Exports of beans also show some volatility, but the overall trend is upward. The volume of bean exports grew from 2015 to 2021 but then declined in 2022 to 13.4 thousand tonnes. However, in 2023, there was a slight recovery in bean exports to 14 thousand tonnes. (Fig. 5). Such fluctuations can be influenced by several factors, including internal and external factors such as yields, global market demand, tariffs, trade agreements and the war, which has significantly reduced legume acreage, yields and production.

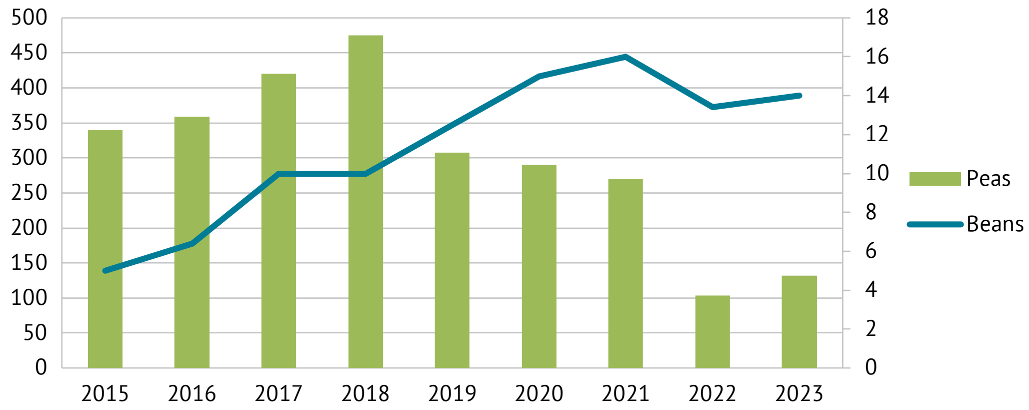

Figure 5. *Exports of peas and beans from Ukraine, thousand tonnes*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

In terms of legumes, the period from 2015 to 2023 is characterised by different price dynamics for chickpeas, beans, peas and soybeans. Chickpea prices remained stable for most of the period, with minor fluctuations in 2015-2017. However, in 2021, there was a significant increase in prices – up to 21.6 thousand UAH/t, which may be due to increased demand for chickpeas. Bean prices also remained stable for the majority of the period, with small price changes in 2019 and 2020. However, from 2021 to 2023, bean prices showed a slight increase to 33-35 thousand UAH/t, which may be due to increased demand or limited supply. Pea prices have remained stable for most years, with an increase in 2021-2023 to 8.1 thousand UAH/t. Soybean prices showed a stable trend for the majority of the period with slight fluctuations. However, from 2021 to 2023, soybean prices showed a slight increase to 17.2-17.4 thousand UAH/t, which may be due to the increased demand for this product for food or animal feed production (Fig. 6).

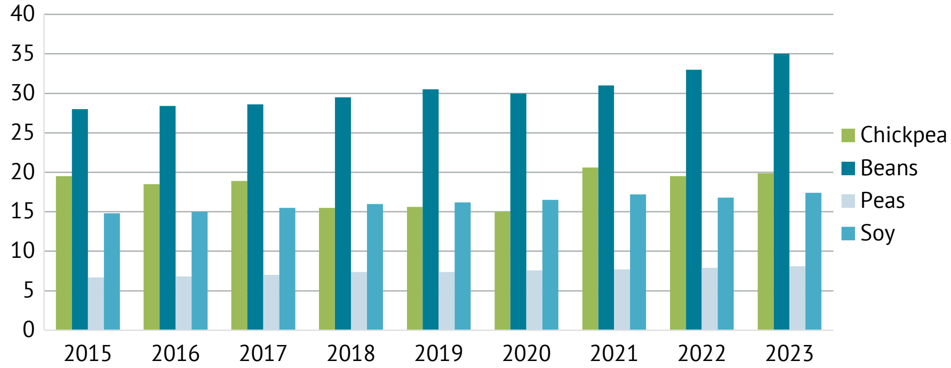

***Figure 6.** Price dynamics of legumes, thousand UAH/t*

***Source:** compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

A SWOT analysis was carried out to identify the strengths and weaknesses of the legume industry and to identify existing opportunities and threats (Table 2). It is worth noting that among the strengths is the fact that Ukraine has significant land resources and favourable natural conditions for growing legumes. This creates great opportunities for the development of this industry. Ukraine can use its legumes as an export commodity, which would expand markets and provide additional income for agricultural producers. Growing legumes helps maintain soil fertility and reduce erosion, which is important for sustainable agriculture and environmental protection. However, the disadvantages include the fact that legumes are subject to weather conditions, which can lead to crop instability and production losses. In some cases, legumes may be less technologically advanced than other crops, which may limit their productivity and competitiveness. Problems with marketing and sales of products in the domestic and foreign markets can be an obstacle to the development of the industry and reduce the motivation of farmers to grow legumes. However, the use of modern agricultural technologies and innovative approaches can increase the efficiency of legume cultivation and ensure more stable production, while the growing demand for Ukrainian legumes in foreign markets can create new opportunities for expanding exports and sales geography.

***Table 2.** SWOT analysis of legume growth in Ukraine*

Advantages	Disadvantages
Great potential for development Cultivation traditions Export potential Ecologic value	Dependence on weather conditions Low technology Sales problems
Possibilities	**Threats**
Growth in demand Implementation of new technologies Export development	Competition in the global market Negative environmental and climate change Uncertainty about the political and economic climate

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

Based on the research on the aspects of legume cultivation, the following strategic directions can be considered to increase the sustainability and development of Ukrainian agricultural production:

- investing in research and breeding of new varieties of legumes that are resistant to stressful conditions, diseases and pests, as well as have high yields and quality;
- the use of advanced agricultural technologies, such as precision farming and biological methods of pest and disease control, will help to increase yields and product quality;
- increasing the production of legumes for export to foreign markets will diversify sales markets and provide additional income for agricultural producers;
- increasing the consumption of legumes in the domestic market by focusing on their health benefits and properties will help develop the domestic market and increase the importance of these crops in the population's diet;

- supporting farmers in growing legumes by providing subsidies and financial support for the development of this industry will help to increase production;
- the development of modern storage and processing systems for legumes will help maintain their quality and provide additional added value.

These strategic directions will contribute to sustainable development and increase the productivity of Ukrainian legume production.

Thus, the overall analysis of the legume sector in Ukraine reflects a complex but promising area of the industry. Given the vast potential of land resources, favourable natural conditions and export opportunities, as well as challenges related to weather, sales and war, the development of legumes requires a comprehensive approach and the introduction of modern agricultural technologies. Continued investment and innovation will contribute to the sustainable development of the agricultural sector and ensure food security in the country.

DISCUSSION

In the Ukrainian agricultural sector, the cultivation of plant-based food products is an important industry that determines the quality and sustainability of the food supply. The favourable natural and climatic conditions, vast land area and long history of agricultural development provide a strong potential for efficient cultivation of various crops, including legumes. However, due to global changes, economic instability, and environmental and geopolitical difficulties, the current challenges facing the Ukrainian agricultural sector require careful consideration to ensure the sustainable development of plant-based food production (Rawtani *et al.*, 2022).

Legumes are valuable in global agriculture, providing valuable protein products to the world's population, as well as contributing to soil fertility and sustainable development of the agricultural sector. Legumes such as soybeans, peas, beans, lentils and others are important crops for human consumption and as animal feed. They are rich in protein, carbohydrates, vitamins and minerals and have significant potential for high-quality products. However, growing legumes requires an integrated approach and careful consideration of various aspects, including variety selection, tillage, fertilisation, weed, disease and pest control, and optimal harvest and storage times (Kebede, 2021; Freidenreich *et al.*, 2022). In this context, it is worth noting the most effective methods and strategies that will help farmers achieve high results and ensure a stable harvest of legumes. M. Behnassi & M. El Haiba (2022) addressed the environmental benefits of growing legumes and emphasised their important role in biodiversity conservation. The authors argue that legumes contribute to increasing the richness of vegetation cover and providing conditions for the development of various plant and animal species. This is considerable for maintaining ecosystems and preserving natural environments. Scientists also emphasise the restorative properties of legumes on soils, which helps maintain fertility and ecosystem stability. This contribution to biodiversity conservation makes legumes an important and environmentally sustainable component of agriculture.

In Ukraine, legumes are one of the most important crops. These crops are known not only for their high yields but also for their ability to fix nitrogen from the air and improve soil structure. These functions make legumes important components for supporting sustainable and resilient agriculture. Expanding the area under legumes can help improve soil quality, increase yields and reduce the use of chemical fertilisers, which will have a positive impact on environmental performance and economic efficiency of agriculture (Kulyk, 2019). In modern Ukrainian agriculture, growing legumes is becoming particularly important given their high economic value on the global market, which has encouraged agricultural enterprises and farms to expand the area under these crops and introduce modern cultivation technologies (Shikovets *et al.*, 2020). However, several specific aspects affect the cultivation of legumes in Ukraine and, thus, are noteworthy. These include climatic and soil conditions, availability of appropriate infrastructure, high competition with other crops, and problems with pests and diseases. Therefore, efficient legume crop production requires an integrated approach that includes modern agricultural technologies, research and careful production planning (Danko *et al.*, 2020; Roberts, 2021).

The study confirms the opinion of I. Irtyshcheva *et al.* (2023), who emphasise that in modern conditions, farmers need not only to increase the cultivation of legumes but also to ensure their sustainability and environmental safety. The authors also emphasise the strategic importance of this for ensuring food security and sustainable development of the country. Y. Wang *et al.* (2022) emphasise that in addition to increasing the volume of legumes grown, it is important to ensure their adaptability to current market requirements and environmental standards. The introduction of such crops can help improve soil quality, reduce negative environmental impacts and increase demand for environmentally friendly products, which is also highlighted in the study. Another proof of this and confirmation of the results obtained is the opinion of C. van der Giesen *et al.* (2020) and T. Glauben *et al.* (2022), who believe that the expansion of the area under organic legumes is becoming a key direction for the development of the agricultural sector. This is not only in line with global trends in ecological production but also increases the competitiveness of agricultural products on the international market. Moreover, similar data are demonstrated by Y. Wang *et al*. (2021) and L.M. Pörtner *et al*. (2022), according to which there is a gradual increase in the production of plant legumes in agriculture. Farmers and peasants are increasingly interested in using modern agricultural technologies, improving plant varieties and using land resources more efficiently. The development of new varieties of legumes can be used to improve yields, pest and disease resistance, and adapt to climate change.

Growing legumes in modern conditions also requires innovative strategies and modern approaches. According to the findings of E. Shahini *et al*. (2023), the introduction of agricultural intelligence and modern irrigation technologies increases the yield of legumes by 15% and reduces irrigation costs by 20%. In addition, modern genetically modified varieties provide high resistance to stressful conditions, which leads to improved quality of the products grown. L. Gutierrez *et al*. (2022) also consider the introduction of modern technologies, rational use of natural resources and expansion of the range of legume cultivation as key factors of efficiency and sustainability in this industry. Supporting innovation through financial support and the creation of specialised centres is an important step in the development of the sector, where advanced technologies are constantly being improved and introduced. I. Salim *et al*. (2019) point out the importance of considering socio-economic aspects, such as military conflicts, which have a significant impact on the agricultural sector due to loss of control over land, economic instability and mass migration. However, the increase in the value of legume exports indicates the successful adaptation of the Ukrainian agricultural sector to international market conditions, which is also confirmed by the study. Another confirmation of the study can be found in the statements of D. Fiott (2022) and J.H.P. Pires Eustachio *et al*. (2023), according to which adherence to the principles of sustainable use of natural resources and interaction between business entities expand prospects for legumes. Reducing the negative impact on the environment and avoiding the risks associated with market lop-sidedness are important aspects for the sustainable development of this industry. At the same time, the active development of export opportunities is a key element in attracting foreign investment and expanding markets. This opens up new opportunities for legume producers in the international market and increases the competitiveness of their products.

Summing up, it is possible to note that in the context of active development and transformation of the Ukrainian agricultural sector, the important role of legumes as a key element of the national economy cannot be underestimated. These crops not only ensure the stability of the economic situation in the country but also have a significant potential to influence global economic and environmental challenges. The identified strategic directions of development can significantly improve the state and prospects of legume production in Ukraine. These strategies, which focus on sustainability and coherent growth, are key to the sustainable and competitive development of the legume sector in the global economic environment. The inclusion of legumes in such strategies can significantly increase the level of development of the agricultural sector and contribute to the economic growth of Ukraine as a whole. In the global economic environment, stability and readiness to adapt are critical factors for successfully overcoming challenges and seizing opportunities internationally.

CONCLUSIONS

Legumes in Ukraine play an important role in agriculture and food security. The analysis of yields shows some stability and even an upward trend, especially in the case of soybeans. An analysis of the dynamics of soybean exports, production and processing suggests that despite fluctuations in volumes over the years, there is a general upward trend. In 2023, soybean exports reached their highest level of 3.6 million tonnes, compared to the lowest volume in 2021, which was only 1.4 million tonnes Soybean processing volumes increased, reaching their highest level in 2023, at 1.6 million tonnes as for peas, chickpeas and beans, their production in Ukraine showed different growth and decline trends during the period 2015-2023. Peas were subject to fluctuations in production, with the highest volume in 2018 at 755 thousand tonnes. Chickpea production was the highest in 2021 at 93.4 thousand tonnes, and beans in 2020 (65 thousand tonnes).

In the period from 2021 to 2023, prices for legumes in Ukraine showed steady growth. Thus, the price of chickpeas rose to 21.6 thousand UAH/t, the price of beans showed an increase to 33-35 thousand UAH/t, and the price of peas rose to 8.1 thousand UAH/t. The price dynamics of soybeans in Ukraine were stable with slight fluctuations, and in the period from 2021 to 2023, there was a certain increase in prices to the level of 17.2-17.4 thousand UAH/t, which indicates an increase in demand for these crops.

The SWOT analysis of legumes in Ukraine has highlighted several strengths and weaknesses, as well as identified opportunities and threats. For example, the cultivation traditions, export opportunities and environmental value of legumes create great potential for development. However, dependence on weather conditions, low technology, sales problems and other factors pose challenges to the sustainable development of the sector. In this context, investing in research and breeding of new varieties, use of advanced agricultural technologies, development of export and domestic markets, support for farmers and development of storage and processing systems are key strategies for achieving success in legumes. Further research is needed to analyse market trends and demand for legumes both in Ukraine and internationally to develop strategies for optimal production, marketing and export.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Аспекти вирощування зернобобових культур в Україні

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Анотація. Вирощування зернобобових культур в Україні є ключовим для сільського господарства та економіки, оскільки вони є стратегічними культурами для продовольчої безпеки, експортного потенціалу та сталого розвитку сільськогосподарського сектору. Мета дослідження полягала у вивченні поточного стану вирощування зернобобових культур в Україні та виявленні основних аспектів, які визначають їх виробництво. Для досягнення поставленої мети проаналізовано валовий збір, урожайність, посівні площі, динаміку експорту та цін таких зернобобових культур, як соя, нут, квасоля та горох за період 2015-2023 рр. Результати дослідження показали стабільність та потенційне зростання виробництва зернобобових культур в Україні. Незважаючи на зміни в рівні експорту, виробництва та переробки сої з року в рік, спостерігається загальний тренд їх збільшення. У 2023 році експорт сої досяг рекордного показника – 3,6 млн т, що є значним зростанням у порівнянні з найнижчим показником у 2021 році, коли було експортовано лише 1,4 млн т. Щодо гороху, нуту та квасолі, їх виробництво в Україні відображало тенденції коливання. Зокрема, максимум виробництва гороху припав на 2018 рік і становив 755 тис. т, виробництво нуту досягло найвищого рівня у 2021 році (93,4 тис. т), а квасолі – у 2020 році (65 тис. т). У період з 2021 по 2023 роки ціни на зернобобові культури в Україні показали стійке зростання, зокрема, ціна на нут становила 21,6 тис. грн/т, на квасолю – 33-35 тис. грн/т, на горох – 8,1 тис. грн/т. Цінова динаміка сої також показала зростання до рівня 17,2-17,4 тис. грн/т. Стратегічні напрями, визначені у дослідженні, вказують на необхідність інвестування у наукові дослідження, технологічний прогрес та інфраструктуру для забезпечення сталості у вирощуванні зернобобових культур

Ключові слова: експорт; посівні площі; урожайність; соя; нут; сільськогосподарське виробництво

UDC: 631.3
DOI: 10.56407/bs.agrarian/2.2024.21

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines

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Abstract. The research was aimed at investigating effective methods of surface strengthening of the working bodies of agricultural machines to increase their wear resistance and extend their service life. The study used surface hardening methods such as heat treatment, chemical and thermal processes, coatings, and mechanical methods. It has been shown that various methods of surface hardening significantly increase the wear resistance of working parts of agricultural machinery. The use of such heat treatment as induction hardening increased the resistance to wear due to localised heating and rapid cooling, which led to an increase in the hardness of the material. Chemical and heat treatment, including carburisation, nitrocementation and nitration, showed a significant improvement in surface layer hardness and increased corrosion resistance. Mechanical methods such as shot blasting and roller hardening have increased hardness and wear resistance by 30-50% due to plastic surface deformation. It has been

Article's History:
Received: 25.03.2024
Revised: 21.05.2024
Accepted: 11.06.2024

Suggested Citation:
Stavinskiy, A., Vakhonina, L., Martynenko, V., Mardziavko, V., & Rudenko, A. (2024). The use of surface strengthening to increase the wear resistance of working bodies of agricultural machines. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 21-32. doi: 10.56407/bs.agrarian/2.2024.21.

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proven that the use of surfacing and coatings of physical vapour deposition/chemical vapour deposition increases the durability of parts by 20-40%, which reduces operating costs and increases the productivity of agricultural machinery. The study examined approaches to enhancing the wear resistance of agricultural machinery's working parts, highlighting a notable issue: Ukrainian agricultural machinery often exhibits a shorter service life (1.2-2 times less) compared to imported counterparts. The analysis focuses on the reasons behind the wear and deterioration of cultivator teeth, with particular emphasis on how wear affects the size and shape of the working parts, resulting in decreased efficiency. The surface strengthening methods under study can be directly implemented in production to increase the durability and reliability of working parts of agricultural machinery, which would help to increase their efficiency and reduce operating costs

Keywords: carburisation; induction hardening; heat treatment; titanium nitride; diamond-like carbon coatings

INTRODUCTION

Agricultural machinery plays a key role in tillage, harvesting, and overall mechanisation of farming processes. Ensuring reliability and efficiency is therefore essential for the sustainable development of the agricultural sector. Increasing the wear resistance of these components not only reduces downtime for repairs, but also lowers operating costs, which is crucial for ensuring efficiency in modern agricultural markets. A significant problem in this area is the lack of a comprehensive approach to choosing the optimal method of surface quenching of agricultural machinery, considering specific tasks and operating conditions.

Agricultural machinery is essential for tillage, harvesting, and general mechanisation in agriculture. The reliability and efficiency of these machines are critical for the sustainable development of the agricultural sector. Increasing the wear resistance of working bodies not only reduces machine downtime due to repairs, but also reduces operating costs, which is important for cost-effective farming in the modern market (Aramide *et al.*, 2021; Tekeste *et al.*, 2022). One of the main problems in the field under study is the lack of an integrated approach to choosing the optimal method of surface hardening of agricultural machinery, considering the specifics of work and operating conditions.

The study by S. Kumar *et al.* (2024) demonstrates the use of chemical and thermal methods to increase the corrosion resistance of working bodies. The study highlights the effectiveness of combining chemical and thermal processes to protect metal surfaces from corrosion in agriculture. H. Huang *et al.* (2022) focus on mechanical hardening techniques such as shot blasting and their impact on wear resistance. The study shows that the use of mechanical hardening methods can significantly increase the strength and service life of agricultural machinery and tools. The study by Y. Hu *et al.* (2021) is devoted to the investigation of the efficiency of induction hardening in increasing the hardness of metal surface layers. The study points to the potential of induction hardening to increase the strength and wear resistance of metal parts used in agriculture. R. Mallick *et al.* (2022) defines the use of PVD (physical vapour deposition)/CVD (chemical vapour deposition) coatings to protect working bodies from abrasive wear. Their study confirms the effectiveness of using thin coatings to increase the duration of operation of agricultural machinery in conditions of aggressive wear.

The research conducted by Y. Wang *et al.* (2022) emphasizes the impact of different parameters in the carburization process on the structure and properties of the surface layer. The study provides important information for optimising carburisation processes to improve the wear resistance of tools in agriculture. The study by R. Dalcin *et al.* (2022) evaluates the effectiveness of nitration in increasing the hardness and improving the wear resistance of metal parts. The work demonstrates that nitration can be an important method for strengthening the surface layers of materials in agriculture. T.-T. Nguyen & T.-M. Le (2021) investigate the effect of roller hardening parameters on the mechanical properties of the surface. The study shows that optimising the parameters of roller hardening can significantly increase the strength and wear resistance of materials used in the production of agricultural machinery.

A. Kostin & V. Martynenko (2017) describe the development of new materials for surfacing coatings that improve the wear resistance of agricultural machinery. The study confirms the importance of developing new technologies in production aimed at increasing the service life of equipment in agriculture. The study by Z. Sydow *et al.* (2021) provides data on the impact of various surface hardening methods on the performance of agricultural technologies. The paper highlights the need for a systematic approach to the selection of strengthening methods to achieve optimal results in improving the efficiency and duration of equipment in the agricultural sector. There is a need to further investigate the impact of a combination of different strengthening methods on the economic efficiency and durability of agricultural machinery in different climatic and geographical conditions. But there is a need to further investigate the impact of a combination of different strengthening methods on the economic efficiency and durability of agricultural machinery in different climatic and geographical conditions.

The purpose of the study was to investigate effective methods of surface hardening of the working bodies of agricultural machines to significantly increase their wear resistance and extend their service life. Objectives of the study:

1. Evaluation of the impact of various heat treatment methods, such as induction hardening and tempering, on the mechanical characteristics of the surface layers of agricultural machinery parts.

2. Investigation of the effect of chemical heat treatment, such as carburisation and nitriding, on improving the wear and corrosion resistance of working parts.

3.Comparison of different approaches to mechanical surface quenching, such as shot blasting and roller quenching.

MATERIALS AND METHODS

This study thoroughly investigated the effect of various heat treatment methods on the surface layers of components used in agricultural machinery. The study focused on quenching, tempering, and induction hardening processes.

The quenching process involved heating the metal to high temperatures, followed by rapid cooling, which significantly increased the hardness and wear resistance of the material. After that, tempering was used to relieve internal stresses that occurred as a result of quenching and further affect the mechanical properties of the surface layer. Induction hardening used high-frequency currents to heat certain areas of metal, selectively hardening those that were exposed to the highest mechanical stresses during operation.

Analysis of various methods of chemical and heat treatment, such as carburisation, nitrocementation, and nitriding, showed their effect on the properties of metal parts of agricultural machinery. Carburisation carried out at high temperatures saturated the surface layer with carbon, which significantly increased the hardness and wear resistance of the material. Soft nitriding and nitriding processes saturated the surface layer with nitrogen, increasing corrosion resistance and creating a hard surface that can withstand the harsh operating conditions of agricultural machinery.

