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Agriculture in the face of new digitization technologies

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Abstract. Agriculture plays a vital role in food production, resource utilization, and employment but faces challenges from population growth, climate change, and food shortages. The development of information technology has significantly contributed to the industry's development, and modern technologies such as artificial intelligence, the Internet of Things, computer vision, and machine learning have revolutionized agricultural practices. The

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purpose of this review is to explore the adoption of digital technologies in agriculture, with a specific focus on their application in livestock breeding. Through the examination of current literature and the utilization of various research methods, this review contributes to the existing knowledge in the field. It is established that the latest information tools allow collecting, analysing data, automating tasks and supporting decision-making, which leads to increased agricultural efficiency, resource management and sustainable development. It has been proven that modern technologies play a crucial role in increasing agricultural production, improving the efficiency of livestock and crop production. These technologies include devices and sensors, data analytics and decision support systems, as well as systems for overall farm productivity assessment. Precision technologies in agriculture, thanks to automation, sensors and machine learning, allow farmers to monitor animal health, optimise feed consumption, detect diseases at early stages and increase overall productivity. IT solutions in agriculture facilitate data processing, visualisation and decision-making, leading to lower costs, greater efficiency and improved food security. The study provides practical insights for farmers and other agricultural stakeholders who can benefit from accurate information, real-time monitoring and automated processes through the integration of modern technologies, ultimately improving agricultural practices and sustainability

Keywords: sustainable agriculture; digitalization; precision livestock farming; farm management systems; data-driven farming

INTRODUCTION

Agriculture is a crucial sector in many countries that includes crop production and animal husbandry. It plays a vital role in food production, resource utilization, and employment (Gamage *et al.*, 2023). The current challenges of global agriculture are the ever-increasing world population, climate change, food shortages, and land degradation (Subeesh & Mehta, 2021). Therefore, to improve the agricultural food production chain and ensure its maximum safety, it is necessary to implement systems to support farmers. The development of information technology has contributed to the rapid development of various industries (Mahfuz *et al.*, 2022). Modern information technologies in agriculture are recognized as a significant driver of the industry's development (De Vries *et al.*, 2023). Large-scale farms invest heavily in computerization, improving systematization and management. Access to computers and the internet opens up opportunities for farmers (Mendes *et al.*, 2022). The application of digital technology in agriculture has improved efficiency and quality of agricultural production (Yao & Sun, 2023), leading to increased awareness among farmers about the potential of computer and IT networks in production processes (Javaid *et al.*, 2023).

Computer programs support animal inventory, veterinary treatments, machinery maintenance, health assessment, and nutrition management. Decision support systems aid strategic and tactical decision-making by providing relevant information (Eriksen *et al.*, 2022). Advanced technologies, including automatic control systems and GPS, optimize productivity and resource utilization in crop and animal production. Modern technologies in animal husbandry improve welfare, profitability, food security, and environmental impact reduction (Balasundram *et al.*, 2023). Precision dairy farming (PDF) utilizes technology to monitor various animal production, physiological, and behavioral parameters, including heat detection, animal activity, and milk yield. R. Antanaitis *et al.* (2021) implemented precision breeding technologies to assess heat stress indicators such as humidity and temperature in dairy cattle. The reticulorumen parameters, including temperature, pH, rumination index, and walking activity of cows, were measured using boluses. The comprehensive farm management software solution DelPro by DeLaval Inc. (Tumba, Sweden) was used to analyze these measurements. The findings confirm the significance of employing innovative solutions to evaluate heat stress and its impact on animals.

The purpose of this review article was to present the most essential and current information on the implementation of digitization in agriculture, with particular emphasis on livestock breeding, by examining the use of IT tools in agriculture and exploring relevant literature from databases like Google Scholar, ScienceDirect, and Web of Science. Moreover, the search was narrowed down to 2018-2020. The review aims to contribute to a comprehensive understanding of the advancements and potential of digital technologies in enhancing livestock breeding practices and overall agricultural productivity.

MODERN TECHNOLOGIES FOR ENHANCED AGRICULTURAL PRODUCTION

Agriculture is pivotal in providing food products and raw materials for industries, shaping the natural environment, creating jobs, and contributing to the landscape (Pawlak & Kołodziejczak, 2020). To ensure satisfactory profits, agriculture must leverage appropriate knowledge and implement modern technologies that enhance farm production, alleviate owners from excessive workloads, safeguard the environment, and ensure food safety (Holzinger *et al.*, 2023). Like other farm sectors, agriculture seeks opportunities to maximize income by adopting modern equipment and software, reducing production costs, determining production direction, and improving decision-making. Modern technologies are also introduced to animal production in order to maximize profit or improve the welfare of farm animals (Bao & Xie, 2022; Racewicz *et al.*, 2021).

IT systems have become an integral and pervasive agribusiness component, seamlessly integrated into every sector's operation (Gabriel & Gandorfer, 2023). Modern technologies used in agriculture include devices and sensors (position determination systems, sensors for the content of soil components, the amount of water in the soil, yield forecasting, environmental, soil preparation for sowing, distribution of fertilizer in the soil), data analysis and decision support systems (standards and protocols used to monitor production, algorithms for data processing and reasoning for individual types of production, easy-to-use software) and general farm performance evaluation systems (Gabriel & Gandorfer, 2023; Saranya *et al.*, 2023; Wakchaure *et al.*, 2023). The devices used in modern agriculture are autonomous tractors, harvesting robots, drones, and sensors that measure and monitor crops. In addition, these devices communicate with each other and collect and exchange data (Adusumalli, 2018). Technologies used in agriculture are divided into guidance systems (hardware systems and software that allow you to drive vehicles and machines in the field), data acquisition technologies (from sensors mounted on machines and stationary on the ground, from detection systems using satellites and aircraft, from data collecting and storing spatial data, e.g., yield maps, soil fertility, vegetation coverage of the substrate, soil water content and from sensors and systems evaluating the welfare of farm animals), as well as executive technologies (software and hardware, e.g., automatically controlled sprayer nozzles, agricultural robots, systems of fertilizer seeders with automatic change of the dose of fertilizers, depending on the information contained in the map of soil fertility) (Sadjadi & Fernández, 2023; Xie *et al.*, 2022; Xu *et al.*, 2022).

Up-to-date and accurate information is most valuable to the modern farmer. Due to the growing world population, the demand for food is growing. For this purpose, precision technology in agriculture is used. Automation can improve agriculture's quality and productivity by reducing errors and early detection of diseases in crops or animals (Shin *et al.*, 2022). IT systems used for decision support require a sufficiently large database and constant data supply to function effectively and achieve desired outcomes. In plant production, the collected data inform about the spatial and temporal variability of plant characteristics and the environment and external conditions, e.g., about the properties of soils, plants, pests, estimated yields, and identification of local variability. The data should also include information on the weather forecast and marketing forecasts. The farmer at each stage of cultivation should be able to locate the place from which the information is provided, properly analyze this data, and use the calculations and information provided (Jones *et al.*, 2022). In animal production, data are collected, e.g., on the milk yield of cows, the physical activity of animals, their health, and consumption of water and fodder. Through proper data management, the farm's production efficiency is increased. Based on the collected information, maps with soil and plant data are created. Then models and application maps are created. Sowing, fertilization, and plant protection are carried out based on the maps. The doses of agents are appropriately specified for each place in the field (Aquilani *et al.*, 2022).

Agriculture stands apart from other industries due to several distinctive characteristics. These include its intimate link with the land, reliance on climatic factors, dependence on the specific needs of cultivated plants and animal husbandry, the time-sensitive nature of economic processes, the influence of seasonal variations, the diversification of production, and the versatility of agricultural products. These unique attributes collectively set agriculture apart and shape its requirements and challenges (Pawlak & Kołodziejczak, 2020). The unique production conditions influence the outcomes and expenses of agriculture. Agricultural production has its own distinct characteristics that set it apart from other sectors of the economy. These conditions, both internal and external, play a crucial role in the operation of agricultural companies. These factors include both natural elements such as soil and climate (including the length of the vegetation period, availability of water resources, average and minimum temperatures, soil fertility, occurrences of floods and droughts, etc.), as well as economic factors (such as price levels, demand, logistics, and transportation conditions, labor availability, costs of raw materials and supplies, etc.). These specific conditions have a decisive impact on agricultural operations, shaping the challenges and opportunities agro-companies face (Sadjadi & Fernández, 2023).

In light of growing global food demand, modern agriculture is significantly benefited by accurate, comprehensive data and precision technology, facilitating early disease detection, efficient resource use, and enhanced productivity. Unique in its dependence on variable natural and economic factors, the sector's outcomes and challenges are directly influenced by the specific conditions, making the integration of predictive and responsive data analysis critical in navigating its unique complexities.

PRECISION LIVESTOCK FARMING AND CROP PRODUCTION

Due to the integration of computer systems, sensors, and machine learning in agriculture, it is possible to implement precision livestock farming (PLF). It aims to make it easier for breeders to monitor product quality, animal health, or welfare, translating into greater productivity (Džermeikaitė *et al.*, 2023). The concept of precise animal production refers to management issues based on real-time feedback aimed at eliminating the variability disturbing the effectiveness of the process itself (Wang *et al.*, 2023). Computer programs in agriculture can be used for animal inventory, recording information on veterinary treatments and lactation data. Programs for comprehensive maintenance of agricultural machinery and equipment are becoming increasingly common. There are also programs to improve efficiency in animal husbandry, which are designed to assess health, feeding rules, environmental conditions, reproduction, and neonatal mortality (Singh *et al.*, 2022). By using modern technologies, such as sensors, and implementing artificial intelligence to manage animal husbandry, breeders can react faster to diseases that do not yet give visual symptoms. For this purpose, monitoring of animal health parameters, which include movement, feed, and water consumption, is used (Neethirajan, 2020). Then, thanks to software and algorithms, deviations or irregularities are predicted in order to be able to identify and quickly react to possible disease entities.