The study also discussed various methods of coating the surface of agricultural machinery. Special attention was paid to thermal sputtering, as well as physical vapour deposition and chemical vapour deposition methods. Thermal spraying was used to create a layer of wear-resistant material on the working surfaces of agricultural machinery. This allowed increasing their durability and reducing wear under abrasive operating conditions. PVD and CVD coatings were used to form thin but very strong films. For example, titanium nitride and diamond-like carbon coatings have been used to protect against mechanical wear and effectively protect surfaces from corrosion. These measures significantly extended the service life of agricultural machinery, providing increased reliability and efficiency in various operating conditions.

All the figures used in the study were taken from the work of L. Tulaganova *et al.* (2022) and were used to visualize changes in the size and shape of the working parts of agricultural machines under the influence of various methods of surface hardening. The study focused on the selection and substantiation of methods aimed at improving the wear resistance and durability of components of tillage units, considering factors such as design, technology, and materials science. These improvements were aimed at increasing wear resistance and performance while reducing the production costs associated with machine components. The study was conducted at the Institute of Agricultural Machinery named after I. Petrov in Ukraine. Various models of tillage machines were used, including the Titan-300 model from Agrotechnica, Italy, and the Agroforce-500 model from Agroforce, Poland. The study was conducted in 2023 on an area of about 500 hectares. Conditions included high soil moisture, uneven structure, and large differences in the composition of soil masses. The significant wear and tear these machines were subjected to highlighted the important factors contributing to wear. Subsequently, these factors gradually changed the size and shape of the tillage unit, which eventually led to its functional deterioration (Figs. 1, 2).

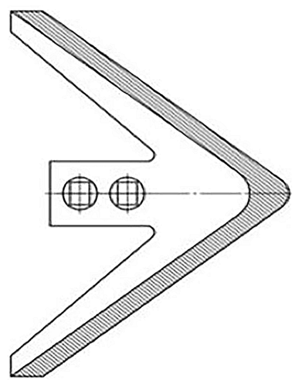

Figure 1. *Profile changes due to wear and tear*
Source: *L. Tulaganova et al. (2022)*

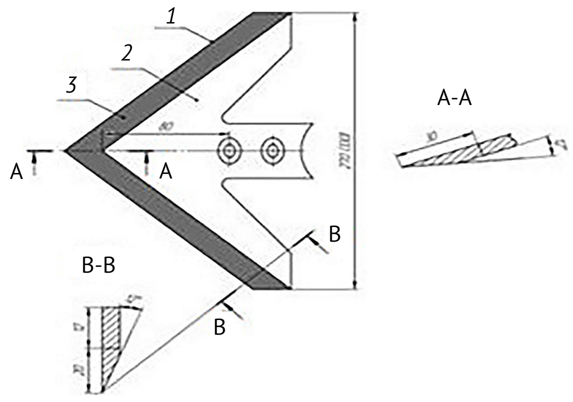

Figure 2. *Schematic representation of the process of restoring the sweep blade of a cultivator*
Notes: *1 – surface area for weld overlay; 2 – component requiring restoration; 3 – position of the corner plate*
Source: *L. Tulaganova et al. (2022)*

The study of profile changes due to wear determined the best methods for restoring or replacing components to ensure a long service life and maximum productivity in working conditions. A schematic representation of the process of restoring the sweep blade of the cultivator clearly showed what steps or techniques are used to restore the working surface of the blade to ensure that it once again performs at its optimum.

RESULTS

The use of surface hardening to improve the wear resistance of working parts of agricultural machinery is a critical factor. Increased wear resistance can extend the service life of components, reduce maintenance and repair costs, and improve the overall efficiency of agricultural machinery. Heat treatment is the main method of surface hardening of metal parts and is widely used in various industries. One of the most common methods is quenching followed by tempering. During quenching, the material is heated to a high temperature, causing structural changes that increase its hardness and wear resistance. This process is then followed by rapid cooling to achieve the desired microstructure of the surface layer. Induction hardening uses high-frequency currents to locally heat the surface of the component. This technology allows hardening only the target surface, minimising the impact on the rest of the material. The effectiveness of induction hardening lies in its ability to achieve high hardness and wear resistance exactly where it is most needed. This makes the method particularly attractive to tool and component manufacturers who place high demands on accuracy and reliability. Heat treatment, which includes quenching and induction hardening, is a highly effective method for improving the mechanical properties of the surfaces of parts, improving wear resistance and overall durability. This approach is of great importance in modern industry (Aswad *et al.*, 2021).

Chemical heat treatment is the most important method of strengthening the surfaces of metal parts and is widely used in industry due to its ability to improve their mechanical and protective properties. The key method in this category is carburisation. During the carburisation process, the metal surface is saturated with carbon at high temperatures in the presence of carbon-rich substances. This process forms a high-carbon layer, which significantly increases the hardness and wear resistance of the surface layer. Nitrocementation is a more complex process that involves saturating the surface with carbon and nitrogen simultaneously. This method allows creating a surface layer with high hardness and improved corrosion resistance, which makes it particularly valuable for parts used in aggressive environments. Nitriding, in turn, is the directed saturation of the surface with nitrogen without adding carbon. This process forms a hard and wear-resistant surface layer, which ensures the durability and reliability of metal parts in conditions of intensive operation. Chemical and heat treatment, including carburisation, nitrocementation, and nitriding, are effective surface hardening methods that can significantly improve the functional properties of metal parts. These treatments increase wear resistance and protect against external influences, which makes them indispensable in modern industry (Kantoríková *et al.*, 2021).

Coatings play a crucial role in the surface hardening of metal parts designed to work in heavy wear and harsh environments. One of the methods is to apply a wear-resistant layer to the surface of the part by welding. This technology significantly improves mechanical properties such as hardness and wear resistance by using materials rich in chromium and hard carbides. Another important approach is to apply PVD and CVD coatings. These approaches allow applying thin, strong, and wear-resistant coatings to the surface of parts. For example, titanium nitride and diamond-like carbon coatings provide excellent protection against mechanical wear and corrosion, making them ideal for applications where high strength and efficient equipment functionality are required. Coatings such as surface coating and PVD/CVD techniques are an effective strategy for improving the performance of metal parts, increasing their durability, and reducing maintenance costs in various industries.

Mechanical methods of surface hardening play a key role in improving the wear resistance and durability of metal parts used in conditions of intensive operation and high mechanical loads. One of these methods is shot blasting, which consists in a directed action on the surface of the shot jet. This process leads to intense plastic deformation of the material, which helps to improve its mechanical properties, including increasing hardness and wear resistance. Shot blasting is effectively used to prepare the surface before applying coatings or to improve the adhesion between parts. In addition, roller hardening is the process of plastic deformation of the metal surface when rolling with special rollers. This method improves the mechanical properties of the surface layer, such as hardness and wear resistance, making it particularly useful for parts exposed to abrasive materials and high mechanical loads. Mechanical hardening techniques, such as shot blasting and roller hardening, play an important role in modern industry, providing increased durability and reliability of metal parts, which ultimately helps to reduce maintenance costs and improve process efficiency (Unal *et al.*, 2022).

Surface quenching is a highly efficient technology that can significantly improve the properties of metal parts used in agricultural machinery. By increasing the wear resistance and hardness of working elements such as ploughshares and cultivator blades, this method can significantly extend their service life, reduce the frequency of replacements and repairs, and reduce operating costs. Increased reliability and durability of parts contribute to more stable and productive operation of agricultural machines, minimising downtime and ensuring continuity of tillage and harvesting processes. Thus, the introduction of surface hardening methods is a key aspect of optimising production processes in the agricultural sector, which contributes to improving the efficiency and economic profitability of agricultural production. Surface hardening plays a key role in agricultural machinery, where high wear resistance and reliability of working bodies are critical for efficient operation (Yadav *et al.*, 2023). For example, when strengthening ploughshares and blades of ploughs and cultivators, their service life is significantly increased, which reduces the time for replacement and repair, and increases the productivity of tillage. In the case of seed drills and harvesters, reinforcing the coulters and blades helps to ensure more precise and even sowing and harvesting, which is important for ensuring high quality agricultural products. Combine harvesters also benefit from strengthening elements in contact with soil and plant material, such as drums and threshing mechanisms, which improves their performance and durability in heavy-duty environments. The introduction of the above-mentioned surface quenching methods can significantly improve the performance of agricultural machinery parts, which ultimately leads to an increase in the efficiency and reliability of agricultural production.

In the course of the study, the wear patterns observed on the working components of the cultivator were studied and evaluated. The blades work at a depth of 6 to 15 cm, colliding with weeds that stick to the blades during processing. The blade tip is subjected to the most significant wear, resulting in a reduction in strength along the blade edge. Once the linear wear at the tip reaches 30 mm, both the blades and bolts experience wear, leading to heightened traction resistance and uneven working depth (Lorenzi *et al.*, 2023). The wear of the hoe blades primarily depends on several key factors. One of the critical factors is the distribution of soil particle size, which determines its abrasive nature. Changes in soil composition can significantly affect this characteristic and therefore affect the rate of blade wear during processing. Another important factor is the soil density. A higher soil density increases the pressure exerted on the blade during operation. This increased pressure accelerates wear around the edges of the blade, thereby compromising their long-term durability and operational efficiency. The choice of materials for cultivator blades significantly affects their physical and mechanical properties (Neill *et al.*, 2022). Blades made of materials with high hardness and exceptional wear resistance usually have a longer service life and greater abrasion resistance. In contrast, blades made of softer or less durable materials tend to wear out faster, resulting in higher maintenance costs and lower tillage efficiency. Therefore, understanding and effectively addressing these factors is crucial to optimise the durability and performance of hoe blades for agricultural purposes.

When restoring these components, it's crucial to enhance the hardness and wear resistance of both the tip and the blade. This improvement significantly extends the service life of the working components of agricultural machinery used for tillage. Various methods are used to achieve this hardening. Heat treatment is a common technology that can change the properties of a material to increase hardness and wear resistance. Another approach is to use bimetallic compounds, such as plating or double-layer steels, which create a layered structure that combines the strength of one material with the wear resistance of another. In addition, spraying wear-resistant coatings effectively adds a protective layer to the surface of parts, providing protection against abrasive wear. Solid alloy plating involves welding or gluing solid materials to the surface of parts to increase their hardness and wear resistance. Ultimately, the vibration hardening of the blades in the cutting elements uses mechanical vibrations to increase the surface hardness of the material, improving its ability to resist wear and extend its service life in agricultural conditions. These hardening methods are crucial for maintaining and improving the efficiency and reliability of agricultural tillage equipment by extending the service life and improving the productivity of the main working components.

In the course of the study, the dynamics of wear of the blades and tips of boom blades under various hardening methods were considered, which is described in detail in Table 1. Based on the outcomes of these hardening techniques, the restoration approach involving welded 45 G steel corner plates with surfacing and vibration-point hardening demonstrated minimal wear while operating the cultivator across 500 hectares. In addition, an analysis of total blade wear was performed, which showed that adhesive wear is 25% of total wear, surface fatigue is 8%, corrosion wear is 2%, and abrasive wear is 20%. It is noted that as the teeth wear out, traction resistance increases, which, in turn, reduces the efficiency of the machine and leads to an increase in fuel consumption by 15-20%.

Table 1. *Signs of wear detected on the edges and tips of the sweep blade*

Choice of tines to use	Cultivator hours worked, ha	Average wear of blades, mm	Average wear of the sweep, mm
New teeth made of 65 G grade steel	500	7.345	22.467
New vibration-reinforced teeth made of 65 G grade steel	500	3.875	14.712
Repaired by welding angle plates made of 45 G steel with enamel surfacing	500	4.652	16.391
Rehabilitated through welding angle plates of 45 G steel with enamel surfacing and vibration hardening	500	2.784	10.126

Source: *compiled by the authors*

Heat treatment increases the strength of the part, but usually does not reach a sufficient quenching depth (0.4-1.2 mm), which leads to relatively low wear resistance (total wear 4.16-11.4 mm). Technological processes utilizing vibration entail subjecting the tool surface to numerous micro-impacts. This method enhances the material of the part, thereby boosting its fatigue strength and resistance to wear. The process of restoring sweep blades and ploughshares includes a structured sequence of technological operations. It starts with cleaning the surface to remove dirt and preparing parts for inspection and sorting, identifying areas that require attention. Next, the worn sections are removed, and depending on whether the part is a cultivator tooth or a ploughshare, corner plates or slats for restoring structural integrity are attached to it. Then the grooves are turned and a surfacing material is applied to increase durability. The cutting edge is carefully sharpened to restore optimal functionality. An important step is vibration hardening, in which the part is treated with micro-shocks to improve its hardness and resistance to fatigue and wear. Ultimately, strict quality control measures are applied to ensure that restored parts meet performance standards before they are returned to service. This thorough process is aimed at extending the service life and improving the efficiency of agricultural machinery components.

After processing 500 hectares, the blade exhibited wear rates of 0.0174 mm/ha for the initial type and 0.0074 mm/ha for the fourth improved type. Likewise, the tine experienced wear rates of 0.0549 mm/ha for the initial type and 0.0227 mm/ha for the improved fourth type. Most failures in agricultural machinery (up to 80%) are caused by mechanical wear caused by abrasion and corrosion, while fatigue failures account for 20-30% of component problems. Corrosion occurs due to the interaction of mechanical components between materials and their environment, which leads to undesirable deterioration of the surface. Abrasive wear is regarded as one of the most hazardous and destructive forms of wear, frequently resulting in catastrophic failures of components. The rate of wear largely depends on the hardness of the abrasive material, and the size and shape of the abrasive particles. Total material loss due to wear can be classified as follows: 15% of wear, 15% of cracks, 55% of surface damage, 15% of material cost loss, and 15% of corrosion. The overall wear distribution consists of 25% adhesive wear, 8% surface fatigue, 2% corrosion wear, and 20% abrasive wear. However, approximately half of all wear issues are attributed to abrasion. Figures 3 and 4 present the results of statistical analysis on the wear resistance and durability of assembled parts and components.

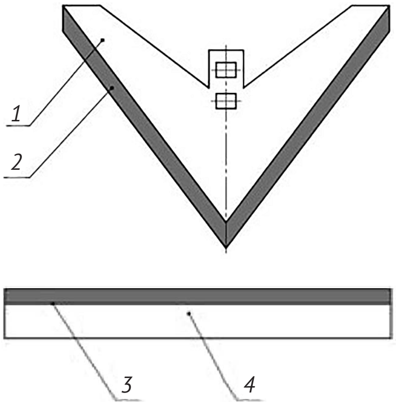

Figure 3. *Cultivator rack diagram*
Notes: *1 – rear surface of the working area; 2 – blade region; 3 – hardened area with enhanced blade hardness towards the rear; 4 – factory-standard hardness zone*
Source: *L. Tulaganova et al. (2022)*

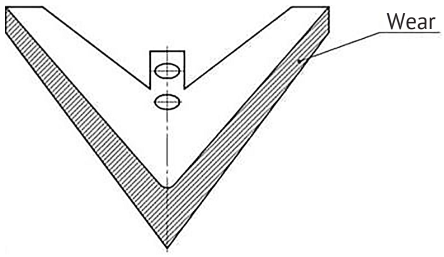

Figure 4. *Example of a geometric imbalance of a tool*
Source: *L. Tulaganova et al. (2022)*

As the workpieces wear out, their cutting edges become less sharp. Blunting results in the formation of reverse chamfers on the cutting edge and drawbar, impacting the consistency of digging depth, drawbar shape, and blade width adversely. Dulling the blade increases traction resistance, decreases performance, and correlates with a 15-20% rise in fuel consumption (Fig. 5).

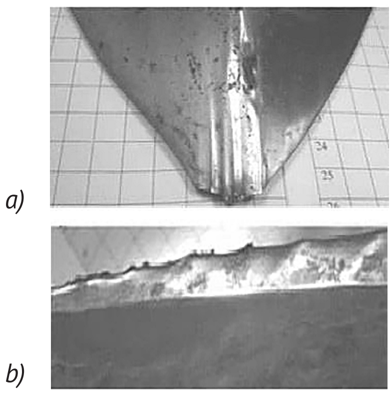

Figure 5. *The wear of the sweep blade encompasses*
Notes: *a) – altering the sweep's shape; b) – modifying the shape and width of the prong blade*
Source: *L. Tulaganova et al. (2022)*

In 2023, tillage tools were typically made of 65 G carbon steel, which was heat-treated to achieve a hardness of 45-50 HRC (Rockwell C Scale Hardness) (Liao *et al.*, 2022). This process ensures the impact strength of the tools. Techniques such as induction surface treatment, plasma spraying, flame surface treatment, and coating are commonly used to increase the durability of these tillage tools. These methods effectively improve the wear resistance of components exposed to abrasive impacts and wear.

DISCUSSION

Enhancing the wear resistance of agricultural machinery's working components is essential for ensuring the equipment operates efficiently and remains durable over time. In agriculture, the working bodies of machines are subjected to intense loads and abrasive wear when interacting with soil and plant residues. The use of surface hardening methods can significantly improve the performance of parts, reduce maintenance and repair costs, and increase the overall productivity of equipment.

The study conducted by A. Gulyarenko & M. Bembenek (2022) also discussed this aspect, concluding that enhancing the wear resistance of agricultural machinery's working components is crucial for maintaining efficient and durable performance in agricultural settings. These working bodies are subjected to significant loads and abrasive wear when interacting with soil, stones, plant residues, and other materials in the field. As a result of this impact, their surfaces can wear out quickly, which reduces their productivity and requires frequent maintenance or replacement. Also in the study conducted by C.E. Okafor *et al.* (2023), it was noted that the use of surface hardening techniques plays a crucial role in improving the performance of working bodies. These methods may include heat treatment to increase the hardness and wear resistance of the material, spraying or surfacing of special coatings to protect the surface from abrasive effects, and induction hardening or vibration hardening to improve the mechanical properties of the material, which is consistent with the results of this study.

The working parts of agricultural machines, such as ploughshares, seed drills, cultivator tines and harrow discs, are in constant contact with abrasive soil particles and crop residues. Due to intensive wear, their efficiency decreases, which requires frequent replacement or repair. This leads to downtime of equipment and increased operating costs. Increasing the wear resistance of these elements reduces costs and increases productivity. A study conducted by A. Sobirjonov *et al.* (2021) further explored this topic, affirming that enhancing the wear resistance of agricultural machinery's working components is pivotal in agriculture, given their constant exposure to abrasive elements such as soil, rocks, and plant residues. Working elements such as ploughshares, seed drills, cultivator tines and harrow discs are the main elements that determine the efficiency and productivity of agricultural machinery. Their wear and tear and the need for regular replacement or repair significantly increase operating costs and can lead to equipment downtime, which negatively affects the production processes and profitability of agricultural enterprises.

Y. Saygili & B. Cakmak (2023) also investigated that the use of modern surface hardening techniques can significantly improve the characteristics of these working bodies. For example, heat treatment to increase the hardness of the material, spraying special coatings or using bimetallic compounds help to increase wear resistance and extend the service life of components. This not only reduces the frequency of replacements and repairs, but also reduces operating costs, which is an important aspect in the context of modern agriculture, focused on improving efficiency and resilience to economic challenges. Therefore, dedicating resources to enhance the wear resistance of agricultural machinery's working components is a critical measure to streamline production processes and boost overall profitability in the agricultural sector. It is worth noting that the use of methods to increase wear resistance plays an important role in agriculture, helping to reduce costs and increase the efficiency of agricultural machinery.

Wear-resistant coating spraying uses materials such as carbides, nitrides, and oxides to create coatings that are resistant to abrasive wear by thermal and vacuum spraying. This aspect has attracted the attention of many researchers, including J. Liu *et al.* (2021), who emphasise that surface hardening techniques play an important role in improving the durability and efficiency of metal parts subject to intense wear. One of the main methods is heat treatment, which includes quenching, carburisation, and nitrocementation. Quenching increases the hardness of the metal by rapidly cooling after heating, making it more resistant to wear. However, this process can make the material more brittle, which requires a balance between hardness and ductility.

B. Białobrzeska *et al.* (2021) concluded that laser hardening is a more modern method that allows local changes in the properties of the metal surface without changing its basic structure. This process is particularly effective for strengthening critical areas where high wear resistance is required. Plasma surfacing creates a wear-resistant coating by applying a layer of solid material to the surface of the part, which increases its resistance to abrasive wear and improves the adhesion of the coating to the base material. These results support the above study, as these methods not only increase the service life of parts, but also reduce operating costs by reducing the frequency of replacements and repairs, which is important for the economic efficiency of agricultural and industrial enterprises.

The advantages of surface hardening are increased service life of parts, which reduces the frequency of their replacement and repair and reduced operating costs, as less wear and tear on parts leads to lower maintenance and replacement costs, which is especially important for farmers and agricultural enterprises. Increased productivity: reliable and wear-resistant working elements ensure smooth operation of machinery, which contributes to increasing the overall productivity of agricultural operations. E. Benami *et al.* (2021) investigated this phenomenon, noting that surface hardening plays a key role in agriculture, where the working bodies of agricultural machinery are subjected to significant mechanical and abrasive loads. The use of methods such as quenching, plasma spraying and chrome plating significantly increases the service life of parts. This is especially important for farmers and agricultural enterprises, where the reliability and durability of agricultural machinery directly affect production efficiency.

Moreover, P. Chen *et al.* (2021) investigated that less wear on the working bodies of agricultural machinery leads to a decrease in the frequency of replacements and repairs, which reduces operating costs and improves the overall economic efficiency of agricultural production. The longer service life of parts also helps to increase the productivity of agricultural operations, ensuring smooth operation of machinery in the field and increasing overall agricultural output. Data on surface hardening and its impact on agricultural machinery confirm the main points outlined in the previous section. Strengthening the surface of the working bodies significantly increases their wear resistance, which leads to a decrease in the frequency of replacements and repairs. This reduces operating costs and increases the overall productivity of agricultural production. Thus, the use of surface hardening methods is a key factor for ensuring efficient and long-lasting operation of agricultural machinery.

The study by H. Pekşen & A. Kalyon (2021), which also showed that increased wear resistance of working bodies reduces the likelihood of downtime and increases the productivity of agricultural operations. Farmers and agricultural enterprises can save on operating costs, as less wear and tear on parts requires fewer resources to replace and repair them. This is especially important in conditions when the efficiency of using agricultural machinery directly affects the competitiveness and sustainability of the agricultural sector, contributing to its development and modern modernisation. Comparing the data obtained in the course of research, the use of surface hardening methods significantly reduces the rate of wear of the working bodies of agricultural machinery. This increases the interval between replacement of parts, saving on maintenance and increasing the reliability of the equipment. Improved wear resistance also helps to improve the production characteristics of machines, reducing friction and increasing the overall productivity of the agricultural process.

Enhancing the wear resistance of agricultural machinery's working components through surface hardening is essential for achieving efficient and durable performance. Under conditions of heavy loads and abrasive wear, methods such as heat treatment, laser hardening, plasma surfacing, chrome plating and spraying of wear-resistant coatings significantly improve the performance of parts. This leads to an increase in the service life of working bodies, a reduction in operating costs, and an increase in the overall productivity of agricultural machinery. The introduction of surface hardening technologies contributes to increasing the competitiveness and sustainability of the agricultural sector, ensuring the cost-effectiveness and reliability of the use of agricultural machinery.

CONCLUSIONS

Surface hardening plays a crucial role in contemporary agriculture, particularly in enhancing the durability of operational parts within agricultural machinery. This method covers various methods, such as quenching, plasma spraying, and laser quenching, which significantly improve the physical and mechanical properties of component surfaces. Increasing the wear resistance of working parts reduces the frequency of maintenance and lowers the economic costs associated with agricultural machinery by increasing the intervals between replacement of parts. This is especially important in intensive use scenarios where reliable and durable equipment is essential for processing large areas. Surface hardening technology also helps to increase the overall productivity of agricultural work. Increased wear resistance allows the working elements to operate efficiently for a longer time, thereby reducing downtime and improving the quality of tillage processes. Increased wear resistance helps to mitigate the adverse impact on the environment. By reducing the need for replacement and repair of agricultural machinery components, resource consumption is reduced, which, in turn, reduces the overall carbon footprint and environmental impact of agricultural operations.

The paper considered modern technological processes of repair of working bodies of cultivators and identified the main factors that limit their wear resistance and prevent extending their service life. Improving the wear resistance of cultivator parts is crucial both to reduce metal consumption and improve maintenance of agricultural machinery, but also to effectively meet operational requirements. Studies show that the most significant wear occurs on the nose and blade of the cultivator teeth, which directly affects productivity. Key technological methods are aimed at surface hardening without changing the design of these working elements. Thus, the inclusion of surface reinforcement technology in the production and maintenance of agricultural machinery is essential to increase productivity, reduce costs, and improve the overall sustainability of the agricultural sector.

This study, however, include a limited number of examples of the use of specific technologies in different climatic and soil conditions, which may limit the overall applicability of the results obtained. Further research should be aimed at investigating the impact of various surface hardening methods on the energy efficiency and economic profitability of agricultural machinery operation. It is important to assess the costs of using and operating these methods, and their impact on energy consumption and component life. This will help develop recommendations for manufacturers on choosing the most efficient and cost-effective methods to improve the performance of work surfaces.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Використання поверхневого зміцнення для підвищення зносостійкості робочих органів сільськогосподарських машин

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Анотація. Дослідження було спрямоване на вивчення ефективних методів поверхневого зміцнення робочих органів сільськогосподарських машин для підвищення їхньої зносостійкості та продовження терміну служби. У ході дослідження використовувалися методи поверхневого зміцнення, такі як термічна обробка, хіміко-термічні процеси, покриття та механічні методи. Було показано, що різні методи зміцнення поверхні значно підвищують зносостійкість робочих частин сільськогосподарської техніки. Використання такої термічної обробки як індукційне загартування дозволило підвищити стійкість до зношування завдяки локалізованому нагріву і швидкому охолодженню, що призвело до збільшення твердості матеріалу. Хіміко-термічна обробка, включаючи цементацію, нітроцементацію та нітрування, продемонструвала значне покращення твердості поверхневого шару та підвищення корозійної стійкості. Механічні методи, такі як дробоструминна обробка та коткове зміцнення, збільшили твердість та зносостійкість на 30-50 % за рахунок пластичного деформування поверхні. Було доведено, що застосування наплавлення та покриттів фізичного осадження з парової фази/ хімічного осадження з парової фази збільшує довговічність деталей на 20-40 %, що знижує експлуатаційні витрати та підвищує продуктивність сільськогосподарської техніки. У дослідженні розглядалися методи підвищення зносостійкості робочих частин сільськогосподарської техніки, при цьому наголошувалося на значній проблемі, пов'язаній з тим, що українські сільськогосподарські машини часто мали більш короткий термін служби (в 1,2-2 рази) порівняно з імпортними аналогами. Проаналізовано причини зносу та погіршення стану зубів культиватора, приділяючи особливу увагу впливу зносу на розмір та форму робочих частин, що призводило до зниження їх ефективності. Вивчені методи зміцнення поверхні можуть бути безпосередньо впроваджені у виробництво для збільшення довговічності та надійності робочих частин сільськогосподарської техніки, що сприятиме підвищенню їхньої ефективності та зниженню експлуатаційних витрат

Ключові слова: цементація; індукційне загартування; термічна обробка; нітрид титану; алмазоподібні вуглецеві покриття

UDC: 631.51.021:[631.43/.445.4+631.55:633.15]
DOI: 10.56407/bs.agrarian/2.2024.33

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

Influence of primary tillage on some soil fertility indicators and corn yield

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Abstract. Cultivated soils are constantly under stress, in particular, from anthropogenic pressure due to their tillage. At the same time, climate change, moisture deficit, trends in crop rotation and improved crop tillage technologies encourage farmers to pay more attention to tillage systems. In addition, this element of technology plays a significant role in ensuring the sustainability of the entire agrophytocenosis. The aim of the study was to determine the effectiveness of different tillage practices on certain soil fertility indicators and corn yield. The research was carried out in 2021-2023 at the Dokuchaevske Experimental Field of the State Biotechnological University, which is located in the Left-Bank Forest-Steppe zone of Ukraine. The experimental design includes the study of different tillage methods: ploughing with PLN-4-35 at 25-27 cm (control); chisel local tillage with PC-2.5 at 33-35 cm; moldboardless tillage with PRN-31000 at 33-35 cm and discing with BDM-2.5 at 10-12 cm. The reaction of the soil to the main tillage in corn crops was determined through its main water and agrophysical parameters: moisture content, density and hardness. The results of the research showed that the condition of typical chernozem is almost the same after ploughing and moldboardless tillage with the PRN-31000 ("paraplough"). A slight increase in the density of the arable soil layer was found after the application of chisel and discing tillage. All tillage options created favourable conditions in the soil, as its hardness in the 0-20 cm soil layer was in the range of 13.3-15.1 kg/cm^2. In corn crops, moisture reserves in the one-metre layer did not differ by tillage options. However, there was a tendency for its decrease in the variants with chisel and discing tillage compared to ploughing. For all variants of soil tillage, compared to ploughing, there was a significant decrease in corn grain yield. The practical significance of the results obtained is to optimise the regulation of water and physical properties of typical chernozem with the achievement of soil protection technologies and stabilisation of corn grain yields in the context of climate change and variability of modern production

Keywords: soil texture density; moisture reserves; soil hardness; yield; row crops; ploughing; moldboardless tillage

INTRODUCTION

The study of the effectiveness of basic tillage methods in corn tillage is a topical issue due to the ambiguous reaction of the crop to the replacement of ploughing and minimisation of tillage. Climate change and the modernisation of the current state of technology with the use of high-performance hybrids, new forms of

Article's History:
Received: 23.02.2024
Revised: 27.04.2024
Accepted: 11.06.2024

Suggested Citation:
Dolia, S., & Shevchenko, M. (2024). Influence of primary tillage on some soil fertility indicators and corn yield. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 33-41. doi: 10.56407/bs.agrarian/2.2024.33.

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fertilisers and plant protection products have prompted research in this area. In particular, a comparative analysis of the intensive use of traditional tillage methods with current technologies aimed at resource conservation and adaptation used in agriculture should be carried out. At the same time, their impact on soil fertility should be taken into account. The structural condition of the soil, moisture reserves, soil density, nutrient regime, etc. are critical for maintaining crop sustainability and ensuring the productivity of technologies.

Corn is one of the world's major food crops, but it is highly susceptible to high temperatures and drought, with yield losses ranging from 17 to 60% (Tandzi *et al.*, 2019). In order to ensure high productivity of this crop, it is necessary to comply with the growing conditions it requires (Dehtiarova, 2022). In this regard, the agrophysical characteristics of the soil (hardness, density of the soil), weediness of crops, and water regime, which depend on tillage and weather conditions, are of great importance. Soil tillage is an important agricultural practice that affects soil properties and leads to the creation of a complex ecosystem in the soil. At the same time, tillage methods can cause soil stress, which manifests itself through the deterioration of water and agrophysical parameters, etc.

The degree of influence of tillage on the agrophysical properties of the soil is determined by the type, depth and methods of tillage. K. Acquah & Y. Chen (2022) noted that in order to create optimal conditions for growing crops, it is necessary to adhere to traditional tillage methods: harrowing, ploughing and loosening. The basic concept is to create favourable conditions for growing crops, including corn. It also takes into account soil and climatic conditions, the predecessor, biological characteristics of the crop, the level and nature of weed infestation, terrain, etc. As of 2024, differentiated tillage, with a depth of 6-8 to 40-45 cm, using ploughing, discing, flat-cutting and chiselling, is the dominant method.

Developed countries are intensively searching for ways to reduce the energy intensity of basic tillage. B. Rosser (2021) noted that an evenly levelled field after ploughing makes it possible to reduce the cost of subsequent tillage. At the same time, due to the rotation of the layer and the absence of stubble residues, the risk of erosion on the soil surface increases (Shaheb *et al.*, 2021; Ledermüller *et al.*, 2021). In Ukraine, the latest tillage technologies are increasingly used: no-till, surface tillage, minimum tillage, etc. The significance of these tillages lies in the combination of a certain number of agrotechnical operations in one technological process, the absence of turning the chop and deep loosening of the soil. Such technologies increase the economic and energy efficiency, as well as provide less stress on the soil. At the same time, they reduce the risk of "plough tread", which manifests itself in excessive soil compaction due to the passage of heavy agricultural machinery. Ye. Yurkevych *et al.* (2020) point out the importance of monitoring the density of the 0-30 cm soil layer, its dynamics during the growing season under different tillage systems, given that the main development of the root system occurs in this layer. Also, porosity, water permeability, moisture accumulation in the soil, growth and development of plants in general depend on this indicator.

The most energy-intensive method of soil tillage is loosening the top layer. In order to reduce energy consumption, a number of researchers propose to use strip tillage and a paraplane-type soil deepener to a two-tier plough (Gilandeh *et al.*, 2022). M. Furmanets & Yu. Furmanets (2023) found that the density of compaction in the case of moldboardless tillage was in the range of 0.86-1.17 g/cm^3 of soil, and with the use of basic surface tillage it increased to 0.9-1.26 g/cm^3. According to the research of P. Pisarenko & V. Piliarsky (2020) also found that the use of deep shelf ploughing at 28-30 cm contributed to the formation of optimal physical and mechanical properties of the soil. The most compacted soil was due to the use of discing tillage at a depth of 12-14 cm. Scientists say that yields can be reduced by 20-40% due to excessive compaction of the topsoil.

The purpose of the research was to study the impact of current tillage practices in modern agriculture when growing corn for grain.

MATERIALS AND METHODS

The study complies with ethical standards and adheres to the Convention on Biological Diversity (Secretariat of the…, 2011). The research was conducted in 2021-2023 at the Dokuchaevske Experimental Field of the State Biotechnological University of Ukraine. The soil cover of the experimental field is represented by typical heavy loamy chernozem on loess loam. In terms of agrophysical and agrochemical properties, it is one of the most favourable soils for growing field crops. It is characterised by high reserves of nutrients available to plants, high humus content and intense biological activity. The 0-30 cm soil layer contains 4.9-5.1% humus, 81 mg/kg of easily hydrolysable nitrogen (according to Kornfield), 100 and 200 mg/kg of mobile phosphorus and exchangeable potassium (according to Chirikov). The content of exchangeable cations: calcium – 37.8%, magnesium – 6.6%, sodium – 0.49% and potassium – 0.5%. Soil reaction: pH_{water} – 7.0, pH_{salt} – 5.2-5.6. Groundwater is located at a depth of about 18 m (Tykhonenko & Degtiarov, 2016).

According to the weather station in Dokuchaevske, the weather conditions in 2021 were not favourable for corn growing. Low precipitation in March (23.5 mm) was partially compensated in April-June (177.1 mm). However, insufficient rainfall in the second half of the summer significantly worsened growth conditions during flowering and grain harvest formation. In 2022, the temperature regime was more favourable and differed from the trends of recent years. In September, there was an increased amount of precipitation – 79 mm, which is almost 2 times more than in previous years. In 2023, the highest amplitudes of air temperature deviations from the long-term average were recorded in February (+5.2°C), March (+5.9°C) and June (+4.3°C). March and June saw the highest rainfall: 79.3 and 104.5 mm, respectively. The deviations from the average long-term norm were the largest in April, exceeding the norm by 33.4 mm, and in August, decreasing the norm by 23.4 mm.

For the experiment, a specially modified mid-early corn hybrid – DB Khotyn (FAO 280) – was used, which was developed by the Institute of Grain Farming of the National Academy of Agrarian Sciences of Ukraine. This hybrid was included in the Register of Varieties of Ukraine in 2013 and is recommended for tillage in all soil and climatic zones. The study was conducted in the third field of a five-field crop rotation with the following crop rotation: 1. Black fallow; 2. Winter wheat; 3. Safflower, corn; 4. Winter rye; 5. Sunflower. The content of corn tillage technology did not differ by experimental variants, except for the main tillage.

The experiment included the following variants of basic tillage methods:

1. Ploughing with PLN-4-35 at 25-27 cm (control).
2. Chisel local tillage by PC-2.5 at 33-35 cm.
3. Non-moldboard tillage with PRN-31000 at 33-35 cm.
4. Discing by BDM-2.5 at 10-12 cm.

Replication of the experiment – three times, placement of variants – sequential. The size of the sowing plot was 150 m^2 and the accounting plot was 50 m^2. The available moisture reserves were determined by the thermostat-weight method in the soil layer 0-100 cm, the density of the soil was determined by the cutting cylinder method according to N.A. Kachinsky every 10 cm (DSTU ISO 11272-2001, 2003), and the hardness was determined by the Revyakin hardness tester (DSTU 5096:2008, 2009). The corn grain yield was determined from the area under study by manually removing the cobs, followed by threshing and recalculation per hectare.

RESULTS AND DISCUSSION

The most significant soil stress is excess or deficit moisture. Most of Ukraine's territory is in the risky farming zone. The reasons for this are irregular precipitation, limited soil penetration and moisture accumulation, and high evaporation losses. The accumulation and preservation of moisture is an important factor in obtaining stable yields in the Forest-Steppe zone of Ukraine. At the same time, basic soil tillage plays a key role in regulating its agrophysical and water-physical properties, and monitoring of soil-water stress is a prerequisite for effective management of its mechanisms (Kharchenko *et al.*, 2019). In view of this, it is necessary to carry out high-quality tillage in a timely manner, taking into account modern technologies and using equipment that can be easily adapted to soil preparation processes with frequent changes in production conditions. Figure 1 shows the data on soil moisture reserves in 2021-2023. In some years, this indicator depended more on precipitation and air temperature than on the impact of tillage methods.

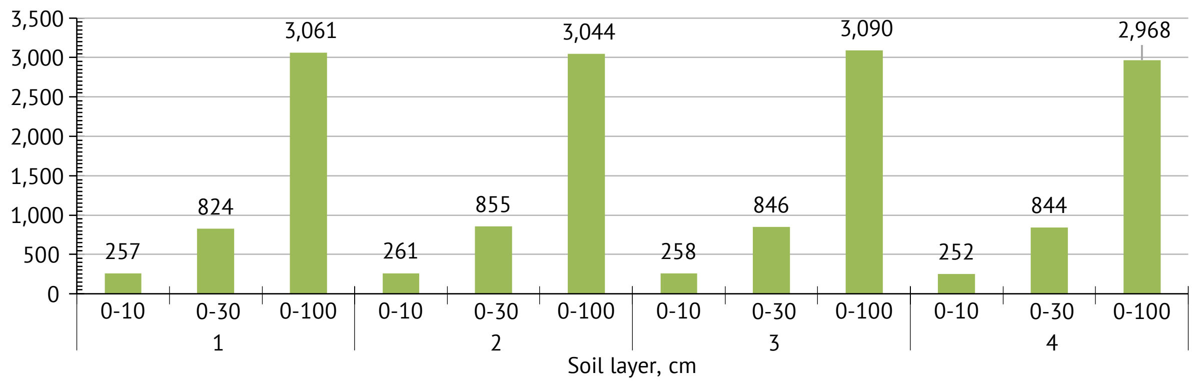

Figure 1. *Moisture reserves in the one-metre soil layer, m^3/ha (average for 2021-2023)*

Notes: *1. Ploughing PLN-4-35 by 25-27 cm (control); 2. Chisel local tillage PC-2.5 by 33-35 cm; 3. No-field tillage PRN-31000 by 33-35 cm; 4. Discing BDM-2.5 at 10-12 cm*

Source: *authors' development*

There was a slight difference between the variants of soil tillage in terms of the impact on moisture reserves in corn tillage. In the 0-30 cm tilth layer of soil, the amount of available moisture was 33-35 cm higher when using chisel tillage with the PC-2.5 compared to the control by 31 m³/ha. Studies show that discing and moldboardless tillage had an advantage over ploughing. These variants increased the moisture reserves in the arable layer by 20 and 22 m³/ha, which is a consequence of the increase in the density and hardness of the arable layer. These results are confirmed by the research of R. Vozhehova *et al.* (2019), where the soil moisture reserves were higher in the variant with discing to a depth of 8-10 cm.

In corn crops, moisture reserves in the one-metre layer did not actually differ by tillage options, but they were found to be reduced with chisel and discing tillage compared to ploughing by 17 and 93 m³/ha. The moisture reserves under the moldboardless tillage of PRN-31000 at 33-35 cm "paraplough" exceeded the values obtained under ploughing PLN-4-35 at 25-27 cm (control) by 29 m³/ha. This can be explained by the fact that this technology does not change the macrorelief of the soil surface and creates a dense network of cracks, the so-called "dense slotting effect", which, in general, contributed to a significant accumulation of moisture. In the research of S. Petrenko (2020) also did not find a clear dependence of moisture reserves on tillage methods. In the 0-100 cm soil layer, they were in the range of 58.1-51.5 mm. The scientist emphasised that this water-physical state of the soil depended more on the amount of precipitation.

Much attention is paid to the need for soil tillage as the main indicator of soil agrophysical properties. The results of scientists' research indicate a close dependence of the decrease in crop yields on the increase in soil density, especially after surface and flat-cut tillage (Stošić *et al.*, 2020). In fact, all studies related to tillage are considered in terms of the impact on this indicator. If there is no clear trend in soil texture between tillage systems, it is worth paying attention to the type of crops grown and the duration of the experiment. Sometimes, short-term studies do not show appropriately noticeable or significant changes in the physical and mechanical properties of the soil (Akinola *et al.*, 2023).

The application of a certain method and depth of basic tillage largely depends on the soil's natural condition. For example, chernozem soils in the Forest-Steppe zone have favourable agrophysical properties and, as a rule, do not require special loosening with layer turnover. Ploughing on such soils in dry conditions leads to excessive looseness of the topsoil and rapid evaporation of moisture (Pysarenko & Chaika, 2016). Chisel tillage, especially to a depth of 33-35 cm, provides similar parameters to ploughing. In addition, its use for local loosening, as well as shallow discing tillage, worsen the physical condition of the topsoil.

Studies conducted in 2021-2023 showed that the density of the 0-30 cm soil layer after corn harvesting ranged from 1.18 to 1.24 g/cm³ (Fig. 2). This value, according to the generally accepted scale (DSTU 4362:2004, 2006), was within the range of optimal values for corn tillage and did not exceed the optimal limit. A looser soil condition was provided by ploughing – 1.18 g/cm³. In the areas where the PRN-31000 was used for 33-35 cm moldboardless tillage, the density of the tilth layer of soil was higher than in the control by 0.03 g/cm. An increase in the density of topsoil was found after the use of chisel PC-2.5 at 33-35 cm and discing BDM-2.5 at 10-12 cm of tillage. The difference compared to the control in these variants was 0.05 and 0.06 g/cm³. Such differentiation of the topsoil by the studied indicator is associated with the mechanism of action of the working tools on the soil surface, which resulted in more compaction of the lower soil layers of 10-20 and 20-30 cm. These results are confirmed by the data of R. Vozhegova *et al.* (2021), which indicate that when ploughing to a depth of 28-30 cm, the soil density is lower (1.35 g/cm³) than in the shallow discing tillage system to a depth of 12-14 cm – 1.39 g/cm³.

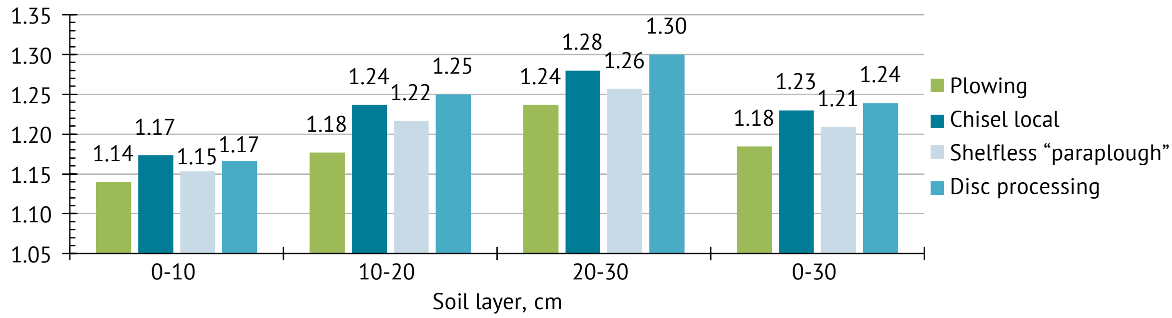

Figure 2. *Topsoil tilth density, g/cm³ (average for 2021-2023)*

Source: *authors' development*

The 0-10 cm soil layer had relatively low values of the density of compaction in all variants, especially when using ploughing and "paraplough" tillage. A slight increase in the density of soil compaction compared to the control occurred under the influence of chisel and discing tillage. On these variants in the soil layer 0-10 cm, the studied indicator was at the same level – 1.17 g/cm^3). However, the research of R.K. Afshar *et al.* (2022) showed that after the application of chisel tillage in corn crops, there was no significant change in soil density compared to ploughing.

With depth, the compaction of the arable layer increased, especially in the variants of chisel and discing tillage. Ploughing and "paraplough" are characterised by compaction of the layer in the lower part of the tilth layer (20-30 cm) to an average of 1.24-2.16 g/cm^3. The increase in density in the lower soil layers (10-20 and 20-30 cm) in these tillage options was due to a lower supply of corn residues than in PLN-4-35 ploughing at 25-27 cm. I. Garo & V. Gamayunova (2021) argue that the long-term use of moldboardless tillage and, especially, discing contributes to the differentiation of the arable layer by density. As a rule, these indicators decrease in the 0-10 cm soil layer, and increase in the 10-20 and 20-30 cm layers compared to ploughing. In order to create a level of soil density close to ploughing, it is necessary to carry out any other tillage to a depth of at least 20-22 cm. However, replacing ploughing with moldboardless tillage does not always provide the same effect as traditional tillage. Tillage with a moldboardless plough with PRN-31000 risers to a depth of 20-22 cm causes a tendency to increase the density of the arable layer compared to ploughing by 0.03-0.04 g/cm^3. The nature of the action of this tool on the soil leaves the density of the cultivated layer virtually unchanged. The study by Ye. Yurkevych *et al.* (2020) indicate an increase in the density of compaction in the soil layer of 10-20 cm by 0.06-0.08 g/cm^3, and in the layer of 20-30 cm by 0.07-0.08 g/cm^3 under flat-cutting and discing compared to ploughing.