In addition, it is possible to reduce production costs thanks to such solutions. Several algorithms have been identified for detecting various diseases (Neethirajan, 2020). In the case of mastitis detection, the Bag of Words (BoW) and Gradient Boosted Trees (GBT) algorithms are used, which are aimed at detecting somatic cells in milk and electrical conductivity (Dhoble *et al.*, 2019). The detection of mastitis using automatic devices is easier. There are several devices on the market to detect this disease, e.g., Fossomatic meter (Hillerød, Denmark), Dramiński mastitis detector/Mastitis detector (Olsztyn, Poland), Afimilk mastitis detector (Kibbutz Afikim, Israel). They are based on the detection of physicochemical and biological changes in milk or udders or on the assessment of milk or blood biomarkers associated with mastitis (Džermeikaitė *et al.*, 2023). To detect lameness, animal limb movement is assessed, along with imaging, using the Fog computing, Classification, and regressive tree (CART) XGBoost algorithm (Coşkun *et al.*, 2023; Kavlak *et al.*, 2023). Swine flu, on the other hand, is assessed using the Optical flow algorithm by measuring animals' mobility and direction (Neethirajan, 2020). Balanced feeds and optimal nutrition are key to ensuring farm productivity. RGB-D cameras and algorithms such as TDIDT (Top-Down Induction of Decision Trees algorithm), ENET (Elastic-Net algorithm), SSD (Single Shot MultiBox Detector), ARIMA (Auto-Regressive Integrated Moving Average) are used to help farmers estimate their animals' feed and water consumption. This is to assist farmers by allowing them to assess feed expenditure according to the needs of the animals, as well as to estimate the performance of the animals (Neethirajan, 2020). Animal husbandry uses digitization in the form of sensors and accelerometers to monitor animal health (Lemmens *et al.*, 2023). Furthermore, by using image processing and machine learning techniques, it is possible to detect heat in cows early. This involves analyzing the behavior of the animals under examination, presenting a significant solution in the realm of precision farming (Myat Noe *et al.*, 2023). Automation of the milking system (AMS) is also used, which is based on digital devices installed in the milking parlors, which record and collect data on the amount of milk obtained and allow for the analysis and selection of the appropriate amount and type of feed separately for each animal. In addition, during the AMS, the teats of the animals are cleaned by the milking robot, which additionally attaches the milking cups (Hansen *et al.*, 2020). Moreover, the use of automation of milking systems allows farmers to be provided with information on milk yield, milk quality, as well as animal activity (Lemmens *et al.*, 2023). Using biosensors, it is possible to manage herd reproduction. Using, among others, DeLaval Herd Navigator (DeLaval Inc., Tumba, Sweden) it is possible to analyze progesterone contained in cow's milk, but also this program is able to confirm pregnancy in cows, detect early embryo losses, as well as determine the optimal time for insemination of cattle) (Džermeikaitė *et al.*, 2023). In addition to programs for animal production, there are many programs for crop production that can be used for crop rotation by registering crops, planning fieldwork (from sowing or planting to applying fertilization and plant protection products), and managing the machinery park. An additional advantage of using computer programs in agriculture is the possibility of filling out applications for subsidies from the European Union. The European Union launched the Horizon 2020 project 'Internet of Farm & Food' (IoF2020)', which aimed to accelerate technological progress and the use of digital techniques in agriculture (Klerkx *et al.*, 2019). Also, the Digital Europe program (2021-2027) launched by the EU aims to bring digital technologies closer to companies and present agriculture as a sector where technology development is highly desirable (Sadjadi & Fernández, 2023).

Many agricultural enterprises use various IT solutions that improve their functioning. The basic role of computer programs is to process a huge amount of data and then visualize them in a form that speeds up and facilitates the decision-making process (Sadjadi & Fernández, 2023). Among the most frequently appearing software on the market, the following can be distinguished: systems for processing and then storing information in database systems (e.g. all Internet and applications integrated with the database), systems for communication with external devices connected directly or indirectly to the computer (e.g. an application communicating with GPS) and systems used to communicate with the outside world (e.g. a web browser) (Balasundram *et al.*, 2023).

Decisions of different scopes (strategic, tactical, and operational) are frequently made on farms. The precision of these decisions relies on the knowledge and experience of the farmer, but additional accurate and detailed information can enhance decision-making (Robert *et al.*, 2016). However, acquiring more precise data is often limited by time and cost constraints. Certain information emerges only through the processing of extensive datasets. The processing itself is not time-consuming; the primary challenge for IT tools lies in the time required to input the data into the system. By automating data acquisition processes, this barrier can be reduced (Zhu, 2022). To facilitate accurate decision-making, one approach is to utilize tools that aid in the decision-making process. Decision support systems are employed to gather, process, and present information to users, enabling them to make informed decisions. These systems are commonly utilized at the strategic or tactical level and assist in various stages of the decision-making process. By combining traditional management skills with precision farming technologies, decision support systems enable users to make optimal decisions for their production systems. The availability of an increasing number of programs of this nature further enhances decision-making capabilities in agriculture (Yao & Sun, 2023).

New technologies used in the production system bring many benefits to the production processes. Sensors on agricultural machines and vehicles are able to measure the values of many parameters, and the user has the ability to create various combinations based on measurement values (e.g. machine performance, size of cultivated area, fuel consumption, amount of funds used per unit area) (Abbasi *et al.*, 2022). One of the most important technological achievements in agriculture is automatic control systems. The combined use of automatic section control and GPS allows the machine to be located and the size of the cultivated area to be recorded, in addition, if the machine moves over a previously cultivated area, the system automatically switches off the relevant sections to avoid overlapping treatments (Subeesh & Mehta, 2021). Very often the fields are not the same everywhere, especially in large fields. Often, the borders of crops differ from the borders of plots on cadastral maps. Using modern technologies such as agricultural robots, artificial intelligence, as well as unmanned aerial vehicles (UAV), it is possible to set boundaries based on satellite images, and virtual boundaries are visible to machines (Bacco *et al.*, 2019). Sensors placed in combines can provide information not only on the yield but also on grain moisture (Xu *et al.*, 2019). Information on cultivated acreage and soil mineral content is combined to create field maps, making it possible to control fertilizer doses as needed. When working with a sprayer, positioning allows you to adjust the right amount of plant protection products, which reduces their excessive consumption and reduces the cost of the treatment (Mikula *et al.*, 2020).