Soil hardness reflected the same trends as the density of the tilth layer. The results of the research indicate that all tillage options created favourable conditions in the soil, as its hardness in the 0-20 cm soil layer was in the range of 13.3-15.1 kg/cm^2 (Fig. 3). The values of this indicator increased significantly in the upper soil layer (0-10 cm) after tillage with PC-2.5 at 33-35 cm, where it exceeded the control by 1.1 g/cm^2. In the lower soil layers, there was an increase in the resistance force after the moldboardless tillage with PRN-31000 by 33-35 cm compared to the control. In general, in the arable layer, the hardness value increased by 1.2 kg/cm^2 after deep continuous loosening with the PRN-31000, by 2.3 kg/cm^2 after local tillage with the PC-2.5, and by 3.3 kg/cm^2 after shallow discing tillage compared to ploughing.

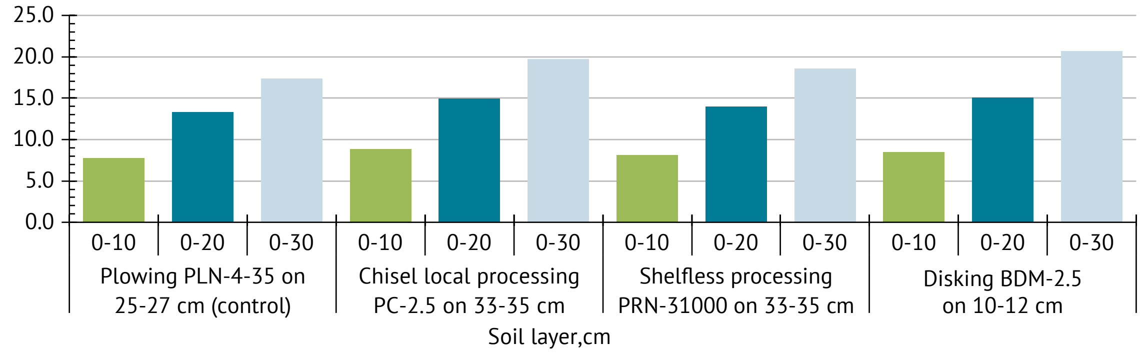

Figure 3. *Topsoil hardness, kg/cm^2 (average for 2021-2023)*
Source: *authors' development*

In almost all variants of the experiment, there was no dense layer in the arable layer. After deep moldboardless tillage, only a steady increase in soil hardness was recorded in all layers compared to ploughing. After applying shallow discing tillage with BDM-2.5, a significant increase in the resistance force was recorded at a depth of 8 to 13 cm, depending on the surface microrelief and the impact of the working bodies of the tool. However, in the conditions of 2022, the presence of this layer was felt to a lesser extent compared to other years of research. Moisture conditions after the winter period, late field work and the absence of additional surface treatments contributed to the mitigation of this problem. M. Shevchenko *et al.* (2020) found that the soil hardness when ploughing in the 0-30 cm layer was 31.7 kg/^{2}, and the use of shallow discing led to an increase of 4.7 kg/cm^2.

Crop yields can indirectly indicate the level of soil protection efficiency. On the one hand, higher crop yields can be the result of better plant development and more effective surface protection during the growing season. On the other hand, with higher yields, the weight of by-products that traditionally remain in the field and can create a protective screen increases accordingly. S. Shevchenko *et al.* (2024) found that ploughing led to faster soil warming and seed germination, which subsequently affected all stages of corn growth and development. The scientists emphasise that lower plant height, leaf area, number of ears per 100 plants and lower weight of 1,000 grains were associated with minimal tillage, which in turn led to a yield loss of 0.37-0.88 t/ha on average compared to ploughing. V. Hanhur *et al.* (2023) determined the highest corn yield after ploughing to a depth of 25-27 cm – 7.91 t/ha, while minimum tillage of 8-10 cm led to a significant decrease.

There was a significant decrease in yields for all tillage treatments compared to ploughing in the control (Table 1). The corn grain yield in 2021 was quite high considering the growing conditions. The main factors behind this result were a good predecessor, high-quality sowing, crop care and a small experimental area (3 ha).

Table 1. *Corn yields depending on the main tillage methods, t/ha (2021-2023)*

Methods of soil tillage	Years			
	2021	2022	2023	2021-2023
Ploughing PLN-4-35 by 25-27 cm (control)	6.92	6.25	6.93	6.70
Chisel local tillage of PC-2.5 at 33-35 cm	6.58	5.62	6.39	6.20
Shelfless processing PRN-31000 at 33-35 cm	6.67	5.96	6.62	6.42
Discing BDM-2.5 by 10-12 cm	6.51	5.59	6.11	6.07
$LSD_{0.05}$	0.10	0.22	0.12	

Source: *authors' development*

The yield of corn grain after replacing ploughing with any tillage was significantly lower. In particular, after applying the PRN-31000 tillage, it was 0.25 t/ha (3.6%) lower than the control, after local tillage with the PC-2.5 – by 0.34 t/ha (4.9%), and after discing shallow tillage – by 0.41 t/ha or 5.9%. Under the conditions of 2022, all the studied tillage methods were inferior to ploughing in terms of their impact on corn grain yield. After tillage with the PRN-31000, this decrease was 0.29 t/ha, after local tillage – by 0.63 t/ha and after discing tillage – by 0.66 t/ha. Discing tillage in 2023 reduced corn yields by 0.82 t/ha compared to ploughing, continuous chisel tillage by 25-27 cm – by 0.71 t/ha, and local tillage with a chisel plough – by 0.54 t/ha. The reason for this decline was the deterioration of the physical condition of the soil, which traditionally occurs after conservation tillage. The smallest decrease in corn grain yield in the experiment was obtained after deep loosening of PRN-31000 by 0.31 t/ha compared to ploughing, which indicates the advantage of this tillage among other soil-protective tillage. However, the use of deep moldboardless tillage of continuous and local impact contributed to an increase in the soil-protective efficiency of the surface and good moisture accumulation in the soil.

According to DSTU 4362:2004 (2006), the range of optimal density of typical heavy loamy chernozem for most crops, including corn, is 1.05-1.20 g/cm^3. A. Cerdà *et al.* (2021) note that conventional tillage practices have a more intense impact on soil density than natural processes. Thus, under the influence of moisture and temperature, the change in this indicator varies within ±0.05 g/cm^3, and depending on tillage methods, this range increases to ±0.20-0.30 g/cm^3. Conducting basic tillage to the same depth involves multiple passes of tractors and other agricultural machinery across the field, and as a result, the density of the soil can reach 1.4-1.6 g/cm^3. F.M. Mamatov *et al.* (2020) emphasise that the most effective way to eliminate the harmful effects of compaction is to carry out deep tillage. V. Hanhur *et al.* (2022) also believe that no-till tillage reduces the effects of machine passes, increases the organic matter content of the soil, improves its structure, regulates soil temperature and allows the soil to store more moisture.

A significant number of researchers prefer ploughing as the main method. According to T. Keller *et al.* (2019), this method provides soil loosening, incorporation of plant residues, organic and mineral fertilisers, and weed control. P.B. Obour *et al.* (2019) also proved that ploughing has an impact on the formation of high productivity of crops, in particular corn. I. Masyk *et al.* (2020), in turn, determined that ploughing instead of discing with a minimum depth ensures a corn grain yield of 10.5 t/ha.

Thus, according to the results of the study, the impact of tillage on corn grain yield varies depending on the methods used. Although some tillage practices show significantly lower results compared to conventional ploughing, and some studies point to the benefits of this technique, there are also arguments in favour of no-till as a means of reducing negative impacts on the soil and improving soil quality, as presented in this study.

CONCLUSIONS

According to the results of the research, it was found that tillage had a minimal impact on the accumulation of moisture in the one-metre soil layer. However, ploughing with PLN-4-35 to a depth of 25-27 cm and moldboardless tillage with PRN-31000 to 33-35 cm provided the highest moisture reserves: 3,061 and 3,090 m^3/ha, and in the variant with discing BDM-2.5 to a depth of 10-12 cm, its accumulation was the lowest – 2,968 m^3/ha. There was also no significant difference in the tilth of the soil in the variants. On average, the density of the topsoil in the experiment was within the optimal range for all tillage options – 1.17-1.30 g/cm^3. In corn crops, the maximum density of soil compaction was observed when using a chisel PC-2.5 at a depth of 33-35 cm and a discing BDM-2.5 at 10-12 cm. The use of chisel local tillage with the PC-2.5 at a depth of 33-35 cm and discing with the BDM-2.5 at 10-12 cm resulted in an increase in the hardness of the tilth layer of soil compared to the control. Under the dry conditions of the second half of summer and moisture deficit in early spring, hybrid DB Khotyn responded positively to the use of ploughing to a depth of 25-27 cm. Shallow discing caused a deterioration in the physical condition of the arable layer. In this regard, in 2021-2023, a decrease in grain yield was obtained compared to ploughing by 0.63 t/ha. The positive impact and prospects of using no-till tillage, which contributes to high yields with a slight decrease compared to ploughing, have also been identified. This method, similarly to local tillage, helps to improve soil protection from erosion and preserve soil moisture. The results presented in this paper are the basis for further research on the impact of different tillage methods on the sustainability of agrophytocenosis in general, taking into account abiotic and biotic stress factors.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Ministry of Education and Science for the appreciation of the research area, the results of which are presented in this article and are the basis for the tasks of the project "Development of measures to ensure the sustainable productivity of agrophytocenoses under the influence of abiotic and biotic stress factors" (state registration number 0124U000457).

CONFLICT OF INTEREST

None.

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Вплив основного обробітку на деякі показники родючості ґрунту та врожайність кукурудзи

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Анотація. Ґрунти, що обробляються, постійно перебувають у стресовому стані, зокрема, від антропогенного навантаження внаслідок їх обробітку. Разом з цим, зміни клімату, дефіцит вологи, тенденції в організації сівозмін та удосконалення технологій вирощування сільськогосподарських культур спонукає аграріїв приділяти більшу увагу системам обробітку ґрунту. Крім того, цей елемент технології відіграє вагому роль задля забезпечення сталості всього агрофітоценозу. Мета дослідження – визначити ефективність проведення різних прийомів основного обробітку ґрунту на окремі показники родючості ґрунту та врожайність кукурудзи. Дослідження проводились у 2021-2023 рр. на базі навчально-науково-виробничого центру «Дослідне поле Докучаєвське» Державного біотехнологічного університету, який розташований у зоні Лівобережного Лісостепу України. Схемою досліду передбачено вивчення різних способів обробітку ґрунту: оранки ПЛН-4-35 на 25-27 см (контроль); чизельного локального обробітку ПЧ-2,5 на 33-35 см; безполицевого обробітку ПРН-31000 на 33-35 см та дискування БДМ-2,5 на 10-12 см. Було визначено реакцію ґрунту на проведення основного обробітку у посівах кукурудзи через його основні водно- та агрофізичні показники: вологість, щільність складення та твердість. Результати досліджень засвідчили, що стан чорнозему типового є майже однаковим після проведення оранки та безполицевого обробітку ПРН-31000 («параплау»). Незначне підвищення щільності складення орного шару ґрунту виявлено після застосування чизельного та дискового обробітків. Всі варіанти обробітків створили сприятливі умови у ґрунті, оскільки його твердість в 0-20 см шарі ґрунту знаходилася у межах 13,3-15,1 кг/см^2. У посівах кукурудзи запаси вологи в метровому шарі фактично не відрізнялися за варіантами обробітку ґрунту. Однак виявлено тенденцію до її зниження у варіантах з чизельними та дисковими обробітками порівняно з оранкою. За всіма варіантами обробітків ґрунту порівняно з оранкою відбулося істотне зниження урожайності зерна кукурудзи. Практичне значення отриманих результатів полягає в оптимізації регулювання водно-фізичних властивостей чорнозему типового з досягненням ґрунтозахисної спрямованості технологій і стабілізації врожайності зерна кукурудзи в умовах зміни клімату та мінливості сучасного виробництва

Ключові слова: щільність складення ґрунту; запаси вологи; твердість ґрунту; урожайність; просапні культури; оранка; безполицевий обробіток

UDC: 631.6.03:636
DOI: 10.56407/bs.agrarian/2.2024.42

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

The influence of water quality in the Western biogeochemical zone of Ukraine on the organisms of farm animals

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Abstract. The research of water indicators in the farms of the Western biogeochemical zone of Ukraine is important and relevant in terms of ensuring water quality for cattle. The aim of the study was to investigate the chemical regime of groundwater used for animal watering in the farms of Lviv and Rivne regions. Methods that were used in the study included: drinking samples; atomic absorption spectrophotometry; turbidimetry; and removal of microbiological and organic biofilm and bacteria. During the study of drinking water supply for cows, it was found that water turbidity was increased in all seasons, especially in summer, but the organoleptic properties of water, such as smell, colour, taste and aftertaste, met the standards. It was found that the alkalinity index exceeded the standard threshold limit value in spring. The amount of calcium ions increased in autumn and winter and generally ranged from 115 ± 25.2 to 156 ± 12.7 mg/dm^3. It was also found that the levels of manganese were increased by two times and iron by three times above normal. Nitrate levels in the water samples were close to exceeding the permissible limit and ranged from 15.2 ± 8.91 to 26.3 ± 14.68 mg/dm^3, while mercury was also within the sub-threshold range and reached 0.1 ± 0.1 to 0.3 ± 0.11 μg/dm^3. It is worth noting that the use of hydrogen peroxide and activated silver solution not only improved the health and productivity of cows but also ensured an increase in the quality of milk produced. The results of the study can be used in practice by ecologists, agricultural workers, and state and local governments to develop and implement programmes and projects to manage the quality of water supply on farms

Keywords: source; watering trough; cows; heavy metals; turbidity; cavitation

INTRODUCTION

Regular researches on methods for assessing water quality are important for maintaining a favourable environmental state of the territory of dairy farms in the Western regions. The study topic requires thorough examination since one of the main problems of farms is the issue of providing quality drinking water from centralised water supply sources. This problem exists because the water supply systems are located in areas where there is significant industrial and agricultural activity, which can lead to contamination of still waters and sources with chemicals and pesticides. The consumption of contaminated water by animals can lead to gastrointestinal diseases and hepatitis.

According to the study on water quality indicators and their impact on the productivity of livestock, presented in S. Movchan *et al.* (2021), the necessity of implementing comprehensive measures to improve water quality on the farm was identified. According to the

Article's History:
Received: 07.02.2024
Revised: 11.04.2024
Accepted: 11.06.2024

Suggested Citation:
Bondar, A. (2024). The influence of water quality in the Western biogeochemical zone of Ukraine on the organisms of farm animals. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 42-52. doi: 10.56407/bs.agrarian/2.2024.42.

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researchers, a possible way to solve the problem of water quality and increased energy costs for the water supply of livestock farms may be the implementation of a water filtration and purification system on farms.

During the study on the health risks associated with consuming drinking water with elevated nitrate (NO_3-) levels, research by M. Danchyshyn (2023) provided new data on the age-related characteristics of metabolic processes during the consumption of nitrate-contaminated drinking water. In particular, these results on the impact of water with excessive nitrate content on blood parameters are of practical significant for farmers in Lviv and Rivne regions, which use local water sources to meet their needs and animals.

O. Berehova & O. Liapina (2020) examined the impact of present impurities on the development and productivity of poultry. It was found that heavy metals in the water used for drinking by animals accumulated in vital organs and slowed down the development of young animals, ultimately leading to a decrease in the quality of meat products.

The study by N. Hetman *et al.* (2022) focuses on the use of cavitation-treated water in the agro-industrial complex and the benefits of measures to introduce the latest technologies for its structuring. Significant benefits of using structured water in animal husbandry and poultry farming, such as reduced animal mortality, cultivation without the use of synthetic vitamins and antibiotics, increased productivity, improved product quality, reduced disease, and reduced need for antibiotics, have been documented.

The analysis of nitrate contamination in water conducted by H. Krupko *et al.* (2023) provided important conclusions for implementing measures to preserve drinking water quality and reduce risks to public health. The measures outlined in the study, such as the optimal use of fertilisers and pesticides in compliance with the time intervals for their application, annual well cleaning and disinfection, can be implemented on farms in the Western regions of Ukraine.

The scientific research by O. Dereza & S. Dereza (2020) examined water purification processes and methods such as sedimentation, coagulation, and filtration. The study presents a possible solution to the problem of water purification from suspended particles and microorganisms. The authors noted that additional water treatment, such as ultrafiltration or irradiation with ultraviolet light, could be a solution to this problem.

The authors S. Kelina & O. Nevinsky (2021) emphasise the urgency of the problem of increasing phosphate content in Ukrainian water bodies, which leads to eutrophication and complicates water treatment. They refer to the data that only when the phosphorus concentration in water bodies is reduced below 0.5 mg/dm^3 eutrophication is limited, and at a concentration below 0.05 mg/dm^3 it almost completely stops. Therefore, the authors highlight the importance of quantitatively determining orthophosphates in natural objects.

It is worth noting that insufficient attention has been given to studying methods for improving wat er quality for cattle and plants as a tool for improving their health and productivity from a technical, economic and environmental perspective. The purpose of the study was to investigate methods and approaches to improve the quality of drinking water in conditions of chemical and bacterial pollution. The research objectives included investigating the effect of the cleaning method on the overall productivity and health of cows; assessing the effectiveness of the method of using a solution of hydrogen peroxide and activated silver on water quality in the drinking water supply system in farms in the Western biogeochemical zone of Ukraine.

MATERIALS AND METHODS

The study was carried out using research methods for assessing water quality established by legislative acts: DSTU 4077:2001 (2002), State Sanitary Rules and Regulations 2.2.4-171-10 (2010) and DSTU 7525:2014 (2014). Water samples for animal drinking in the farms were collected from the drilled water well and watering troughs seasonally according to the guidelines of the methodology for sanitary and hygienic water quality assessment. The study was conducted in compliance with ethical standards:

1. Ensuring dignified standards of dairy cow welfare, including proper nutrition, access to clean water, free access to open spaces, and medical care.

2. Minimising resource use (water, land, energy) and reducing waste associated with milk production.

3. Providing accurate and reliable information to consumers about the conditions of dairy cow farming, milk production, and its potential impact on health.

In the study, the method of drinking samples (n = 3) was used to assess the concentration of substances in the liquid. The method of atomic absorption spectrophotometry was used for determining the content of heavy metals in water; the turbidimetry method for measuring water turbidity; the method of removing microbiological and organic biofilm and bacteria for cleaning and disinfecting the water supply system; and the M.H. Kurlov formula for analysing the major ions and salt composition of water (Khilchevskyi *et al.*, 2012).

The research was conducted during 2022-2023 in five farms located in the Western biogeochemical zone of Ukraine in Lviv and Rivne regions, namely: privately held company (PHC) Agrofirma Luhove; agricultural service cooperative (ASC) Pokrova; Lesya Ukrainka agricultural producer cooperative (APC); agricultural limited liability company (ALLC) Idna; Peasant (farm) household (PFH) Kalynivske. Water from the groundwater of the Volyn-Podilsky artesian basin was used as a source of water supply in the farms of the Western biogeochemical zone of Ukraine (Table 1).

Table 1. *Indicators of aquifers whose water is used for animal watering*

Name of the enterprise	Water abstraction depth, m	Aquifers
PHC Agrofirma Luhove, Luhove village, Brody district, Lviv region	70	Maastricht fissured marls of Upper Cretaceous deposits
ASC Pokrova, Zabolottsi village, Brody district, Lviv region	60	Maastricht fissured marls of Upper Cretaceous deposits
Lesya Ukrainka APC, Ploska village, Dubno district, Rivne region	85	Chloride-sodium waters of Myrhorod type in volcano-sedimentary rocks of the Vendian and Paleozoic
ALLC Idna, Ostrozhets village, Dubno district, Rivne region	70	Chloride-sodium waters of Myrhorod type in volcano-sedimentary rocks of the Vendian and Paleozoic
PFH Kalynivske, Kalynivka village, Sarny district, Rivne region	110	Radon mineral waters of Vendian and Paleozoic volcano-sedimentary rocks

Source: *compiled by the author*

The depth of artesian drilled water wells on agricultural and farm enterprises ranged from 60 to 110 m. According to the water abstraction technical documentation, the water supply systems of the studied farms had been in operation for 30-40 years. The research was conducted on experimental farms housing 155 milking cows, 15 dry cows and 126 calves and heifers. The water was measured at the following points: from the sources, water storage tanks, calf watering troughs, chutes for dry and milking cows, as well as heifers.

The study of qualitative and quantitative indicators of impurities in drinking water from the water supply sources of agricultural and farm experimental enterprises was conducted at the State Scientific Research Institute of Laboratory Diagnostics and Veterinary Sanitary Expertise in Kyiv. Equipment used for detecting heavy metals in sample specimens included: an atomic absorption spectrophotometer AA-7000 (manufactured in Japan) with a hollow cathode lamp and a titanium burner, operating on an acetylene-air mixture principle; a water quality scanner consisting of a device for measuring adenosine triphosphate (ATP) content, and a turbidimeter the Orion AQ4500 (manufactured in the USA), which utilised a photometric operating principle with the light source aligned on the same axis as the sample.

RESULTS

The water towers, water conduits (pipelines) and water supply systems through which water was transported from artesian aquiferous drilled water wells to the places of consumption were made of steel electric-welded pipes belonging to Group B (a material that is resistant to chemical attack). During operation, the water supply equipment was corroded, which reduced the quality of the drinking water. The water supply network in the buildings of the peasant (farm) household Kalynivske was installed with galvanised steel pipes (using the hot-dip galvanisation method), which negatively affected the qualitative characteristics of the drinking water used for animal watering.

Artesian drilled water wells were located on the territory of farms at a distance of 25-60 m from the buildings where animals were kept, paddocks, hay storage pits, silage, pulp and household wastewater reservoirs. The area where the water abstraction wells are located is unfenced and littered, and could be freely accessed by unauthorised persons, pets, and vehicles. The area where the water abstraction wells are located is unfenced and littered, and could be freely accessed by unauthorised persons, pets, and vehicles. Thus, it can be stated that the territory of the farms where drinking water was supplied did not meet the requirements of sanitary standards, which could lead to a decrease in the quality and hygienic characteristics of water intended for animal consumption. The organization of water supply in the research facilities was designed to ensure high-quality water at an economically feasible cost. Dairy farms were supplied with water from centralised water supply sources. The results of the study of water quality and the state of underground water sources in farms of the Western biogeochemical zone of Ukraine are presented in Table 2.