The use of modern technologies into animal husbandry is related to the development of ICT technologies, including computer technology and digital technologies, as well as the development of microprocessor chemical, optical, and biophysical sensors, and biomarkers. The use of digitization in farm management has a breakthrough effect, automating many processes, reducing expenses and waste, while increasing the efficiency of farms, which translates into economic profits (Džermeikaitė *et al.*, 2023). Moreover, thanks to the implementation of IT solutions in agriculture, it ensures increased food security and food security, improved animal welfare, increased work safety, as well as reduced environmental impact and counteracting climate change (Zorić *et al.*, 2023). Physically, they translate into reduced fuel consumption (by 10%), reduced costs of crop protection (by 30%), time of agrotechnical treatments (by 6%), and service in animal husbandry (by 40%). As a result of the use of precision farming, fertilization costs may be reduced, and the use of precise animal production in animal nutrition will reduce its cost (Vrchota *et al.*, 2022). The specificity of the issues to be solved, the sensors used, the products obtained, and the approach to animals encourages the use of a species approach. In the case of cows and fatteners, individual monitoring and management are used, while in the rearing of other species, they are treated in groups. Currently, the most advanced technological solutions in animal production are used in the production of dairy cattle, which in combination with breeding programs constitute commonly functioning systems of integral animal husbandry (e.g. AfiFarm). As part of the systems offered for dairy cattle, there are pedometers and accelerometers (mounted on the limbs or neck of the cow), whose original function was to detect heat by intensifying physical activity. Modern devices can also determine changes in body temperature, pH, monitor the intensity of food intake, chewing and digestion, water consumption, animal activity and the number of breaths (Džermeikaitė *et al.*, 2023). By analyzing volatile organic compounds, it is possible to assess metabolic processes and detect their disorders by analyzing the breath, sweat, and saliva of animals. This technique is employed to test for bovine tuberculosis, brucellosis, or ketoacidosis in cattle. Additionally, the measurement of animal sweat can serve as an indicator of physical stress. Infrared thermography (IRT) is another method utilized for diagnosing and assessing pain in animals, as well as detecting thermal abnormalities. Through IRT, fluctuations in body temperature can be identified, along with conditions such as lameness in horses, mastitis in sheep, and inflammations or infections (Džermeikaitė *et al.*, 2023). Out of concern for the well-being of cows and their health, thanks to the use of automatic feeding systems (e.g. Vector, Optimat T4, Trioliet B. V., Jeantil), it is possible to feed animals individually. These systems are fully automatic (from the automatic collection of the feed material to the dispenser to its delivery to the feed table), but they also have the ability to control feed portions so that the amount in each place is the same (Mahfuz *et al.*, 2022). Real-time information on digestion processes is provided by rumen pH sensors, which also allow for measuring its temperature (e.g. eCow, SmaXtec), which directly translates into the quick diagnosis of metabolic diseases such as acidosis or ketosis. Infrared sensors and cameras are also available to identify mastitis and abomasal displacement. In dairy cattle breeding with the use of milking systems, milk monitoring is used – real-time analysis of milking, e.g. protein, fat, lactose, and somatic cell count. Milk with incorrect parameters can be redirected to another tank, and the measurement results are transferred to the software, creating a much more accurate database than the one from trial milking (Schori & Münger, 2022).

In pig farming, as in dairy cattle, individual feeding systems are used, equipped with electronic feed stations (EFS). The system is based on the use of EFS and individual RFI transponders for pig identification, combined with automatic weighing machines. It is possible to use it both in bedding and slatted systems. The advantages of using this system include lower feed consumption, higher body weight gains, and 30% less nitrogen and phosphorus excreted into the environment. Similar solutions are being tested for broiler chickens, turkeys, and laying hens (Mahfuz *et al.*, 2022). Self-weighing and separating systems are highly favored by pig farmers as they allow for the individual identification of each animal and redirecting them to specific sectors based on their weight. This enables the segregation of heavier animals to sectors with feed containing lower protein and energy concentrations, while lighter animals are directed to sectors with feed rich in protein and energy. Measurement methods rely mainly on obtaining image data of animals, which are processed by appropriate software (Chen *et al.*, 2023). Automatic weighing systems (e.g. Flockman) are used in the rearing of slaughtered poultry, which allows obtaining information, e.g. on growth and feed utilization. Modern technologies in animal production are also used in the management of natural fertilizers or in controlling the microclimate of farm premises (Havelka *et al.*, 2022).

The integration of computer systems, sensors, and machine learning in agriculture enables precision livestock farming and the detection of various diseases, leading to improved productivity, animal welfare.