Table 2. Sanitary and chemical indicators of safety and quality of drinking water for animals from drilled water wells in the Western biogeochemical zone of Ukraine, M ± m, n = 3

No.	Indicators title	Measurement units	TLV	Spring	Summer	Autumn	Winter
I. Organoleptic characteristics							
1	Smell: at t = 20°C, t = 60°C	Points	≤2	4/2	1/2	1/2	2/4
2	Colour	Degrees	≤20	18 ± 1.1	5 ± 1.1	8 ± 2	16 ± 3
3	Turbidity	NTU	≤1	1.4 ± 0.5	1.6 ± 0.45	1.5 ± 0.1	1.5 ± 0.16
4	Taste and aftertaste	Points	≤2	1.5 ± 0.24	1.1	1.3 ± 0.1	1.3 ± 0.1
II. Indicators of epidemic safety of drinking water							
5	Coliform index	-	<3	<2	<2	<2	<2
6	MAFAM	CFU/cm³	He>100	112.8 ± 4.15	116.2 ± 7.54	137.5 ± 7.1	128.4 ± 6.01
III. Physico-chemical parameters A) inorganic indicators							
7	pH value	pH	6.5 - 8.5	5 ± 0.05	5.1 ± 0.05	5 ± 0.04	5.1 ± 0.02
8	Alkalinity	mEq/dm³	≤6.5	7 ± 1.8	6.2 ± 1.2	5.5 ± 1.2	5.2 ± 0.36
9	Total hardness	mEq/dm³	≤7	5.1 ± 1.96	5.2 ± 2.1	5.7 ± 2.55	6.3 ± 0.84
10	Calcium ions Ca^{2+}	Mg/dm³	≤130	115 ± 25.2	129 ± 25.1	141 ± 36.4	156м12.7
11	Magnesium ions Mg^{2+}	Mg/dm³	≤80	8 ±м3.1	9 ± 2.8	9 ± 5.6	9 ± 0.5
12	Chloride	Mg/dm³	≤250	42 ± 7.7	44 ± 7	49 ± 9	48 ± 10
13	Sulphate	Mg/dm³	≤250	77 ± 20.7	72 ± 17	64 ± 15.6	60 ± 18.4
14	General minerals	Mg/dm³	≤1,200	867 ± 207.1	808 ± 144.2	738 ± 150.3	722 ± 70.2
15	Dry residue	Mg/dm³	≤1,000	593 ± 150.6	547 ± 108.2	536 ± 112.1	487 ± 17.3
16	Permanent oxidation	MgO/dm³	≤5	2.4 ± 0.3	2 ± 0.4	2.5 ± 0.85	3.7 ± 0.42
17	Divalent copper cations Cu^{2+}	μg/dm³	≤1,000	17.2 ± 0.4	20 ± 2.07	12.2 ± 1.07	22.0 ± 1.2
18	Divalent zinc cations Zn^{2+}	μg/dm³	≤1,000	14 ± 3.4	12.7 ± 2.77	15.3 ± 2.15	27.0 ± 5.5
19	Iron Fe	μg/dm³	≤200	678 ±м83.5	587 ± 92	626 ± 143.5	559 ± 159.6
20	Divalent manganese cations Mn^{2+}	μg/dm³	≤50	163 ± 7.6	160 ± 5.5	162 ± 18.7	164 ± 26.8
B) organic components							
21	Divalent cadmium cations Cd^{2+}	μg/dm³	≤1	0.03 ± 0.014	0.02 ± 0.003	0.02 ± 0.008	0.02 ± 0.006
22	Lead acetate Pb^{2+}	μg/dm³	≤10	0.2 ± 0.11	0.4 ± 0.2	0.2 ± 0.9	0.3 ± 0.05
Sanitary and toxicological parameters A) inorganic indicators							
23	Ammonium nitrogen	mgN/dm³	≤0.5	0.06 ± 0.011	0.06 ± 0.02	0.06 ± 0.011	0.03 ± 0.001
24	Nitrates	mgN/dm³	≤50	26 ± 18	15.2 ± 8.91	25 ± 18	26.3 ± 14.68
25	Nitrites	mgN/dm³	≤0.5	0.03 ± 0.001	0.03 ± 0.001	0.03 ± 0.002	0.02 ± 0.001
26	Potassium and sodium ions $K^+ + Na^+$	Mg/dm³	≤200	20 ± 0.93	11 ± 2.95	19.6 ± 3.07	19.4 ± 4.87
27	Bicarbonate ions HCO_3^-	Mg/dm³	-	251 ± 21.2	226 ± 25.4	248 ± 18	274 ± 10.8
28	Arsenic acetate As^{2+}	μg/dm³	≤10	1.6 ± 0.29	1.5 ± 0.36	1.2 ± 0.17	1.5 ± 0.22
29	Divalent mercury cations Hg^{2+}	μg/dm³	≤0.5	0.3 ± 0.04	0.3 ± 0.11	0.2 ± 0.06	0.1 ± 0.1
B) integral indicator							
30	Divalent cations of carbon monoxide (cobalt) Co^{2+}	μg/dm³	≤100	8 ± 1.8	8.5 ± 10.1	4 ± 0.57	7.6 ± 0.7

Notes: *TLV – threshold limit value; NTU – nephelometric turbidity units; CFU – colony-forming unit; MAFAM – aerobic and facultative anaerobic microorganisms*
Source: *compiled by the author*

It should be noted that in case of non-compliance with the standard organoleptic indicators, water is deprived of the ability to support the secretory function of the digestive system (Sokolyuk *et al.*, 2019). When there is a disturbance in the secretion of enzymes in saliva (amylase, maltase), gastric (pepsin, lipase), pancreatic, intestinal juices (trypsin, lipase, amylase, lactase, maltase), and bile in animals, there is a physiological reaction of complete refusal or reduced consumption of poor-quality water. It is worth noting the compliance of the organoleptic properties of water (smell, colour, taste and aftertaste) comply with the TLV standards in the spring, summer, autumn and winter. However, the indicator of water turbidity exceeded the established TLV standard (the NTU indicator ranged from 1.4 ± 0.5 to 1.6 ± 0.45) and was observed at an elevated level in all studied seasons. The exceeding of the water turbidity index indicated the presence of suspended particles of organic origin and bacterial contamination. Deviations from the requirements of the current DSTU 7525:2014 (2014) were recorded in the epidemiological safety indicators of all drinking water samples. There was a noted variation in the indicators of the quantity of MAFAM throughout all periods of the study, ranging from 112.8 ± 4.15 to 137.5 ± 7.1 CFU/cm^3. The quantitative indicator of faecal contamination of water (Coliform index) remained below the established normative TLV.

The investigation of the pH value showed that in all examined farms in the Western biogeochemical zone of Ukraine, the hydrogen reaction was weakly acidic, ranging from 5 ± 0.05 to 5.1 ± 0.05 pH. The alkalinity index exceeded the norm in the spring season, reaching 7 ± 1.8 mEq/dm^3, while in summer, autumn and winter the alkalinity of water was within the standard values. To reduce alkalinity, remove salts, heavy metals, pesticides, bacteria, and other contaminants from water, reverse osmosis filtration systems should be used. In the studied households, the water contained minor amounts of calcium salts, and based on the hardness index, the water was classified as soft. The total water hardness did not exceed the norm and ranged from 5.1 ± 1.96 to 6.3 ± 0.84 mEq/dm^3. It should be noted that if the concentration of chlorides in water exceeds 1%, it will have a salty taste, leading to dehydration of tissues and disruption of electrolyte balance in animals' bodies. Regarding the effects of sulphates on animals, concentrations above 1 g/dm^3 can lead to diarrhoea.

The study of the water's salt composition showed that hydrocarbonate ions, chloride and sulphate anions, and magnesium ions had stable levels within the acceptable range. It was found that the calcium ion level in summer was 129 ± 25.1 mg/dm^3, while in autumn and winter, it increased to levels ranging from 141 ± 36.4 to 156 ± 12.7 mg/dm^3, which exceeded permissible concentrations. However, potassium and sodium cation levels gradually decreased throughout the entire study period, from 20 ± 0.93 mg/dm^3 in spring to 19.4 ± 4.87 mg/dm^3 in winter. The water samples showed low concentrations of magnesium ions, making the soft water less suitable for animal consumption due to insufficient mineral salts. In case of insufficient salt content in drinking water, mineral salts should be additionally included in the animal diet. Water salinity at the level of 300 to 500 mg/dm^3 was considered optimal. Throughout the year, the total salinity decreased from 867 ± 207.1 mg/dm^3 in spring to 722 ± 70.2 mg/dm^3 in winter, indicating an unstable hydrochemical regime of the aquifer. The degree of mineralisation of the water of the studied farms was characterised as fresh with an increased level of mineralisation. The water class and group were determined by the Kurlov formula. Accordingly, the water in the studied farms belonged to the hydrocarbonate class, the calcium group of the first type. The dry residue was within the regulated values. Nitrate levels in the water samples were close to exceeding the TLV level (from 15.2 ± 8.91 to 26.3 ± 14.68 mg/dm^3), while the content of ammonium nitrogen and nitrite did not exceed the permissible limits of the standard. The concentration of lead, cadmium, arsenic, copper, zinc, and carbon monoxide in water samples was insignificant. The mercury content in the water was on the verge of exceeding the permissible standard in terms of TLV and reached 0.3 ± 0.04 μg/dm^3 in spring and 0.3 ± 0.11 μg/dm^3 in summer.

In the artesian basin, water is characterized by high concentrations of iron and manganese, which enter the water as a result of leaching from rocks. The manganese content in the water exceeded permissible concentrations throughout the year, reaching its highest levels during the spring-winter period, specifically 163 ± 7.6 and 164 ± 26.8 μg/dm^3 respectively. Water samples also showed a high iron content, which ranged from 559 ± 159.6 μg/dm^3 in winter to 678 ± 83.5 μg/dm^3 in spring. Therefore, in the studied water samples, the manganese content exceeded permissible limits by two times, while the concentration of iron exceeded the established TLV values by three times. To reduce the content of manganese and iron, it is necessary to correct the water parameters before it is supplied to the distribution network of the buildings where the animals are kept. The recommended filtering material for reducing the content of iron, manganese, calcium and magnesium salts, as well as ammonium and hydrogen sulphide in artesian water is the synthetic zeolite Crystal Right CR 200, a white crystalline powder made from sodium aluminosilicate salt. According to a study by H. Van den Berg *et al.* (2023), wastewater treatment plants were identified as a likely source of infection during outbreaks of pneumonia in the Netherlands caused by the bacterium *Legionella pneumophila*. To increase milk yields and improve cow health, it is recommended to use methods to remove microbiological and organic biofilms (cleaning) and bacteria from the water supply system (disinfection) (Aftanaziv *et al.*, 2018).

The water quality was assessed using a scanner consisting of a device for measuring the content of ATP, which is produced by living organisms and measured in relative light units (RLU). This method was employed to determine the quality of various water samples collected from five farms in Lviv and Rivne regions (Table 3).

Table 3. *Water quality indicators from farms and households in Lviv and Rivne regions*

Values of relative light units	Characteristics	Incoming water (n = 14)	Buffer capacity (n = 8)	Drainage gutters and lines (n = 124)
<70	Water is allowed for human consumption	11	2	13
70-300	Water is allowed for animal consumption	2	1	24
300-500	Recommended water quality testing		2	6
500-1,000	Measures to improve water quality are needed			20
>1,000	Immediate water testing is required		2	52

Source: *compiled by the author*

Thus, in the first place, with an RLU indicator >1,000 in 54% of cases, immediate water testing is required. In the second place (RLU 70-300), in 27% of cases, the water was deemed safe for animal consumption. In the third place (RLU <70), in 26% of cases, the water was considered safe for human consumption. For an RLU value of 500-1,000, in 20% of cases, measures to improve water quality were needed. Additionally, with an RLU of 300-500, in 8% of cases, water quality testing was recommended. A possible solution to the problem of water turbidity and bacteriological contamination could be the use of hydrogen peroxide and activated silver solution. Based on the quality indicator, the water from the source was suitable for human consumption (9 RLU), but in the storage tank, the RLU indicator exceeded 300, and at an RLU value of 1,000, measures to improve water quality were necessary. The quality indicators of water sampled from five points are presented in Figure 1.

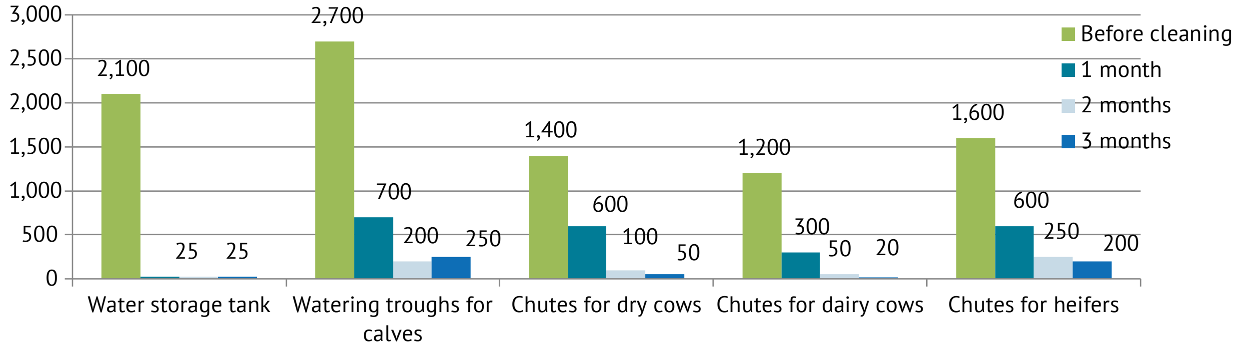

Figure 1. *Water quality indicators*

Source: *compiled by the author*

The water storage tank was emptied and cleaned, followed by the addition of 40-90 mg/m^3 of hydrogen peroxide and silver solution to treat the water system until the RLU dropped below 300 at all sample collection points. The water quality in the reservoir immediately reached the level acceptable for human consumption (<70 RLU). Water quality indicators in other points improved over time to levels acceptable for animal drinking (below 300 RLU). Within a month, the quality also improved in the troughs for dry, milking cows and heifers. After this initial improvement, the solution was introduced only once a week until good water quality indicators were consistently achieved. Consequently, all samples showed 300 RLU, which was considered a positive result since the animals often contaminated the troughs with feed residues and mucous secretions. Table 4 compares the effects on milk yield and protein without using the solution (2022) and with using the solution (2023).

Table 4. *Efficiency of hydrogen peroxide and activated silver solution for the period 2022-2023*

Indicators	2022 (the solution was not used)	2023 (the solution was used)
Average number of cows, heads	155	178
Number of young animals per 10 milking cows, heads	7.7	5.3
Average daily milk yield per cow per day, kg	28.2	29.6
Protein content, %	2.33	2.49

Table 4, Continued

Indicators	2022 (the solution was not used)	2023 (the solution was used)
Urea, mg/dL	29	25
Fat content, %	5.2	5.24
Average dry period, days	64	52
Calf mortality rate from 3 to 63 days, %	7.4	4

Source: *compiled by the author*

Therefore, during 2022-2023, the average daily milk yield per cow increased by 1.4 kg. There was a noted increase in protein content by 0.9%, and due to better protein absorption, the urea level decreased by 4 mg/dL. Additionally, it became possible to increase the herd size while maintaining a lower number of young stocks per 10 milking cows and reducing the dry period by 12 days. It was recorded that the calf mortality rate before weaning from 3 to 63 days decreased from 7.4 to 4%, indicating the undeniable effectiveness of using hydrogen peroxide and activated silver solution to improve the quality indicators of water. Thus, it can be stated that the removal of biofilm from the centralised water supply system ensured positive results such as the complete absence of *Escherichia coli* bacteria (strains *E. Coli*), reduced oxidative demand, reduced formation of dangerous disinfection by-products, increased filter cycle, and mucus removal.

DISCUSSION

According to the obtained research results, it was found that the quality of drinking water in the investigated farms of the Western biogeochemical zone of Ukraine required corrective measures. In the scientific study by W. Feng *et al.* (2020) on the example of nitrate pollution of groundwater in a mining area, it was noted that the concentration of nitrate ions exceeded national standards by 5.48 times. A comparison of research results showed that the researchers recorded a significant exceedance of the normative values of nitrates in the water, while in the present study, it was indicated that the concentration of nitrates in the water samples was close to exceeding the TLV level and ranged from 15.2 to 26.3 mg/dm^3, with the TLV standard being ≤50.

The study by G. Yu *et al.* (2020) focused on examining the impact of nitrate concentration in drinking water in rural areas on the health of the population. The researchers found that high nitrate concentrations in rural areas could result from the interaction of fertilizers and geological factors. The impact of nitrates on minors and adults exceeded the permissible level. This study primarily focused on investigating the quality and safety of drinking water in agricultural farms through a comprehensive analysis of organoleptic and chemical indicators.

The study by P. Li *et al.* (2021) focused on analysing the impact of groundwater pollution on human health and ecological systems in various countries. The researchers found that anthropogenic pollution, caused by the discharge of chemical wastes and uncontrolled wastewater dumping, had a serious impact on the ecosystem and the health of local populations in China, Turkey, and Ethiopia. In the conducted study, atomic absorption spectrophotometry was used to determine the content of heavy metals in the water, while the researchers' study relied on chromatographic methods to analyse organic pollutants in groundwater.

The researchers R. Ennajeh *et al.* (2018) conducted an analysis of water samples from surface and groundwater wells to detect nitrates using a UV spectrophotometer Shimatzu 2401PC. They studied the population's impact on the quality of drinking water and found that an 81.8% exceedance of permissible nitrate levels in water could be attributed to uncontrolled fertilizer use and improper wastewater disposal. The focus of this study was on analysing the physicochemical parameters of drinking water, such as turbidity, pH, alkalinity, mineralisation, ion concentrations, and various pollutants.

N. Kalvani *et al.* (2021) conducted a study to evaluate the effectiveness of different modules for removing iron and manganese at a water treatment plant. The researchers found that the use of Module No. 1 with open aeration and chlorine as an oxidizer was the most effective method for removing iron and manganese at the water treatment plant. The study focused on identifying optimal technologies and purification parameters for treating groundwater to ensure reliable and safe access to drinking water for the population. The research aimed to assess the quality of drinking water and determine compliance with chemical composition standards and safety norms to ensure proper animal health.

In the study by I.V. Roch *et al.* (2023), it was found that the chemical pollution of river water is caused by elevated levels of phosphorus, ammonia, nitrogen, sodium, iron, calcium, and magnesium. This research focuses on analysing the quality of drinking water and its impact on the organisms of agricultural animals, while the scientists' research is oriented towards studying the impact of agricultural and industrial activities on the river ecosystem, as well as developing and implementing strategies for conserving and restoring the quality of water resources in its basin.

The study by H. Kutay (2024) demonstrated that poor water quality containing harmful substances or microorganisms could cause illnesses and weaken the immune system of animals. The researcher employed a method for monitoring water quality and controlling its consumption, which involved using modern analytical instruments such as spectrophotometry, chromatography, and nuclear magnetic resonance spectroscopy. This study utilised a method to analyse the physicochemical parameters of water based on standard techniques for determining the concentration of various components, including turbidimetry for measuring turbidity, photometry for determining substance concentrations, and bacteriological analyses to assess microbiological contamination.

According to the findings of G. Jain & J. Singh (2023), the productivity of dairy cows was shown to depend on the quality of drinking water, as elevated levels of iron in water could lead to digestion issues and reduced appetite. The researchers' methods relied on chemical analysis of water, considering parameters such as pH level, mineral salt content, heavy metal content, and other chemical components. The study explored potential methods to improve conditions to increase milk yields and enhance cow health, such as removing microbiological and organic biofilms and bacteria from the water supply system. The researchers' paper, as well as the results of the study, highlight the importance of maintaining water quality for animal health and productivity.

The study by P. Erdei-Tombor *et al*. (2024) was conducted to explore the impact of biofilms on the quality and safety of drinking water, as well as to determine effective materials and disinfection methods aimed at controlling biofilm formation in water distribution networks. The presented research focused on evaluating the organoleptic properties of water and detecting turbidity. Therefore, in the researchers' study, as well as in the scientific article carried out, the use of filtration and disinfection systems was recommended for purifying water from bacteria and contaminants.

To investigate the impact of intermittent water supply on the microbiological and physicochemical characteristics of drinking water, researchers C.C. Preciado *et al*. (2021) conducted an experimental run of a chlorinated pipe system. The findings of their study indicated that minimising the time of interruptions in the water supply could help prevent an increase in the concentration of disinfection by-products and improve the safety of the water supply for consumers. The researchers' study aims to understand the impact of intermittent water supply on drinking water quality and biofilm in water distribution systems, while this study focused on the chemical composition and bacterial contamination of water in an artesian basin and the development of methods to reduce the content of dangerous bacteria in it.

In the study by D.C. Onuoha & O.G. Ogbo (2022), research was conducted on the application of nanotechnologies for water purification and treatment to improve water supply quality. According to their findings, this technology not only effectively cleans water from various contaminants but also reduces energy consumption and resource usage. The study identified issues with water quality, including exceeding standards for turbidity, epidemic safety, manganese, and iron content in water. The researchers focused on using nanomaterials such as carbon nanotubes, membranes made from carbon nanotubes, and aluminium oxide fibres for nanofiltration. G. Mitropoulou *et al*. (2023) explored the potential of removing biofilm from non-cellular supernatants of five strains of *Lacticaseibacillus rhamnosus* to address water turbidity issues and bacterial contamination, proposing the use of hydrogen peroxide solution and activated silver.

L. Gallina *et al*. (2022) conducted a review of recent methods for extracting solid substances from water for industrial applications. The researchers demonstrated the potential of ultrasound and hydrodynamic cavitation methods. These methods not only increased extraction speed but also reduced the use of harmful organic solvents. The study also examined similar research focused on studying plant growth parameters such as height, root length, leaf count, physiological indicators of plants (such as photosynthetic activity), as well as nutrient content and trace elements in plants after irrigation with water treated using cavitation technology.

Therefore, the section included a literature review and comparison of research results concerning aspects such as water quality and its impact on animal health, methods for water quality analysis and monitoring, the effectiveness of measures to improve water supply quality, and methods for water purification from contaminants.

CONCLUSIONS

A general study of water indicators on farms in the Western biogeochemical zone of Ukraine indicated several problematic aspects. The organoleptic properties of water, such as smell, colour, taste and aftertaste, were in line with the TLV, but water turbidity was elevated in all seasons of the year, with a particularly high level in summer – 1.6 ± 0.45 NTU. This indicated the presence of suspended organic impurities and bacterial contamination. The study of the epidemic safety of drinking water showed deviations from the requirements of the State Standard. The pH of the water was weakly acidic with normal values, but the alkalinity exceeded the standard in the spring and reached 7 ± 1.8 mEq/dm^3.

Despite the low water salinity, the calcium ion content exceeded the permissible limits and reached the highest level of the season in winter (156 ± 12.7 mg/dm^3). In addition, the concentration of nitrates and mercury increased to levels that were close to exceeding the standards. A particular problem was the increase in manganese (163 ± 7.6 μg/dm^3 in spring and winter) and iron in water (164 ± 26.8 μg/dm^3 in summer and winter), which exceeded the permissible limits by two and three times, correspondingly. To ensure water quality and safety, additional measures are required, such as the use of reverse osmosis filter systems and monitoring of manganese and iron in water.

Thus, the results of the study showed that the use of a solution of hydrogen peroxide and activated silver effectively reduced bacteriological contamination of water in the water supply system for cows. This led to an improvement in water quality, a reduction in RLU to acceptable levels for animals, and an improvement in animal health and productivity. The study showed an increase in milk yield by 1.4 kg, a 0.9% increase in protein content, a 4 mg/dL decrease in urea levels, and a reduction in calf mortality from 7.4 to 4%.