CONCLUSIONS

Agriculture plays a key role in providing food, resources, employment, and the environment. The effective use of systems in farm management brings numerous benefits, including better monitoring of information, improvement of economic indicators, improvement of data quality on the farm. The implementation of modern sensor-based technologies such as artificial intelligence, the Internet of Things and computer vision has significantly improved farm management, efficiency, and resource utilization in agriculture. These technologies enable data collection, analysis, task automation and decision support, leading to better resource management, sustainability and animal welfare, disease prevention, and soil properties, environmental conditions, and weather. The integration of sensor technology and digital solutions in agriculture has further improved productivity, profitability, food security and environmental sustainability. By harnessing the potential of digital technologies and sensors, future research could focus on improving existing technologies, exploring innovative solutions, and addressing socio-economic issues and adoption challenges. Areas include advances in artificial intelligence and machine learning for smart decision making, development of advanced IoT systems for precise monitoring and control, and exploration of emerging technologies such as robotics. Through research in these areas, the benefits of digital and sensor technologies can be fully exploited, ensuring a more sustainable and productive future for the agricultural industry.

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CONFLICT OF INTEREST

None.

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Сільське господарство в умовах нових технологій оцифрування

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Анотація. Сільське господарство відіграє життєво важливу роль у виробництві продуктів харчування, використанні ресурсів та забезпеченні зайнятості, але стикається з проблемами, пов'язаними зі зростанням населення, зміною клімату та нестачею продовольства. Розвиток інформаційних технологій зробив значний внесок у розвиток галузі, а сучасні технології, такі як штучний інтелект, інтернет речей, комп'ютерний зір і машинне навчання, зробили революцію в сільськогосподарській практиці. Мета цього огляду – дослідити впровадження цифрових технологій у сільському господарстві з особливим акцентом на їх застосування у тваринництві. Завдяки вивченню сучасної літератури та використанню різних методів дослідження, цей огляд робить внесок в існуючі знання в цій галузі. Встановлено, що новітні інформаційні інструменти дозволяють збирати, аналізувати дані, автоматизувати завдання та підтримувати прийняття рішень, що призводить до підвищення ефективності сільского господарства, управління ресурсами та сталого розвитку. Доведено, що сучасні технології відіграють вирішальну роль у збільшенні сільськогосподарського виробництва, підвищенні ефективності тваринництва та рослинництва. Ці технології включають пристрої та датчики, системи аналізу даних та підтримки прийняття рішень, а також системи загальної оцінки продуктивності фермерських господарств. Точні технології в сільському господарстві, завдяки автоматизації, датчикам і машинному навчанню, дозволяють фермерам стежити за здоров'ям тварин, оптимізувати споживання кормів, виявляти хвороби на ранніх стадіях і підвищувати загальну продуктивність. IT-рішення в сільському господарстві полегшують обробку даних, візуалізацію та прийняття рішень, що приводить до зниження витрат, підвищення ефективності та поліпшення продовольчої безпеки. Дослідження надає практичну інформацію для фермерів та інших учасників сільськогосподарської галузі, які можуть отримати вигоду від точної інформації, моніторингу в режимі реального часу та автоматизованих процесів шляхом інтеграції сучасних технологій, що в кінцевому підсумку покращує сільськогосподарські практики та стійкість

Ключові слова: стале сільське господарство; діджиталізація; точне тваринництво; системи управління фермами; кероване даними сільське господарство

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Accounting outsourcing as a modern effective tool of enterprise management

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Abstract. The relevance of the following article is determined by the need to elaborate on the economic benefits of using accounting outsourcing for agro-industrial enterprises. The purpose of the study is to analyze the main advantages of delegating enterprise`s accounting functions to a specialized company, as well as to prove the economic feasibility of outsourcing. The basis for the methodological approach includes: data analysis regarding the level of outsourcing, method of average values, comparison method, graphic method, generalization method. The article reveals the essence, types, main advantages and disadvantages of outsourcing, and compares the features of workplace organization and pay for full-time employees, freelance workers and outsourcing companies. Drawing from the previous experiences of the USA, Germany and Poland, the ways to apply accounting outsourcing in Ukraine were singled out, namely: enshrining in legislation the procedure for providing outsourcing services; transparency in regards of their clients from the outsourcing companies` side; determining the approximate amount of financial costs for maintaining a full-time employee performing the accountant duties. In the course of the research, the volumes of expenses for maintaining the accounting department of the enterprise and for payment for the services of an outsourcing company were compared, and the amount of economic benefit from the use of accounting outsourcing was determined, the dynamics of administrative costs of agricultural enterprises before and after the transfer of accounting functions to outsourcing were analyzed, and the expediency of using accounting outsourcing at agrarian enterprises as a way of reducing administrative costs and increasing the efficiency of accounting functions at the enterprise is substantiated. The results of the study provide recommendations on expanding the practice of using accounting outsourcing, in particular by increasing the trust of enterprises in outsourcing companies, and have a practical value for agricultural enterprises in regards of organizing the performance of accounting functions and outsourcing companies, for example, while developing a marketing policy for the promotion of services

Keywords: costs; economic benefits; effective management; full-time employee; agricultural sphere

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INTRODUCTION

Outsourcing services are successfully used by companies all over the world as an effective management tool to optimize costs, increase efficiency and productivity, as it allows to transfer company's non-core functions to more experienced professionals in that area. The agricultural sector is the leading one in Ukraine`s economy, and in the conditions of wartime and the dire state of the world economy, it is utterly important to maintain food security on both national and global levels. To increase the profitability of agricultural enterprises, it is necessary to use modern tools in the management system, in particular through the delegation of accounting functions to outsourcing companies. However, the use of outsourcing has not yet become widespread in Ukraine, which slows down the transformation of organizational processes of Ukrainian enterprises in line with global tendencies. Thus, the study of disadvantages and advantages, as well as the determination of the level of economic profitability of accounting outsourcing, which will contribute to increasing trust and persuading company managers to use these services, becomes relevant.

Ukrainian, Slovenian, and Croatian scientists were concerned with the study of issues related to the transfer of accounting functions of enterprises, in particular agro-industrial ones, to other specialized companies. Problems of organization and accounting at enterprises were studied by S. Yekimov *et al.* (2021), whose work substantiates the need to use accounting outsourcing in small agricultural enterprises both to strengthen control over production costs and to reduce the company's expenses for accountants' services. I. Yaremko & V. Huzandrova (2022) pointed out the insufficiency of clear legal provisions regulating the use of accounting outsourcing services, which indicated characteristic features and approaches to evaluating the effectiveness of transferring accounting and financial reporting functions to an outsourcing company. The authors argued that outsourcing is an effective means of minimizing the company's costs and noted the advantages of its use in the crisis economy.

Meanwhile, methodical approaches to evaluate the effectiveness of the use of accounting outsourcing were studied by I.K. Shushakova *et al.* (2021), who clarified the list of costs accompanying accounting by full-time employees of the enterprise, and also gave examples of calculating the economic effect of using accounting outsourcing. Analysis of the accounting outsourcing market in Ukraine was carried out by O. Romashko *et al.* (2021), who also identified groups of enterprises for which accounting outsourcing is a more effective form than the performance of functions by a full-time employee and characterized horizontal (American), pyramidal (Japanese) and mixed models of accounting outsourcing.

T. Sierikova *et al.* (2021), paid attention to the problem of determining the main advantages and disadvantages of various forms of organization of accounting at enterprises, concluding that outsourcing among other forms has the most advantages and justifying the feasibility of using accounting outsourcing as a progressive tool for business development and new areas of activity. The organization of accounting of agricultural enterprises in modern world from the point of view of the digitalization of all spheres of activity was studied by N. Potryvaieva *et al.* (2022). The authors considered innovations that can be used in the business environment for the digital transformation of business for the purpose of productive organization of accounting processes and noted outsourcing services among such innovations. When considering the benefits of outsourcing, scientists also consider to the factors that influence the decision of company management to transfer accounting management to an outsourcing company. I. Tomašević *et al.* (2023), using the transaction cost economy model, analyzed and determined the main factors that influence the high level of outsourcing of accounting tasks on the example of enterprises in Montenegro.

However, despite the significant contribution of scientists to the study of this topic, the issue of clarifying all aspects of the outsourcing of accounting functions requires a more thorough study. The main goal of the research was to analyze of the level of application and the list of services of individual outsourcing companies in Ukraine, Europe and other countries in order to articulate suggestions on applying the practices of other countries in Ukraine, to compare various ways of involving employees in the performance of accounting functions, and to prove the economic benefit from the application accounting outsourcing as a tool for increasing the efficiency of enterprises.

MATERIALS AND METHODS

The methodological approach in the article was based on a combination of data analysis methods on the range of services, prices and financial indicators of outsourcing companies and enterprises of the agrarian sector, the method of average values for calculating average costs, the comparative method for comparing information about costs and peculiarities of the organization of the accountant's workplace, as well as graphical and generalization methods. The theoretical basis of this research work is provided by the works of scientists from Ukraine, Slovenia, Croatia, Turkey, Germany and other countries, who considered the specifics of outsourcing services for production, accounting functions in various spheres of activity, in particular the agricultural sector. The numbers of

Ukrainian companies in The Best of the Global Outsourcing 100 (n.d.) rating were based on data from the International Association of Outsourcing Professionals (IAOP). The comparison of the performance of accounting functions by employees engaged under different conditions of cooperation was carried out on the basis of data obtained from the analytical material of the management of the Ukrainian accounting company "Agrooblik" (Kozubovych, 2023).

The application of the data analysis methods made it possible to research the list and cost of services of outsourcing companies in 2023 by using the Clutch research company`s website, which analyzes the market of IT services and compiles the rating of companies in various areas, as well as by using the official websites of outsourcing companies such as Ante Consulting Group, Solvency and BDO Limited Liability Company (BDO LLC) (Top accountants and…, 2023). The average value of the enterprise's maintenance costs (organization of the workplace, provision of necessary materials and payment of wages) of one full-time employee performing accounting functions was determined by applying the average value method.

The comparison method was used to compare and analyse the areas of services provided by outsourcing companies in the USA, Poland, the UK, Germany and Ukraine, the annual cost of maintaining the accounting department and payment for outsourcing services of Farm "Organic Systems", PAE "AF "Rodnichok" and ALLC "AF "Korsun", whose cost data were obtained from their financial statements posted on the website of the Clarity Project Open Data Analytics System. With the help of a graphic method, the data obtained in the research process on the dynamics of administrative costs of the specified enterprises for the years 2020-2022 are displayed in the form of a graph.