Further research into the method of using a hydrogen peroxide solution with the addition of activated silver to maintain the purity of the water supply system may include studying the effect of different concentrations of hydrogen peroxide solution and different amounts of activated silver on the efficiency of water purification from bacteria and other contaminants, assessing the stability of such a system to different operating conditions, and comparing this method with other traditional methods of water purification.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Вплив якості води західної біогеохімічної зони України на організм сільськогосподарських тварин

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Анотація. Дослідження водних показників у господарствах західної біогеохімічної зони України є важливим і актуальним з погляду забезпечення якості води для утримання великої рогатої худоби. Метою роботи було дослідження хімічного режиму підземних вод, які використовуються для напування тварин в господарствах Львівської та Рівненської областей. В ході дослідження застосовувались методи: напувальних проб; атомно-адсорбційної спектрофотометрії; турбідіметрії; видалення мікробіологічної та органічної біоплівки та бактерій. Під час проведення дослідження питного водопостачання для корів виявлено, що мутність води була підвищеною у всі сезони, особливо влітку, однак органолептичні властивості води, такі як запах, кольоровість, смак і присмак, відповідали нормам. Встановлено, що показник лужності перевищував норму гранично-допустимої концентрації весною. Кількість іонів кальцію підвищувалась восени і взимку, і загалом складала від 115 ± 25,2 до 156 ± 12,7 мг/дм^3. Також було виявлене понаднормове збільшення рівня марганцю в два рази та заліза в три рази. Показник нітратів у пробах води був близьким до перевищення допустимої норми і його значення встановилось на рівні від 15,2 ± 8,91 до 26,3 ± 14,68 мг/дм^3, тоді як ртуть також перебувала в межах підпорогового перевищення і досягла від 0,1 ± 0,1 до 0,3 ± 0,11 мкг/дм^3. Варто відзначити, що використання розчину перекису водню та активованого срібла сприяло не лише покращенню стану здоров'я та продуктивності корів, але й забезпечило підвищення якості виробленого молока. Результати дослідження можуть бути використані на практиці екологами, працівниками сільського господарства, державними та місцевими органами управління з метою розробки та впровадження програм та проектів з управління якістю водопостачання в фермерських господарствах

Ключові слова: джерело; напувалка; корови; важкі метали; мутність; кавітація

UDC: 338.43
DOI: 10.56407/bs.agrarian/2.2024.53

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

State regulation of agriculture in the conditions of digitalisation of Ukraine's economy

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Abstract. Agriculture has a strategic role in providing food for the population. This causes significant government intervention in this sector, and therefore the development of high-quality approaches to this process remains relevant. This study aimed to provide recommendations for this process in Ukraine, particularly in the context of economic digitalisation. To achieve this, graphical analysis, modelling, abstraction, and the method of logical reasoning were used. The role of digital technologies in achieving more effective results in the context of improving the efficiency of agricultural development was described in detail in the paper. In addition, a conclusion was made about the necessity of cooperation between the state and enterprises in this area. This is primarily associated with the challenges that may arise in companies implementing such practices. Understanding the presence of these challenges, the likelihood of further implementation of such type of technologies in enterprises decreases. Several approaches were proposed in the paper to reduce the negative impact on agricultural companies. Given the consequences of the full-scale Russian invasion of Ukraine, particular attention was paid to non-financial approaches, as well as to the problems existing within the current legislative framework. Furthermore, separate conclusions were drawn based on statistical data regarding the development of science and education in Ukraine overall. The study's practical value lies in that the findings will enhance the efficiency of the state sector's functioning in Ukraine in agricultural regulation

Keywords: innovation; agricultural sector; technology implementation; regulatory framework; management and governance

Article's History:
Received: 27.02.2024
Revised: 05.05.2024
Accepted: 11.06.2024

Suggested Citation:
Stender, S., Borkovska, V., & Balla, I. (2024). State regulation of agriculture in the conditions of digitalisation of Ukraine's economy. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 53-64. doi: 10.56407/bs.agrarian/2.2024.53.

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INTRODUCTION

Agriculture is one of the most important sectors of the Ukrainian economy, which is, in turn, a leading global producer of grains, sunflower oil, and other agricultural products. This sector also plays a crucial role in ensuring the country's food security and stockpiling food resources for the Ukrainian population. Additionally, agriculture serves as the primary economic driver for many rural communities, and its development contributes to job creation and maintaining the viability of rural areas.

Digitalisation, in turn, remains a critical component of the country's development across various spheres of life, including the economy, the social sector, and science (Nasirahmadi & Hensel, 2022; Abbasi *et al.*, 2022). It enables process automation, management optimisation, cost reduction and innovation acceleration, stimulating gross domestic product (GDP) growth, enhancing international competitiveness, fostering job creation and the development of small and medium-sized businesses, which are the primary source of employment in most countries, and stimulating innovation and scientific research (Zscheischler *et al.*, 2022). Another significant factor is the ability to improve people's quality of life through digital technologies, including enhanced access to education, healthcare, e-government services, e-commerce, and other services, which enable more effective resolution of social problems and reduction of social inequality.

Digitalisation can also be implemented in agriculture. Given the role of agriculture, ensuring the development of its digital component remains relevant. Considering the situation in the country (2024) related to Russian aggression, it is quite difficult to formulate such a policy that would be aimed at developing digitalisation in this sphere. Although the state and enterprises have the same goal in this context, especially considering that digitalisation has a positive impact not only on the economy but also on other components of the economy's functioning, they often cannot reach an agreement to ensure the effective implementation of this concept. Nevertheless, the search for such approaches remains relevant. Thus, A. Subeesh & C.R. Mehta (2021) conducted a comprehensive review of the role of artificial intelligence and the Internet of Things in agriculture, focusing on their contribution to digitalisation and automation. They described that these components play an important role in modernising agriculture through the automation and control of various types of agricultural activities. In addition, the researchers described the role of these technologies in ensuring food security and more effective management. The impact of digitalisation on the development of agriculture was also assessed by Y. Tang & M. Chen (2022). The researchers concluded that digitalization has a significant impact on agriculture, although they noted the existence of regional differences (the degree of this impact may vary depending on the territory). Particular attention was paid to the need for a high-quality workforce to ensure a high-quality transition to digital principles. However, neither of the above-mentioned studies provided recommendations for state policy in this area at the state level.

The significant role of technologies in agriculture was also highlighted by H. Panetto *et al.* (2020). They emphasised the increasing complexity of doing business in agriculture and the growing demand for innovative solutions. This indicates the need for more active involvement from the state to support digitalisation in such enterprises. The situation in Ukraine was studied by G. Duginets & K. Nizheyko (2023). The researchers paid particular attention to the need for more active involvement of research institutions in digitalisation processes, based on the evaluated experience of the European Union. Attention was also paid to the impact of digital technologies on the activities of farmers, including the potential benefits that can be obtained from this process. M. Nehrey (2023) and M. Marchenko (2023) focused on the potential for the development of the digitalisation of agriculture in Ukraine. The researchers noted that the successful implementation of digitalisation processes in this sector in the country will make it possible to achieve a significantly higher level of competitive advantage in the international market. In addition, it will make it possible to manage various processes at enterprises more effectively. However, it is worth noting that not much attention was paid to the possibility of interaction between the state and private enterprises.

The purpose of this study was to formulate recommendations for state policy in the field of agriculture in the context of the digitalisation of the economy. The objectives of the study were: to build a model of the functioning of agricultural enterprises in the context of digitalisation and their interaction with the state; to analyse the economic consequences of digitalisation and to evaluate the regulatory framework of Ukraine in the field of agriculture and digitalisation.

MATERIALS AND METHODS

A certain source base was used in the writing of this article. The main part of it is statistical data provided by the State Statistics Service of Ukraine (Ukrstat, n.d.). In addition, the content of the legislative framework was studied, namely Law of Ukraine No. 2297-VI (2022) and Law of Ukraine No. 2163-VIII (2024). However, it is important to note that as of 2024, not all information is publicly available, which causes some limitations in the study.

Nevertheless, it was decided to build a model to explain the need for government support for businesses in adopting digital technologies, how the profitability of such enterprises changes, and the consequences of these changes. Additionally, the model was expected to demonstrate the benefits to the government of supporting such enterprises and to describe the decision-making logic behind providing support. The model was constructed in the form of three graphs with the abscissa axis T (time) and the ordinate axis – I (income, for enterprises) or G (utility, for the state). The implementation of digitalisation as a whole project and its impact on business revenue were depicted in the figures. The entire time period was divided into stages to more clearly describe how changes occur within the business. The corresponding important indicators of revenue change over time were also reflected through appropriate markings. In addition, the changes that would occur in the company's operations in case of government assistance were analysed. For this purpose, it was assumed that the level of government support in such a case should be sufficient to prevent the company from reaching the point of unprofitability. It was also assumed that the company would be obliged to repay the assistance over time, namely during the period of receiving the highest level of income. The analysis itself was presented visually.

Subsequently, it was decided to analyse the retrospective benefits and losses for the government from helping such companies. For this purpose, the dependence G(T) was considered, where G – the utility of assisting such companies (by analogy with an investment project), and T – time. However, at the end of any project, there should be a benefit, which is presented in the form of an infinitely positive/negative part of the area. Thus, the total utility of the project can be represented as the difference between the sums of the areas above and below the graph. It was concluded that to find this, it is necessary to find the points of intersection of the graph with the T axis and to determine the sign of each part. Thus, the formula for finding the government's utility in aiding such companies is as follows:

$$\mathrm{G} = \pm \int_0^{\mathrm{a}} \mathrm{G(T)} \pm \int_{\mathrm{a}}^{\mathrm{b}} \mathrm{G(T)} \pm \ldots \pm \int_{\mathrm{z}}^{\infty} \mathrm{G(T)}, \qquad (1)$$

where G – the benefit of the state from the company's assistance; a, b … – the corresponding points of intersection of the graph with the T-axis; G(T) – the formula for the dependence of the state's benefit on the company's assistance; if G(T) is positive at points between a certain interval (from 0 to a, from a to b …), then the sign before the integral is plus, and if it is negative, then minus.

It is important to note that the representation of the benefits of state-owned companies in the model is somewhat conditional, since the vertical axis within the model reflects utility rather than revenue. This utility is reflected in both social effects and environmental benefits. Therefore, their assessment requires rather complex evaluations. It is also worth noting some additional conditions for the model, specifically that the state will not try to find funds for the implementation of the project by creating new taxes or any similar action, but rather by foregoing alternatives. Also, for simplicity, the factor of discounting future cash flows/benefits from the project was not considered in detail, although this can be done when evaluating the schedule, reducing the weight of all future receipts compared to the initial ones: in this case, the schedule for an infinitely large period should approach zero.

The construction of the graphs was based on a theoretical understanding of how the enterprise functions and the probable impact of individual internal and external factors on it. A fairly large number of research methods were used to construct them, including the mathematical method, which made it possible to optimise the model by forming an equation for calculation and formalising the model; the graphical analysis method for evaluating the data that was formed within the framework of this model. A modelling graph was used to construct such a model. The Logical Reasoning method was used to form connections within the model, internal interaction. Abstraction was used to more effectively build a model by mentally highlighting the essential, most significant features, relationships, and aspects of the subject. In addition, the analysis method was used to study the impact of digital technologies on the development of agriculture, as well as its role in the state as a whole.

RESULTS

Supporting agricultural enterprises in adopting digital technologies plays a key role in increasing their efficiency, competitiveness and sustainability. This support can be financial, advisory or otherwise. The need for such support can be explained using the model shown in Figures 1, 2 and 3.

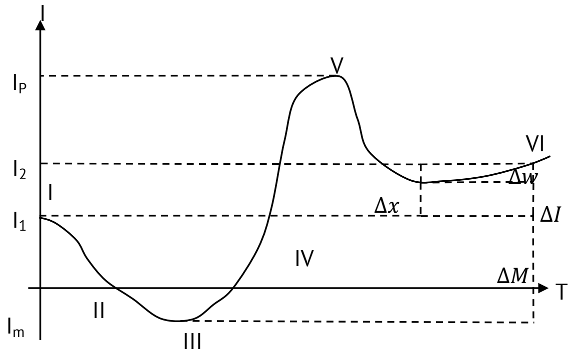

Figure 1. *Model of the implementation of digital technologies in enterprises*

Notes: *I, II, III, IV, V, VI – stages of implementation of digital technologies in enterprises; I – enterprise income; T – time; I1 – initial level of enterprise revenue; I2 – level of enterprise income after implementation of digital technologies; Im – minimum revenue level; Ip – peak profitability; Δx – difference between income before and after implementation of digital technologies; Δw – profit from further development of the enterprise; ΔI – total change in the level of enterprise revenue (Δx+Δw); ΔM – the amount of losses received due to the implementation of digital technologies at the enterprise in the short term*

Source: *compiled by the authors*

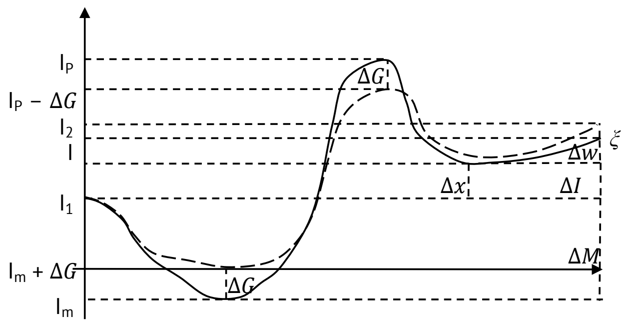

Figure 2. *Model of the implementation of digital technologies in enterprises in the case of state support*

Notes: *ΔG – the amount of assistance/return of funds from/to the state; ξ – the amount of excess profit received as a result of the implementation of digital technologies at the enterprise*

Source: *compiled by the authors*

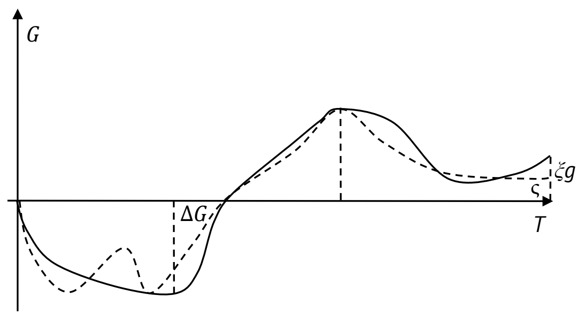

Figure 3. *Impact of support on the state*

Notes: *ξg – benefit received from helping the enterprise to implement new technologies; ς – benefit received from the alternative project*

Source: *compiled by the authors*

Figures 1, 2 and 3 show in detail why the state should be interested in helping enterprises (including agriculture) to implement new (digital) technologies. Nevertheless, it is worth describing in more detail the logic depicted in these figures. Thus, Figure 1 shows how the company's revenues look (change) during the period of implementation of digital technologies. At stage I, the company is just starting to implement technologies, as a result of which it receives a gradual decrease in profitability (stage II), which can even lead to losses for a certain period. At stage III, the company is at the lowest point in terms of income level (lower than the initial one by the indicator ΔM, where the risk of bankruptcy is the highest). The risks that the company bears at this stage are different, depending on both the financial condition of the company at stage I and the complexity of the process itself, as well as the company's preparedness for it. Thus, the enterprise may not feel the process of implementing digital technologies at all, or, at least, not get into the loss zone. At stage IV, there is a recovery of profitability, to the peak level V, which is associated with the effect of introducing new technologies and maximising profitability from it at the first stages (until it is implemented by competitors, demand does not fall, consumers do not get used to it). After that, profitability falls to a new level (I_2), which is already higher than the initial one (I_1) by the level Δx. In the future, the company continues to develop normally (stage VI), receiving a new growth rate, which should be higher than those observed in previous periods due to the effect of introducing new technologies (Δw), and therefore the total change in income for this period is equal to ΔI (in this case, this is Δx + Δw).

Thus, the implementation of digital technologies increases the company's income level in the medium and long term. However, in the short term, the company makes losses due to the significant difficulties associated with the implementation of these technologies. These difficulties are related to: the cost of technologies, the complexity of their implementation, maintenance and application, and the need for highly qualified personnel. This leads to the fact that not all companies are ready to implement such technologies, which in fact has a negative impact on the development of the country and these companies in the medium and long term. Therefore, in this case, the introduction of state support is becoming relevant. The change in the company's income level over time, taking into account the factor of state support, is shown in Figure 2. In this case, the maximum loss of the company is reduced by the amount of ΔG, which is the amount of state support. At the same time, the decrease in income in this case reaches the level of ΔM - ΔG, and the point of income level becomes equal to I_m - ΔG. In Figure 2, the level of state revenue is such that it does not allow the company to incur losses during the process of implementing digital technologies, since although in this case the company may agree to such an initiative, in reality, the volumes may be fundamentally different. Similarly, the same happens with the level of maximum profitability, which decreases by the amount of state support (the assumption is that the support amounts should be repaid over time on an interest-free basis) and becomes equal to I_p - ΔG. However, due to the benefit received from the use of state funds at the initial stage, the level of income that the company receives in the future becomes higher than that which would have been received without state assistance. This excess profit reaches the level of ξ. Thus, the state not only stimulates enterprises to implement digital technologies, but also allows them to increase their income, and therefore can also receive more benefits for itself, at least due to an increase in tax revenues.

How this process looks from the point of view of the state can be seen in Figure 3. The state has a certain amount of budget revenue, which it distributes among various projects from which it expects to receive a certain benefit. However, for the state, this benefit manifests itself not only in economic terms but also in other components – ecological and social. Thus, it is a derivative of the company's income and its activities, and is denoted in Figure 3 as ξ_g. On the other hand, the state will also receive benefits from the implementation of alternative projects: Figure 3 shows a variant of a set of projects that require state support, the benefit from the implementation of which is equal to ς. Thus, the total result obtained by the state can be depicted on the graph as the sum/difference of the area of the figures obtained as a result of the implementation of one or another project. It should be understood that the result may be negative, in which case the provision of such assistance is not necessary. Figure 3 is constructed in such a way that supporting enterprises in the implementation of digital technologies is beneficial, but the situation may also be the other way around.

While the model generally explains the basic principles of this approach, some other scenarios are also worth considering. For example, assistance can be non-reimbursable or, on the contrary, take the form of a loan. Moreover, it can be non-financial in nature: even assistance in the form of recommendations can significantly facilitate the process of implementing innovative technologies at enterprises. It is worth considering each of these options in more detail. Suppose the option of helping the company is such that it does not involve its return. In this case, the losses incurred by the state will be permanent, but the benefits that it will receive from the activities of such an enterprise should be comparatively greater. If, however, assistance is provided in the form of a loan, the state can also receive financial benefits from this kind of investment, but this will create an additional burden on the enterprise. Thus, one should expect a relatively lower level of utility to be obtained from the operation of such a company.

A separate type of support that should be evaluated is non-financial assistance. It may include recommendations or advice provided to such companies on the digitalisation of their enterprises. However, the principles for forming such support programs are usually quite large-scale, prepared in advance and aimed at providing recommendations to all similar companies at once. In this case, assistance to the enterprise is part of a large-scale program, and therefore it is not correct to make calculations, since it is necessary to carry out more global assessments that can evaluate the combined result of all potential companies that plan to implement digital technologies, with an assessment of the estimated costs of such support. To understand and assess the situation in the context of the digitalization of agriculture in Ukraine, an analysis of statistical data from the agricultural sector was carried out (Table 1).

Table 1. *Costs of conducting various scientific research in Ukraine, considering inflation, and expenditure structure*

Years	Expenditure on research and development	Fundamental scientific research	Applied scientific research	Scientific and technical (experimental) developments
2010	8,107	2,175	1,589	4,343
2011	8,139	2,104	1,734	4,301
2012	9,024	2,505	1,938	4,580
2013	9,769	2,572	1,965	5,232
2014	7,240	1,871	1,437	3,932
2015	5,860	1,310	1,044	3,506
2016	5,463	1,055	1,214	3,195
2017	5,575	1,219	1,318	3,038
2018	6,366	1,426	1,354	3,586
2019	6,291	1,364	1,325	3,601
2020	5,910	1,479	1,379	3,053
2021	6,604	1,627	1,510	3,467
2022	4,268	1,018	1,204	2,047
Years	**Expenditure on research and development, %**	**Fundamental scientific research, %**	**Applied scientific research, %**	**Scientific and technical (experimental) developments, %**
2010	100	26.8	19.6	53.6
2011	100	25.9	21.3	52.8
2012	100	27.8	21.5	50.8
2013	100	26.3	20.1	53.6
2014	100	25.8	19.8	54.3
2015	100	22.4	17.8	59.8
2016	100	19.3	22.2	58.5
2017	100	21.9	23.6	54.5
2018	100	22.4	21.3	56.3
2019	100	21.7	21.1	57.3
2020	100	25	23.3	51.7
2021	100	24.6	22.9	52.5
2022	100	23.8	28.2	48

Source: *compiled by the authors based on data Ukrstat (n.d.)*

Table 1 shows that the largest share of expenditures on research work is occupied by scientific and technical (experimental) developments. However, it is worth noting that, despite the nominal increase in expenditures on scientific work, taking into account inflation, the volume of expenditures is decreasing, which indicates negative trends in the development of the scientific sphere in Ukraine.

The volume of support for the digitalization of the agricultural sector can be partially estimated by evaluating the volume of state support for the sector (Fig. 4).

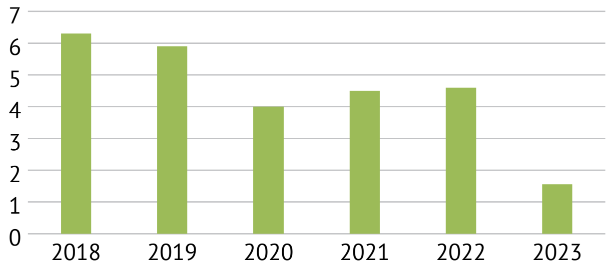

Figure 4. *Government support for agriculture in Ukraine, 2018-2023, billion UAH*
Source: *compiled by the authors based on Support for agriculture... (2023)*

As can be seen from Figure 4, the volume of government support for agriculture in Ukraine has been gradually decreasing over time, due to the onset of the COVID-19 crisis in 2020 and subsequently, the full-scale Russian invasion of Ukraine in 2022. In 2023, the volume of government support is the lowest, however, it is worth noting that it is provided not only from the state budget but also from individual international organizations, which is not considered in this figure. This trend is quite natural, given the problems in the country caused by the war. Nevertheless, the state should make more efforts supporting public sector enterprises if it intends to achieve better results in this direction. However, likely, this can only be done after the end of the war.

The digital economy interacts with agriculture through the introduction of technologies that enable more efficient production and management activities. For example, digital technologies such as sensors, drones, data analytics, and artificial intelligence are helping farmers manage their farms (Annosi *et al.*, 2020; Shoushtarian & Negahban-Azar, 2020). Precision irrigation and fertilization systems, for instance, ensure that crops receive the right amount of water and nutrients at the right time, leading to improved crop growth and yields (Bonvoisin *et al.*, 2020; Trivedi *et al.*, 2021). Digital technologies are also helping farmers anticipate and manage risks such as pests, diseases, and weather conditions. Sensors and monitoring systems can detect problems early on, enabling timely interventions that minimise crop losses (Lajoie-O'Malley *et al.*, 2020; Jiang *et al.*, 2022). They help to improve the management of the agricultural supply chain, and producers, in turn, can interact directly with potential buyers, optimising the processes of storage, transportation and sales. Furthermore, the digital economy is fostering innovation in agriculture (Lioutas *et al.*, 2021; Kukk *et al.*, 2022). Innovative startups and companies are developing new digital solutions for agricultural needs, leading to continuous improvement in the industry. Overall, innovative technologies in the context of digitalisation are contributing to increased efficiency, quality, and sustainability in agriculture. This results in enhanced production potential and competitiveness.

In the area of digitalisation, the state and companies engage in a complex interplay with several key aspects (Mihailova, 2020; Zhong *et al.*, 2022). The government's role encompasses providing incentives such as tax exemptions and grants for research and development, establishing essential infrastructure like communication networks and data centres, and promoting digital education to cultivate a skilled workforce (Prause *et al.*, 2020). Additionally, it safeguards citizen interests and human rights, ensures adherence to compatibility and security standards, and regulates the sector to enforce data protection and privacy regulations. State-driven innovation is crucial for advancing digital technologies and enhancing a nation's global competitiveness. Financial support such as grants, subsidies, and investments serve as a key instrument to stimulate digital technology research and development, benefiting both startups and established companies (Shepherd *et al.*, 2020; Rijswijk *et al.*, 2021). Moreover, reducing the tax burden, creating educational programmes for digital skills, especially targeting young people, and engaging in public procurement can further promote digital innovation.

A promising approach in this context is public-private partnership, which is essentially a form of cooperation between the state and private companies aimed at achieving common goals and solving specific tasks in the agricultural sector. This form of cooperation provides more opportunities to invest in new agricultural technologies and digitalization solutions (Sridhar *et al.*, 2023). Collaboration with the private sector allows for faster implementation of innovative solutions such as agricultural sensors, monitoring systems, data analysis, machine learning and other technologies that improve the efficiency and productivity of the industry. In some cases, this improves the ability to scale up and enter new markets.

As of 2024, Ukrainian companies are taking steps to introduce the latest technologies in the agricultural market. For example, Myronivsky Hliboproduct has implemented a large-scale SAP digital technology project aimed at improving the quality of management in key business sectors (Approach to digital..., 2023). The SAP system portfolio includes various modules for enterprise resource management, customer relations, procurement, master data, human resources, and poultry management; the company expected to achieve concrete results in terms of increased profits through its implementation. The implementation is still ongoing, so it is difficult to say how effective this initiative has been. Nevertheless, it is reasonable to assume that it will lead to an overall increase in the efficiency of the company's internal operations.

Regulating agriculture in the digital economy necessitates a comprehensive approach and the adoption of modern technologies, particularly in the context of Ukraine's current situation, which is characterized by a decline in innovation. Therefore, the government should invest in establishing digital infrastructure for rural areas, ensuring access to high-speed internet and other digital technologies. This includes providing financial incentives and support to farmers who adopt digital technologies such as agricultural drones, IoT devices, and farm management systems. Furthermore, it is important to provide access to training and advisory services on digital technologies for agriculture and to develop appropriate regulations to govern the use of digital technologies in agriculture, including data, privacy and cybersecurity. Monitoring and evaluating the effectiveness of digital technology implementation in agriculture is also important to identify successful practices and areas for further support. Moreover, engaging the private sector in developing digital solutions for agriculture through partnerships and investments is critical.

Regulating agriculture in the context of digitalisation entails the utilisation of digital technologies and policies aimed at fostering innovation, enhancing productivity, and ensuring the sustainability of the industry. This encompasses establishing a legal framework, stimulating innovation practices, and ensuring data protection and privacy. Implementing appropriate norms and legislation is a crucial aspect of regulating agriculture in the digital era. Clear rules regarding the collection, storage, and processing of data, particularly the personal data of farmers and other agricultural stakeholders, must be established. This should include requirements for storing data in a secure environment and restricting access to third parties without data owners' consent. Ukraine has certain legislative acts related to data processing and personal data protection. The primary law in this sphere is Law of Ukraine No. 2297-VI (2022), which regulates relations associated with the processing and protection of personal data, aiming to protect the fundamental rights and freedoms of individuals and citizens, including the right to privacy in the context of personal data processing. Nevertheless, this law has certain shortcomings, including a lack of strictness and clarity in the legal framework, leading to non-compliance by companies with data processing and storage regulations. This is less relevant to agricultural companies specifically, as they deal less extensively with personal data. In the context of digitalisation, cybersecurity has become a more pressing issue. To safeguard against cyberattacks, cybersecurity standards for farms and digital solution providers must be established. The full-scale Russian invasion of Ukraine further highlights this urgency. Ukraine has Law of Ukraine No. 2163-VIII (2024), but the law is relatively new, making it difficult to definitively assess its effectiveness.

Given the current war situation in Ukraine, where a significant portion of funding comes from partners The direct costs of the war are also enormous, including both payments to the military and the need for constant infrastructure repair. Thus, a likely way out of the situation is to establish more direct interactions with the state to facilitate the digitalisation process at enterprises. The maximum amount of assistance should be provided in the form of recommendations or any other services that do not require significant financial injections. Providing monetary assistance for such purposes may be practically impossible in the current budgetary circumstances.

DISCUSSION

The study revealed that digital technologies in agriculture have led to significant positive outcomes. This underscores the need for governments worldwide to actively promote the adoption of such technologies among businesses. The Ukrainian government is no exception, and they have taken some steps in this direction, as evidenced by some of the nascent legislative frameworks. However, as of 2024, these measures are insufficient to maximise the promotion of economic digitalisation in the country. Supporting companies in this endeavour, as suggested in the study's model, would be an effective strategy. Nevertheless, the ongoing war in the country complicates the implementation of such initiatives, as available funds are primarily directed towards military needs or social support. Therefore, providing consultative advice from the government is an effective measure in cases where direct financial allocation is not feasible or challenging.

In the current study, considerable attention was paid to describing the role of agriculture, in particular for Ukraine. A similar assessment was conducted by J. MacPherson *et al.* (2022), who noted that the potential of digital agriculture in addressing sustainable development challenges hinges on its integration into existing policies and how future conditions and regulatory frameworks shape its implementation. Overall, the authors formulated recommendations aimed at integrating digital technologies in agriculture to facilitate a gradual transformation in this direction. They further called for the use of the latest technologies in other areas of activity, not just agriculture. These recommendations remain relevant for Ukraine as well.

M.-H. Ehlers *et al*. (2021) also examined the characteristics of the agricultural sector in the context of digitalisation. They emphasised that digitalisation can increase the precision of policy instruments, but its impact on other parameters, such as freedom of action, cost distribution, and data domains, can be ambiguous. The authors described the significant role of digitalisation in developing flexible policy instruments in this sector. In this regard, the researchers formulated specific recommendations for politicians: they consisted of using digitalisation methods for more flexible use of traditional agricultural policy instruments, as well as to reduce costs in this context. However, this can also lead to a conflict of interest, primarily because not all interested parties may want such changes. All of this remains relevant in the context of Ukraine as well.

The benefits of digitalisation for agricultural companies were explored by A.M. Ciruela-Lorenzo *et al*. (2020). Their work highlights the transformative impact of digitalisation on the agricultural sector. It has been shown that these technologies contribute to economic stability by increasing operational efficiency and creating new customer engagement opportunities. However, challenges such as poor rural internet infrastructure, low technological literacy among farmers, and the scale of agricultural operations were also described. In this context, the authors emphasized the need for agricultural cooperatives to adopt digital technologies, diversify their activities, innovate, collaborate, and use digital tools to remain competitive. S. Fielke *et al*. (2020) noted that digitalisation leads to increased transparency, diversification, and ongoing restructuring of agricultural management. Additionally, attention was drawn to the growing focus on identifying opportunities to use digital technologies to improve sustainability in agricultural enterprises. In contrast, in Ukraine, significantly less attention is paid to such issues due to the complex situation in the country, primarily associated with the consequences of Russia's full-scale invasion.

It is noteworthy that digitalisation and the introduction of new technologies in agriculture allow for more effective achievement of sustainable development goals. While in Ukraine any such goals are relegated to the background, in the world as a whole, this is a rather important component of long-term state policy. In this context, digitalisation as a method of achieving sustainability of agro-food systems was studied by R.A. Bahn *et al*. (2021). The researchers noted that the use of digital transformation in the agro-food system allows for an increase in the potential of this sphere, and increases productivity and resource efficiency. However, they also drew attention to the fact that, despite all the advantages, problems may arise in this process, and the result may actually be negative. The researchers identified political priorities for digital transformation in agriculture, which should include, first of all, both financial support and training. The conducted study offered similar recommendations on how to promote digitalization in agriculture in the country. It is also worth noting that in any case, achieving sustainable development goals will become one of the important goals of state policy in Ukraine, at least after the end of the war.

This study also considered the components of a state policy that should be formed to achieve better goals in the context of the introduction of digital technologies. The formulation of more long-term goals in this context would be important for Ukraine. On the other hand, the question arises of how much this is possible at all in wartime conditions. This is why the political leadership should learn to act flexibly, in accordance with changing world events, in order to be able to appropriately and most effectively respond to any challenges.

CONCLUSIONS

The integration of digital technologies into the agricultural sector has brought significant advancements in efficiency, productivity, and sustainability. Innovative technologies such as sensors, drones, big data analytics capabilities, and artificial intelligence have revolutionised agricultural practices, enabling farmers to make data-driven decisions and optimise various aspects of their operations. This has led to increased yields, improved resource management, and enhanced product quality.

However, as presented in the study, successful implementation of digital technologies in agriculture requires cooperation between the state and the private sector. The government plays a crucial role in providing support and incentives to encourage innovation and adoption of digital solutions. This includes financial support through grants, subsidies, and investments in research and development, as well as the development and maintenance of appropriate infrastructure: in particular, the study showed a downward trend in support for the agricultural sector in the country, first due to the effects of the COVID-19 crisis and then to the outbreak of the full-scale invasion. The study showed that as of 2024, taking into account inflation, the costs of performing various types of research in Ukraine are gradually decreasing. Although not accounting for inflation, the level of expenditure on such work has increased. However, examining the real indicators reveals that research costs have nearly halved compared to 2010. At the same time, structurally more funds have begun to be allocated to applied scientific research. Thus, the state is currently facing the task of finding new sources of funding to improve the efficiency of the scientific research apparatus.

Some difficulties related to the legislative framework for the digitalisation process in Ukraine were considered, which, however, are difficult to resolve given the full-scale Russian invasion. Discounting of cash flows was not used in the evaluations. In addition, rather limited attention was paid to the analysis of the impact of the war on this process, due to the difficulty of evaluating this factor. Nevertheless, the analysis of this component remains relevant for future research. In addition, it is important to find opportunities for innovation in other types of enterprises.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Державне регулювання сільського господарства в умовах цифровізації економіки України

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Анотація. Сільське господарство грає стратегічну роль у забезпеченні населення продовольством. Це стає причиною значного втручання в даний сектор держави, а отже й формування якісних підходів до цього процесу залишається актуальним. В рамках даного дослідження метою стало надання рекомендацій до цього процесу в Україні, зокрема, на процеси в розрізі цифровізації економіки. Для цього було використано графічний аналіз, моделювання, абстрагування та метод логічних міркувань. В рамках роботи було детально описано роль цифрових технологій для досягнення більш ефективних результатів в контексті підвищення ефективності розвитку сільського господарства. Крім того, було зроблено висновок стосовно потреби взаємодії між державою та підприємствами в цьому напрямі. Пов'язано це, в першу чергу, зі складнощами, що можуть виникнути в компаніях, які будуть запроваджувати подібні практики. Розуміючи їхню наявність, менш вірогідним є подальше впровадження такого виду технологій на підприємствах. В роботі було запропоновано декілька підходів, що можуть бути використані для зниження негативного впливу на сільськогосподарські компанії. Зважаючи на наслідки повномасштабного вторгнення Росії в Україну, особлива увага була приділена нефінансовим підходам, а також проблемам, що існують в рамках актуальної законодавчої бази. Крім того, окремі висновки були сформовані на основі статистичних даних про розвиток науки та освіти в Україні в цілому. Практична цінність дослідження полягає в тому, що отримані результати дозволять підвищити ефективність функціонування державного сектору в Україні у сфері регулювання сільського господарства

Ключові слова: інновації; аграрний сектор; впровадження технологій; нормативно-законодавча база; менеджмент та управління

UDC: 664.3:633.85
DOI: 10.56407/bs.agrarian/2.2024.65

Ukrainian Black Sea Region Agrarian Science
Vol. 28, No. 2

Use of oilseeds as organic raw materials for the food industry

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Abstract. In the modern period, research on the creation of waste-free technologies and sustainable development of the food industry are relevant due to the need for rational use of natural resources and reduction of the environmental burden on ecosystems. The study was devoted to studying the possibilities of using oilcake, the residue after oil extraction from oilseeds, in the food industry. The study aimed to determine the effect of adding sunflower, rapeseed, soybean and flaxseed oilcake on the nutritional value, organoleptic properties and economic feasibility of food production. In the experimental part, the necessary analyses were carried out for bread, bars and biscuits made with the addition of oilcake in different proportions (10, 20, 30%). Study results showed that the use of oilcake significantly increases the content of proteins, fats and vitamins in products, improves their taste and texture, and reduces production costs. The greatest savings were achieved by adding 30% sunflower oil oilcake to the bread, about 10% compared to the control sample. Products with the addition of oilcake in proportions of

Article's History:
Received: 23.03.2024
Revised: 20.05.2024
Accepted: 11.06.2024

Suggested Citation:
Shevchuk, N., Petrova, O., Ziuzko, A., Trybrat, R., & Oliinychenko, T. (2024). Use of oilseeds as organic raw materials for the food industry. *Ukrainian Black Sea Region Agrarian Science*, 28(2), 65-76. doi: 10.56407/bs.agrarian/2.2024.65.

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10-20% had better organoleptic characteristics, without any noticeable effect on the taste, texture and overall perception of the products. The addition of 30% oilcake in most cases led to a deterioration in taste, especially in the case of rapeseed and mustard oilcake. Based on the research, it is possible to conclude that soybean oilcake is the best among the tested products for use in the food industry. The results of the experiments confirmed that oilcake can be effectively used as an ingredient in the food industry, helping to reduce production waste, increase the nutritional value of products and reduce their cost. This opens new opportunities for the development of innovative food products and contributes to the sustainable development of the food industry. The use of soybean oilcake can significantly improve the nutritional properties of breads, bars and biscuits, while also expanding the range of functional foods

Keywords: oilcake; waste-free technologies; sustainable production; functional foods; agricultural enterprise

INTRODUCTION

In the modern food industry, one of the main areas of focus is the search for new sources of raw materials that will increase the nutritional value of products, reduce their cost and help reduce production waste. The oilcake, which is the residue left over from the extraction of oilseeds, has significant potential for use in food production due to its rich composition of proteins, fats, vitamins and minerals. Currently, studies are exploring the possibility of using oilcake in the food industry. For example, sunflower oilcake is used as an additive in animal feed and for biofuel production (Abedini *et al.*, 2022). However, the use of oilcake in human food remains an area that has not been sufficiently explored.

Indian scientists R. Rani & L.S. Badwaik (2021) noted that the removal of fats from the dry residue of oilseeds improves the functional properties of such dry mass, an example being the analysis of sunflower, soybean and mustard seed oilcake. The removal of fats can make the oilcake more homogeneous and suitable for use in the food industry. This is especially relevant to produce products with a specific texture, such as bakery products. A noteworthy study of the impact of adding oilseed waste to sweets was also conducted in Turkey, where the dry residue after degreasing *Abelmoschus esculentus* seeds was obtained and added to muffins. As determined, the introduction of *Abelmoschus esculentus* seed oilcake into the recipe of muffins in concentrations from 0 to 20% increased their nutritional value, reduced the glycaemic index and improved oxidative stability (Akcicek *et al.*, 2024). However, this crop is not widely distributed in colder climatic zones. On the other hand, most of these studies focus on single types of oilcake and do not provide a comprehensive assessment of different types of oilcake and their impact on different types of products. At the same time, G. Difonzo *et al.* (2021) provided optimistic data on the use of oilcake in the diet of people on a gluten-free diet, both in terms of functional and organoleptic parameters. This indicates the prospects for further study and a vector for future research.

When studying oilseed by-products, it is necessary to address the possible biochemical toxicity of their composition, as noted by I. Smeu *et al.* (2022). Their study also noted that the regulation and control of this category of goods is insufficient for further commercialisation and requires additional attention. Solving the problem of quality control can increase the economic potential of using green crop processing technologies in the global market. The potential risks of using dry, defatted crop residues, such as soybean oilcake, were also reported in the Indian review by Z. Aksoylu Özbek & P. Günç Ergönül (2020), which notes the impact of anti-nutrients on the gastrointestinal tract of young animals. However, research on the health effects of oilcake in the human diet is still insufficient.

Thus, this study aimed not only to confirm the possibility of using oilcake as an ingredient in the food industry but also to provide specific recommendations for its use in oilseed processing processes to reduce waste and improve the nutritional value of products.

MATERIALS AND METHODS

The experimental part of the work on the study of the use of residues after oil extraction in the food industry was carried out in several research institutions in Ukraine (Institute of Food Biotechnology and Genomics of the National Academy of Sciences of Ukraine, National University of Food Technologies, Ukrainian Research Institute of Oils and Fats), which had the necessary infrastructure and equipment.

First, the crops for further analysis were selected. The choice of oilseeds for the study was based on several key factors, including their availability, chemical composition, economic feasibility and relevance to the food industry. These crops are the widely consumed sunflower *(Helianthus annuus*), rapeseed *(Brassica napus*), soybeans *(Semelita Saidina*), flax *(Linum usitatissimum*) and mustard. The raw material for the study was dry residues from soybean, sunflower and flax processing, which were provided by industrial enterprises specialising in oil production and farming and oilseeds cultivation. This provided access to high-quality oilcake for further experimental research.

The collected oilcake was dried in an oven at 60°C to a stable moisture level (5-7%). The dry oilcake was then ground in a mill to a powdered state for easy use in recipes. The developed recipes for bread, bars and biscuits with different proportions of oilcake (10, 20, 30%) were used to make samples that were subsequently analysed for vitamins and minerals, total energy value, and the organoleptic characteristics of these products. Control samples were also made without the addition of oilcake according to standard technological processes. The study used modern laboratory equipment from leading global manufacturers to ensure the accuracy and reliability of the results required for a comprehensive study of the properties of oilseed oilcake and its potential in the food industry.

The obtained samples were used for study and analysis: laboratory scales Sartorius Quintix 213-1S (high-precision scales with an accuracy of 0.001 g, designed for analytical work, Germany), Memmert UF110 drying oven (universal drying oven with adjustable temperature up to 300°C, Germany), Retsch ZM 200 oilcake grinder (high-speed mill for grinding dry samples with adjustable particle size, Germany), analyser, that uses near-infrared (NIR) spectroscopy to quickly and accurately determine the content of proteins, fats, moisture and other components in food products PerkinElmer DA 7250 NIR Analyzer (USA), Agilent Cary 60 UV-Vis spectrophotometer (with a range of 190-1100 nm, designed for the analysis of vitamins and minerals, USA).

To conduct the organoleptic evaluation of the samples, a group of 10 experts with strong taste buds was selected, who gave the appropriate scores based on certain criteria, such as taste, smell, texture and appearance, on a 5-point scale, where 1 is the worst score and 5 is the best. The results were averaged for each parameter. The taste characteristics of the products made with the addition of the respective test samples were also analysed. The products were coded for blind tasting and presented to the panellists. Experts filled in questionnaires to rate each product on a 5-point scale. The parameters evaluated were taste, smell, texture, appearance and overall impression. Three types of products with sunflower oilcake were selected for evaluation: bread, biscuits and energy bars. Sunflower, rapeseed, soybean, flax and mustard oilcake were added to the products in a certain ratio (10, 20 and 30% of the total dry ingredients). The ethical and safety aspects of the study were compiled following the Law of Ukraine No. 3221-IX (2023), as well as International Ethical Guidelines... (2016). The survey participants were informed about how their anonymity would be ensured, as well as understood the purpose of the survey and agreed to the use of their personal information necessary for the study. All risks were also warned of in advance. To ensure the accuracy and reproducibility of the results, recipes that comply with accepted standards used in the food industry, such as DSTU ISO 8586:2019 (2019) and DSTU 9188:2022 (2023), were selected.

RESULTS

Research on the use of oilseed oilcake in the food industry has broad prospects for improving technologies, optimising production and improving product quality to meet modern sustainability requirements and consumer preferences. In addition, formulating a rational approach to food use can help avoid difficulties associated with the disposal of edible residues in the food industry. When considering oilseeds, it is worth noting that the scope of their use is not limited to agriculture, although it is a significant part of it. In addition to the obvious use of vegetable oils in the pharmaceutical and cosmetic industries, they can also be used as raw materials for the technical production of lubricants, varnishes, soaps, and plastics, or as an environmentally friendly substitute for fuel. This indicates the generation of a large amount of dry waste, which often has no further use, although its chemical and biological composition is often not inferior in nutritional value and benefits to oil extract.

Considering various literature sources, the feasibility of using the oilcake of some of the above crops in the food industry is not unambiguous. For instance, rapeseed, which is popular in Europe due to its adaptability to different climatic conditions, can be toxic to some consumers. Due to glucosinolates and their breakdown products (isothiocyanates), rapeseed oilcake can cause thyroid disorders and other health problems. Therefore, a detailed study of various aspects of both the chemical composition of dry oilseed residues and their organoleptic characteristics is important for determining the most optimal ways to fully process plant material. The detailed analysis of the chemical composition of oilcake from five oilseeds for the content of proteins, fats, carbohydrates, vitamins and minerals conducted in this study demonstrated that soybean oilcake has the highest content of proteins and fats, and is additionally enriched with vitamins and minerals, which indicates its partial advantage in nutritional value over other samples in comparison (Table 1).

Table 1. *Chemical composition of oilcake of different oilseeds*

Parameters	Sunflower	Rapeseed	Soybean	Mustard	Flax
Proteins (%)	32.1	38.5	40.5	29.2	35.3
Fats (%)	12.5	15.7	19.3	14.2	13.1
Carbohydrates (%)	27.8	21.4	23.1	28.4	30.2
Fibre (%)	16.3	17.9	15.2	18.6	17.1
Vitamin E (mg/100g)	34.5	22.3	9.8	19.6	15.4
Calcium (mg/100g)	270	198	277	210	250
Iron (mg/100g)	6.2	7.8	15.7	9.5	8.1

Source: *compiled by the authors*

After selecting the types of oilseeds and obtaining dry residue from them, the next step was to adapt the recipes for biscuits, energy bars and bread with the addition of oilcake in different percentages. At the same time, there was a risk of changes in the consistency of the finished products, as well as a negative impact on their taste, texture and appearance. The crushed oilcake was stored in airtight containers until use to prevent moisture from entering. To ensure reproducibility of the results obtained during the study, the same percentages of added oilcake (10, 20 and 30%) were used, and a control sample was prepared for each product. Classic products with affordable prices were used in the preparation, namely: flour, oatmeal, honey, sugar, butter, yeast and water (Table 2).