The generalization method made it possible to: firstly, summarize the results obtained in the research process regarding the level of application of accounting outsourcing services in Ukraine in comparison with the European countries, the USA and Israel, the advantages and disadvantages of outsourcing, the specifics of the area of activity at enterprises that are most suitable for the transfer of accounting functions to outsourcing; secondly, to reflect the results in form of a conclusion, namely: to justify the expediency and rationality of the application of accounting outsourcing for the enterprise of the agricultural sector of Ukraine and to condition further approaches to the study of the problems of the development of outsourcing services in Ukraine, in particular for the agrarian sphere of activity.

RESULTS

The concept of "outsourcing" means the transfer of certain functions of an enterprise (company) to another business entity that specializes in a specific field and contractually undertakes to perform these functions with high quality and at a high professional level. A common type of outsourcing is the transfer of the duties of the company's accounting service to another entity, i.e. accounting outsourcing. Analyzing the types of outsourcing services in the field of accounting, it is possible to provide a classification characteristic of accounting outsourcing (Table 1).

Table 1. *Classification characteristics of types of accounting outsourcing*

Feature	Types
Time period	Long-term Temporary
Cooperation order	Remote Stationary
Implementation mechanism	Direct Cross
Delegation of functions (List of works)	Full Partial

Source: *based on I. Yaremko & V. Huzandrova (2022)*

The data of Table 1 shows that business entities can use different forms and types of outsourcing depending on their needs. The use of outsourcing services gives a business entity with a number of advantages, the main of which is the reduction of enterprise costs. However, in order to more broadly assess all the advantages, a comparison of the performance of accounting functions by a full-time employee, a freelance accountant, and an outsourcing company should be provided (Table 2).

Table 2. *Comparison of the performance of accounting functions by employees involved in different conditions of cooperation*

Feature	Staff accountant	Freelance specialist with occasional visits	Outsourcing company
Qualification level	Mostly low	Mostly sufficient, but the risk of low is still present	Highly professional with sufficient work experience
Official employment with a social package (sick leave, vacation)	Yes	No	No
Workplace and office equipment	Yes	No	No
Payment	A professional requires a high salary, with no guarantees of high results	Requires lower payment, but with no guarantees of the results	Fixed subscription fee with guaranteed high results
Keeping in touch with the company	Working hours only, but not always	Not always	All the time
Expediency in problem solving	Not always effectively, some tasks require the involvement of additional specialists	Not always effectively	Effective and quick solution
Need for constant management supervision	Direct supervision is required	Direct supervision is required	No. Liability is determined by the contract

Source: *based on A. Kozubovych (2023)*

The data in Table 2 show that an accounting company that provides outsourcing services has significant advantages in organizing the performance of accounting functions compared to staff and freelance accountants. Global companies and specialists constantly analyze the use of outsourcing and highlight its main advantages (6 reasons to outsource..., n.d.):

- saving financial resources and optimizing costs (reducing up to 70% in personnel costs, wages and workplace organization in particular);
- diversification of the company's activities, which allows access to specialists from all over the world;
- enabling the company to get more focused on its main tasks, without being distracted by the non-core functions;
- creation of a core staff team or customer support groups, which increases the efficiency of the company's work;
- available external expertise. Outsourcing allows to gain experience (from sales, marketing, technical and management positions) to manage the business more effectively in a crisis period.

Other advantages worth mentioning:

- reducing the risk of making mistakes in accounting and reporting, as outsourcing companies have quality control systems that prevent errors and violations, which reduces the risk of financial losses and improves the financial stability of the enterprise;;
- obtaining access to modern technologies and software, which allows to increase the efficiency and accuracy of accounting operations;
- easy access to financial statements: balance sheets, profit and loss statements and other financial documents useful for business management and commercial decision-making.

Alongside with the advantages of using outsourcing accounting services, it is also worth noting some risks which can negatively affect the performance of said services and the customer`s work (Kozubovych, 2023): the threat to the confidentiality of the customer's data. Outsourceng companies cannot guarantee complete confidentiality of the processed information. In such companies, however, there is usually a provision on commercial secrecy of information about the customer's activities, which is transferred only in accordance with the current legislation; the threat of bankruptcy of the outsourcing company, which causes additional problems: violation of deadlines for solving accounting issues, prompt search for a new outsourcing company and transfer of necessary functions to it.

Utilizing outsourcing is much more common in other countries. Foreign companies prefer accounting outsourcing services more than Ukrainian ones: in the European Union (EU) countries 86% of small and medium-sized businesses, in the USA – 92%, in Israel – 96%. Meanwhile, in Ukraine, only about 30% of companies use outsourcing services. This field began to develop since early 2000s. However, today most companies have full-time accountants. The total market volume of outsourcing services reaches 10 million dollars (Rybalchenko, 2021).

The success of accounting outsourcing is evident if looking at the examples of other foreign companies around the world. Outsourcing is always a crucial element in the business organization of such companies as Amazon, Google, Facebook, and Ford. The successful organization of business processes in these companies, including the outsourcing of most functions, is evidenced by their leadership in the world and their high profits. The Ford Motor Company was one of the first to use outsourcing services, with H. Ford introducing the outsourcing of accounting and other business processes in the late 1990s. Today, about 70% of typical Ford vehicles are manufactured with parts, components and services purchased from external suppliers. Also, the work of the accounting service and designers has been outsourced. The company's management substantiates this by reducing production and administrative costs (Farrugia, 2020).