Table 2. *Recipes for products with added oilcake*

Product	Ingredient	Control sample	Sample with 10% oilcake	Sample with 20% oilcake	Sample with 30% oilcake
Bread	Flour, g	500	450	400	350
Oilcake, g	0	50	100	150	
Water, ml	300	300	300	300	
Yeast, g	10	10	10	10	
Bars	Oat flakes, g	200	180	160	140
Oilcake, g	0	20	40	60	
Honey, g	100	100	100	100	
Cookies	Flour, g	300	270	240	210
Oilcake, g	0	30	60	90	
Oil, g	150	150	150	150	
Sugar, g	100	100	100	100	

Source: *compiled by the authors*

Food products obtained with the addition of rapeseed and soybean oilcake were subjected to detailed chemical analysis as promising targets for further research. The inclusion of oilcake in the bread improved its nutritional value by increasing the protein and mineral content (Table 3). However, as the concentration of oilcake increased, the volume of bread decreased, and its texture changed.

Table 3. *Energy value of bread made with rapeseed and soybean oilcake*

Parameters	Control	Soybean oilcake (10%)	Soybean oilcake (20%)	Soybean oilcake (30%)	Rapeseed oilcake (10%)	Rapeseed oilcake (20%)	Rapeseed oilcake (30%)
Calorie content (kcal)	250	245	240	235	245	240	235
Proteins (%)	8.5	10.5	12.5	14	10	12	13.5
Fats (%)	4	5.5	7	8.5	5	6.5	8
Carbohydrates (%)	45	42.5	40	37.5	42	39.5	37
Fibre (%)	2.5	3	3.5	4	3	3.5	4

Table 3, Continued

Parameters	Control	Soybean oilcake (10%)	Soybean oilcake (20%)	Soybean oilcake (30%)	Rapeseed oilcake (10%)	Rapeseed oilcake (20%)	Rapeseed oilcake (30%)
Vitamin E (mg/100g)	0.5	1	1.5	2	1	1.5	2
Calcium (mg/100g)	20	25	30	35	25	30	35
Ferum (mg/100g)	1	1.5	2	2.5	1.5	2	2.5

Source: *compiled by the authors*

However, the resulting modified biscuit structure provided it positive textural characteristics, and changes in the overall nutritional value were also observed compared to the control sample (Table 4).

Table 4. *The energy value of cookies made with rapeseed and soybean oilcake*

Parameters	Control	Soybean oilcake (10%)	Soybean oilcake (20%)	Soybean oilcake (30%)	Rapeseed oilcake (10%)	Rapeseed oilcake (20%)	Rapeseed oilcake (30%)
Calorie content (kcal)	500	490	480	470	495	485	475
Proteins (%)	6	8	10	12	7.5	9.5	11.5
Fats (%)	25	27	29	31	26.5	28.5	30.5
Carbohydrates (%)	60	57	54	51	57.5	54.5	51.5
Fibre (%)	4	5	6	7	5	6	7
Vitamin E (mg/100g)	1	1.5	2	2.5	1.4	1.9	2.4
Calcium (mg/100g)	30	35	40	45	35	40	45
Iron (mg/100g)	1.5	2	2.5	3	2	2.5	3

Source: *compiled by the authors*

The addition of rapeseed and soybean oilcake to the energy bars resulted in a significant increase in the content of vitamin E and iron per 100 g of the finished product, while the calorie content decreased (Table 5).

Table 5. *Nutritional value of energy bars made with rapeseed and soybean oilcake*

Parameters	Control	Soybean oilcake (10%)	Soybean oilcake (20%)	Soybean oilcake (30%)	Rapeseed oilcake (10%)	Rapeseed oilcake (20%)	Rapeseed oilcake (30%)
Calorie content (kcal)	400	390	380	370	395	385	375
Proteins (%)	10	12	14	16	11.5	13.5	15.5
Fats (%)	15	17	19	21	16.5	18.5	20.5
Carbohydrates (%)	50	46.5	43	39.5	47	43.5	40
Fibre (%)	5	6	7	8	6	7	8
Vitamin E (mg/100g)	0.8	1.3	1.8	2.3	1.2	1.7	2.2
Calcium (mg/100g)	50	55	60	65	55	60	65
Iron (mg/100g)	2.5	3	3.5	4	3	3.5	4

Source: *compiled by the authors*

These data show that the addition of both soybean and rapeseed oilcake significantly increases the content of proteins and some vitamins and minerals, with a slight decrease in calorie content. However, organoleptic properties and economic factors must also be addressed when determining the optimal proportions of oilcake in recipes. First, an expert group of 10 people tasted samples of oilcake from 5 different types of oilseeds, and the average result was tabulated (Table 6). Soybean oilcake received the highest scores for all parameters, including taste (4.5) and texture (4.3). This indicates high quality and suitability for use in the food industry.

Table 6. *Evaluation of organoleptic parameters of dry residue of oilseeds*

Sample	Taste	Odour	Texture	Appearance
Sunflower oilcake	4.2	3.8	4	4.1
Rapeseed oilcake	4	3.9	3.8	4
Soybean oilcake	4.5	4.2	4.3	4.4
Flaxseed oilcake	3.6	3.4	3.9	3.8
Mustard oilcake	4.1	4	4	4.2

Source: *compiled by the authors*

The smell of the bars with rapeseed and flaxseed oilcake was rated the lowest among the other samples. This may indicate the presence of specific aromatic components in these oilcakes that affect consumer perception of the product. Flaxseed oilcake also received the lowest overall score, indicating the need for further study and improvement of technologies and processing of plant material. To ensure that the results obtained previously were representative of the blind tasting method, participants were asked to fill out questionnaires, where they had to rate the taste, aroma, texture and appearance of the product on a 5-point scale. The evaluation results are presented in tables below (Tables 7-9).

Table 7. *Evaluation of organoleptic parameters of bread*

Parameter	Taste	Aroma	Texture	Appearance
Control	4.5	4.4	4.5	4.6
Soybean oilcake (10%)	4.3	4.2	4.3	4.4
Soybean oilcake (20%)	4	3.9	4	4.1
Soybean oilcake (30%)	3.5	3.4	3.6	3.7
Rapeseed oilcake (10%)	4.2	4.1	4.2	4.3
Rapeseed cake (20%)	3.9	3.8	3.9	4
Rapeseed oilcake (30%)	3.4	3.3	3.5	3.6
Rapeseed oilcake (10%)	4.1	4	4.1	4.2
Rapeseed oilcake (20%)	3.8	3.7	3.8	3.9
Rapeseed oilcake (30%)	3.2	3.1	3.3	3.4
Mustard oilcake (10%)	4	3.9	4	4.1
Mustard oilcake (20%)	3.6	3.5	3.6	3.7
Mustard oilcake (30%)	3	2.9	3.1	3.2
Sunflower oilcake (10%)	4.4	4.3	4.4	4.5
Sunflower oilcake (20%)	4.1	4	4.1	4.2
Sunflower oilcake (30%)	3.7	3.6	3.7	3.8

Source: *compiled by the authors*

Table 8. *Evaluation of organoleptic parameters of bread*

Parameter	Taste	Aroma	Texture	Appearance
Control	4.8	4.7	4.8	4.9
Soybean oilcake (10%)	4.6	4.5	4.6	4.7
Soybean oilcake (20%)	4.3	4.2	4.3	4.4
Soybean oilcake (30%)	4	3.9	4.1	4.2
Rapeseed oilcake (10%)	4.5	4.4	4.5	4.6
Rapeseed oilcake (20%)	4.2	4.1	4.2	4.3
Rapeseed oilcake (30%)	3.9	3.8	3.9	4
Rapeseed oilcake (10%)	4.4	4.3	4.4	4.5
Rapeseed oilcake (20%)	4.1	4	4.1	4.2
Rapeseed oilcake (30%)	3.7	3.6	3.8	3.9
Mustard oilcake (10%)	4.3	4.2	4.3	4.4
Mustard oilcake (20%)	3.9	3.8	3.9	4
Mustard oilcake (30%)	3.5	3.4	3.6	3.7
Sunflower oilcake (10%)	4.7	4.6	4.7	4.8
Sunflower oilcake (20%)	4.4	4.3	4.4	4.5
Sunflower oilcake (30%)	4.1	4	4.1	4.2

Source: *compiled by the authors*

Table 9. *Evaluation of organoleptic parameters of energy bars*

Parameter	Taste	Aroma	Texture	Appearance
Control	4.7	4.6	4.7	4.8
Soybean oilcake (10%)	4.5	4.4	4.5	4.6
Soybean oilcake (20%)	4.2	4.1	4.2	4.3
Soybean oilcake (30%)	3.8	3.7	3.9	4
Rapeseed oilcake (10%)	4.4	4.3	4.4	4.5

Table 9, Continued

Parameter	Taste	Aroma	Texture	Appearance
Rapeseed oilcake (20%)	4.1	4	4.1	4.2
Rapeseed oilcake (30%)	3.7	3.6	3.8	3.9
Rapeseed oilcake (10%)	4.3	4.2	4.3	4.4
Rapeseed oilcake (20%)	4	3.9	4	4.1
Rapeseed oilcake (30%)	3.5	3.4	3.6	3.7
Mustard oilcake (10%)	4.2	4.1	4.2	4.3
Mustard oilcake (20%)	3.8	3.7	3.8	3.9
Mustard oilcake (30%)	3.3	3.2	3.4	3.5
Sunflower oilcake (10%)	4.6	4.5	4.6	4.7
Sunflower oilcake (20%)	4.3	4.2	4.3	4.4
Sunflower oilcake (30%)	3.9	3.8	3.9	4

Source: *compiled by the authors*

For bread, the lowest scores were obtained for samples using mustard oilcake, especially at higher percentages. Therefore, for the further application of this technology in large-scale food production, it is necessary to focus on the development of this recipe. The expert group highly appreciated the organoleptic characteristics of the biscuits with the addition of defatted dry sunflower residue.

Based on the results of chemical analysis, organoleptic evaluation and economic analysis, it is possible to conclude that the proposed technology is feasible, as well as to formulate the direction of further research and prospects for the use and processing of oilseeds. The results of the study showed that soybean and rapeseed oilcakes demonstrated high protein composition and functional properties, which makes them the most promising for use in the food industry. While rapeseed oilcake has potential for use in the food industry due to its high protein and healthy fats, it also contains antinutrients that can cause anaemia if consumed over a long period. The taste characteristics of products made with modified formulations are also controversial, as they may not be suitable for products with neutral or delicate flavours. To overcome these problems, additional technological processes may be required, such as detoxification, solvent purification, and others, but for a clearer understanding of the algorithm of action, this topic needs to be studied in more detail in future research papers. Thus, it is possible to conclude that the addition of oilcake to food products can improve their nutritional value, but careful consideration should be given to the choice of culture and percentage of addition to avoid deterioration of organoleptic properties. Moreover, after analysing the cost of food products with the addition of previously recycled raw materials, the attractiveness of introducing this technology becomes even more obvious (Table 10). Sunflower oilcake provides the greatest savings, and mustard oilcake the least.

Table 10. *Summary analysis of the cost of bread with the addition of oilseed oilcake (per 100 kg of bread), UAH*

Parameter	Cost of oilcake	Cost of flour	Other ingredients	Electricity	Salary expenses	Packaging materials	Total cost of sales
Control	0	1,500	500	50	100	30	2,180
Soybean oilcake (10%)	80	1,350	500	50	100	30	2,110
Soybean oilcake (20%)	160	1,200	500	50	100	30	2,040
Soybean oilcake (30%)	240	1,050	500	50	100	30	1,970
Rapeseed oilcake (10%)	100	1,350	500	50	100	30	2,130
Rapeseed oilcake (20%)	200	1,200	500	50	100	30	2,060
Rapeseed oilcake (30%)	300	1,050	500	50	100	30	1,990
Rapeseed oilcake (10%)	90	1,350	500	50	100	30	2,120
Rapeseed oilcake (20%)	180	1,200	500	50	100	30	2,050
Rapeseed oilcake (30%)	270	1,050	500	50	100	30	1,980
Mustard oilcake (10%)	110	1,350	500	50	100	30	2,140
Mustard oilcake (20%)	220	1,200	500	50	100	30	2,070
Mustard oilcake (30%)	330	1,050	500	50	100	30	2,000
Sunflower oilcake (10%)	70	1,350	500	50	100	30	2,100
Sunflower oilcake (20%)	140	1,200	500	50	100	30	2,030
Sunflower oilcake (30%)	210	1,050	500	50	100	30	1,960

Source: *compiled by the authors*

The use of oilcake in the food industry is an economically viable solution if the right crop and percentage are chosen. Soybean and sunflower oilcake are particularly beneficial, as they provide the lowest cost while maintaining or even increasing the nutritional value of the products. Flax and mustard oilcake have the highest cost, which can reduce their economic attractiveness despite their potential nutritional benefits.

DISCUSSION

The choice of oilseeds for further research was based on the prevalence of certain crops and the problem of their waste disposal, and a detailed literature analysis addressed possible problems in the processing of experimental data.

In general, the processing and utilisation of agricultural waste has become a hot topic among various scientific groups as food demand grows. Several studies point out that there are not enough ways to solve this problem (Ginni *et al.*, 2020; Valencia *et al.*, 2024). On the other hand, a review by Portuguese scientists provides ways to implement such processing safely, accounting for environmental safety (Berenguer *et al.*, 2023). In their research, they used green extraction methods, which are a promising area in the face of environmental impact from various sources of environmental pollution, such as military operations, industrialisation, and others. However, such methods also have disadvantages, namely the use of solvents that are not universal, and therefore the extracts obtained from them have a nutrient-poor composition, although in this case the dry residue, on the contrary, will contain a greater variety of useful compounds. However, in this study, the emphasis is shifted towards the utilisation of waste generated during oilseed processing, so the use of green extraction methods is likely to be detrimental to obtaining reproducible results.

Waste bioprocessing was also discussed in earlier scientific papers, which noted the prospects for its further use in value-added products (Jin *et al.*, 2018; Singh *et al.*, 2022; Tsykhanovska *et al.*, 2023). According to Czech scientists J. Bárta *et al.* (2021), a noteworthy idea for the further sale of oilseed oilcake is also its use as a substrate to produce antibiotics or enzymes. A similar study was conducted on the fermentation of *Cannabis sativa* meal, the author of which noted positive changes in the biochemical composition of products during the controlled fermentation of yoghurt and kefir on the matrix of dry oilseed residue (Łopusiewicz *et al.*, 2022). However, although this is an innovative approach, it requires significant financial support, and its subsequent profitability when applied to technological processes is not fully optimised.

Moreover, I. Usman *et al.* (2023) highlighted the potential medicinal properties of oilseed waste and consider their role in society to be more valuable than is accepted in the world scientific community. To confirm such statements, well-funded studies are needed, but whether this is economically feasible remains a question. Another thing is the implementation of affordable solutions, an algorithm that can be easily implemented even on a limited budget. Although there are currently sufficient sources of information to formulate general theses and gaps in the study of the potential use of defatted dry residues from the production of vegetable oils and other agricultural products, it is of particular interest to compare different types of such crops, to find patterns between the properties of edible oilseed oilcake and those used in the cosmetic and pharmaceutical industries (Krzyżostan *et al.*, 2024).

Several scientific papers mention the use of sesame, pumpkin, soy, flax and other meals (Teh & Bekhit, 2015). Most of them are used as animal feed, but some are also used in other areas (Raksha-Slusareva *et al.*, 2019; Kokić *et al.*, 2024; Nouska *et al.*, 2024). Thus, oilcake is used not only as animal feed but also for pest management in agriculture. The oilcake has properties that can help in the management of nematodes, and microscopic worms that cause damage to plants (Abedini *et al.*, 2023). Although the environmental friendliness of these methods is questionable and not yet well understood, it is also worth understanding that such innovations require comprehensive consideration and calculation of risks. Healthy food is gaining popularity, with large companies seeking to offer gluten-free products with a high protein content (Kiewlicz & Rybicka, 2019). The oilseed oilcake is well suited to be added to the diet of athletes or other people following a protein diet.

Experimental innovative additions to food products are a good marketing strategy, i.e. in addition to increasing the nutritional value of products, changing recipes can also affect their consumer appeal. Scientists from several countries have also come to similar conclusions when studying functional natural foods (Samakradhamrongthai *et al.*, 2021). Sunflower oilcake has already been widely used in the food industry, which is why there is more comprehensive data on the safety and biochemical composition of potential products made from it (Kachel-Jakubowska *et al.*, 2016; Grahovac *et al.*, 2024). As such, B.G. Subaşı *et al.* (2021) noted that sunflower oilcake can be modified according to the needs and desired organoleptic properties of the products formed from it. Given its satisfactory flavour and low cost, it is possible to conclude that sunflower oilcake is a noteworthy object for research. Degreased dry oilseed residues have significant prospects for use in the food industry due to the presence of plant proteins, amino acids, vitamins and fatty acids necessary for the human body (Cestonaro *et al.*, 2024). However, further research is needed to identify new beneficial properties and potential harms that these products may have.

Addressing flaxseed, known for its high content of omega-3 fatty acids, linolenic acid, proteins and dietary fibre, as a raw material for obtaining samples, it was noted that there is a contradiction in the position of different scientists regarding its use in the food and agricultural industries. Although flaxseed oilcake has a high nutritional value (Wirkijowska *et al.*, 2019), its use in the food industry faces certain challenges, such as high fibre content, presence of toxic substances, limited fat stability, allergenicity, impact on texture and specific flavour properties (Taglieri *et al.*, 2022). Overcoming these shortcomings requires additional technological solutions and adjustments to production processes. In this study, the use of flaxseed oilcake compared to the dry residues of other oilseeds studied showed the worst performance, but the main characteristics of taste and chemical parameters are sufficient for use as food or additives to food, so this crop should not be excluded from further research in a similar direction.

CONCLUSIONS

The study showed that oilcake from various oilseeds can be effectively used in the production of bread, energy bars and biscuits. Flax and sunflower were chosen as the main oilseeds for the study due to their availability, high yields, valuable chemical properties, economic feasibility and relevance to the food industry. These factors provided optimal conditions for research and further use of products with the addition of oilcake. Based on the research, it is possible to conclude that soybean oilcake is the best among the tested products for use in the food industry. High protein and fat increase the nutritional value of products, which is well received by consumers in terms of organoleptic properties and helps to reduce production costs. The use of soybean oilcake can significantly improve the nutritional properties of bread, bars and biscuits, as well as help reduce production waste and increase the profitability of food products.

The best results were obtained by adding 10-20% oilcake, which improved the nutritional value of the products without significantly deteriorating their organoleptic properties. Rapeseed oilcake had certain disadvantages due to its high content of glucosinolates, which could affect the taste of products. The economic analysis confirmed the feasibility of using oilcake as an additional raw material in the food industry. Most studies describing research on the use of oilcake in the food industry mainly focus on specific types of oilcake and limited product types. For instance, as of 2024, sunflower oilcake is used as an additive to animal feed and for biofuel production, as well as in certain bakery and confectionery products. However, there has been no comprehensive approach to the study of different types of oilcakes and their impact on different types of food products.

The research novelty is determined by the systematic approach to the study of the use of oilcake from different oilseeds in various food products. The chemical analysis, organoleptic evaluation and economic analysis of bread, bars and biscuits with the addition of oilcake was used to conclude the feasibility of using oilcake in different types of products. The optimal proportions of oilcake addition were also determined to achieve the best results. On the other hand, this work also has several limitations, including a small variety of proportions of oilcake use and the lack of studying the impact of oilcake addition on the shelf life of new food products, which can be implemented in further research. Among the samples studied, the worst results were observed for the dry residue of flaxseed, but further study of this topic may open new ways of modernised technology for the utilisation of oilseed waste with a specific biochemical composition.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Використання олійних культур як органічної сировини для харчової промисловості

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Анотація. У сучасний період, дослідження, спрямовані на створення безвідходних технологій та сталого розвитку харчової промисловості, стало актуальною темою через потребу в раціональному використанні природних ресурсів і зниженні екологічного навантаження на екосистеми. Дана наукова робота присвячена дослідженню можливостей використання макухи, залишків після екстракції олії з олійних культур, у харчовій промисловості. Метою дослідження стало визначення впливу додавання макухи соняшника, ріпаку, сої та льону на харчову цінність, органолептичні властивості та економічну доцільність виробництва харчових продуктів. В експериментальній частині були проведені необхідні аналізи для хліба, батончиків і печива, виготовлених з додаванням макухи в різних пропорціях (10 %, 20 %, 30 %). Результати дослідження показали, що використання макухи значно підвищує вміст білків, жирів і вітамінів у продуктах, покращує їх смакові характеристики та текстуру, а також знижує собівартість виробництва. Найбільшу економію забезпечило додавання 30 % соняшникової макухи до хлібу, близько 10 % в порівнянні з контрольним зразком. Продукти з додаванням макухи в пропорціях 10-20 % мали кращі органолептичні характеристики, без помітного впливу на смак, текстуру та загальне сприйняття продуктів. Додавання 30 % макухи у більшості випадків призводило до погіршення смаку, особливо у випадку макухи ріпаку та гірчиці. На основі проведених досліджень можна зробити висновок, що макуха сої є найкращою серед досліджуваних для використання в харчовій промисловості. Результати проведених експериментів підтверджують, що макуха може бути ефективно використана як інгредієнт у харчовій промисловості, сприяючи зменшенню відходів виробництва, підвищенню харчової цінності продуктів і зниженню їх собівартості. Це відкриває нові можливості для розробки інноваційних харчових продуктів та сприяє сталому розвитку харчової промисловості. Використання макухи сої може значно покращити поживні властивості хліба, батончиків і печива, розширюючи також асортимент функціональних продуктів харчування

Ключові слова: макуха; безвідходні технології; стале виробництво; функціональні харчові продукти; аграрне підприємство

ВІСНИК АГРАРНОЇ НАУКИ ПРИЧОРНОМОР’Я

Науковий журнал

Том 28, № 2. 2024

Заснований у 1997 р.
Виходить чотири рази на рік

Оригінал-макет видання виготовлено у видавничому відділі
Миколаївського національного аграрного університету

Відповідальний редактор:
Г. Чижевська

Редагування англомовних текстів:
С. Воровський, К. Касьянов

Комп'ютерна верстка:
О. Глінченко

Підписано до друку 11 червня 2024 р.
Формат 60*84/8
Умов. друк. арк. 9,1
Наклад 300 прим.

Адреса видавництва:
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UKRAINIAN BLACK SEA REGION AGRARIAN SCIENCE

Scientific Journal

Volume 28, No. 2. 2024

Year of establishment: 1997
Publication frequency: Four times a year

The original layout of the publication was made in the Publishing Department
of Mykolaiv National Agrarian University

Managing Editor:
H. Chyzhevska

Editing English-language texts:
S. Vorovsky, K. Kasianov

Desktop publishing:
O. Glinchenko

Signed for print of June 11, 2024
Format 60*84/8
Conventional printed pages 9.1
Circulation 300 copies

Publishing Address:
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
tel.: +38(0512) 70-93-54
E-mail: info@bsagriculture.com.ua
https://bsagriculture.com.ua/en