The web giant Amazon is building an outsourcing business with clients such as Virgin Megastores, America Online and Target. Company management claims that remote workers are more cost-efficient for companies than full-time ones. Accounting and reporting analysis are among the 10 tasks that contractors can perform for Amazon. From the practical application of accounting outsourcing in European companies, the following should be emphasized. In Germany, large business entities use the services of external accountants. The general professional duties of an accountant are set out in the Accountant Act and include the following: act accordingly, independently and honestly; have proper professional behavior; prevent conflicts of interest; not to offer assistance in matters of unauthorized taxation (Accountant in Germany..., 2023).

In the Ukrainian legislation, it is also appropriate to define restrictions for the employees of the accounting service on providing assistance in the preparation of unreliable financial statements, unauthorized taxation and other illegal transactions. In Poland, more than 65% of entrepreneurs do not hire accountants as a full-time staff, but delegate bookkeeping to a special accounting office or use the services of freelance accountants. In total, there are more than 40,000 accounting offices in which independent accountants work. Accounting outsourcing is mainly used by small and medium-sized enterprises, because it is expensive for them to keep an accountant on staff, because the average salary of a qualified specialist is 1000-3000 euros and more (Nesterenko, 2023).

The high rate of outsourcing in Poland is facilitated by the establishment of this concept and employment standards for both national and foreign workers in the legislation. In the Labor Code of Poland, the outsourcing of employees is called leasing, and it can be implemented on the basis of a written contract between the employee and the employer. At the same time, the legislation does not regulate the form of an agreement that involves hiring a person (Outsourcing of workers and..., 2022). In addition, in Poland, the division of responsibility between the manager and the employee performing accounting duties is defined by law. The manager is responsible for the organization and maintenance of accounting records and economic operations at the enterprise, and the accountant is responsible for the correctness of the display of transactions in accounting and the calculation of taxes. Therefore, the Polish accountant does not bear criminal responsibility, but only administrative and financial ones.

Transparency plays an important role in increasing trust in any company. Websites of many European outsourcing companies contain information about their clients, many of them are widely known. For example, Polish outsourcing company Dudkowiak Kopeć Putyra provides services to Airfrance KLM, AIR Liquide, Ambienta environmental investments (Dudkowiak Kopeć Putyra Law..., n.d.). According to the information posted on the official website of the German outsourcing company ICS adminservice, its clients are: Deutsche Wohnen SE, InterContinental Hotels Group, Storengy Deutschland GmbH, InfraLeuna GmbH (Official website of ICS adminservice, n.d.).

By analyzing the foreign experience of using accounting outsourcing, it is possible to formulate recommendations for Ukraine as well. For instance, to pot the procedure for applying outsourcing into national legislation, which will contribute to increasing the state protection of outsourcing companies and their customers, as well as to increase transparency in regards of the actions of outsourcing companies, in particular by posting information about their clients, which will bolster the trust of enterprises in search for outsourcing companies to cooperate with. The implementation of these proposals will increase the trust of Ukrainian enterprises, organizations and other business entities and will contribute to the development of outsourcing activities.

Annually, the IAOP conducts comprehensive research in the field of outsourcing, which helps global companies to choose IT service providers (The Best of the..., 2023). The rating of companies is formed on the basis of the following criteria: innovative approach to work and service provision; certificates and awards for successful projects; positive dynamics of activity; customer feedback and corporate social responsibility projects. The Best of the Global Outsourcing 100 (2023) rating includes 17 companies with offices in Ukraine (either based in Ukraine or have a representative office there). In 2020, for comparison, this rating included over 20 outsourcing Ukrainian companies. That is, in the course of three years, the number of Ukrainian companies in the IAOP rating has decreased, indicating a slowdown in the activity of Ukrainian outsourcing companies. Outsourcing companies all over the world have a wide range of services to offer and they set a different price range for their services, considering the specifics and organizational structure of their customers (Table 3).

Table 3. *Analysis of the list of outsourcing services and their cost in the USA, Polish, British, German and Ukrainian in companies in 2023*

Feature	The Accountrepreneur LLC	Business Process InnovatiON	Salient Accounting & Finance	Invensis Inc	Solvensy	Ante Consulting Group	Finevolution
City, country	Chicago, USA	Warsaw, Poland	Basildon, Great Britain	Wilmington, Germany	Kyiv, Ukraine	Kyiv, Ukraine	Kyiv, Ukraine
Cost of services, per hour, in US dollars	100-149	50-99	50-99	from 25	from 25	25-49	50-99
List of services							
Accounting of operations (in particular, accrual and payment of wages, vacation and sick leave)	+	+	+	+	+	+	+
Financial reporting	+	+	+	+	+	+	+
Payable and receivable management	+		+	+			
Balance reconciliations	+				+	+	
Audit support	+	+					
Order and contract management		+				+	+
Accounting and cash management		+		+	+	+	
Financial controlling and interim financial director services		+	+	+	+	+	+
Tax payment control		+	+	+	+	+	+
Assistance in voluntary dissolution and liquidation		+					+

Source: *based on Top accountants and accounting firms (2023)*

From the data in Table 3, it can be seen that the outsourcing companies of the USA, Poland, Great Britain, Germany and Ukraine set quite different price ranges for their services. For example, in European countries and the USA, said range can be 2-3 times larger than in Ukraine. Regarding the list of services, it is almost similar for all companies. Also, by agreement with clients, outsourcing companies can provide any services related to accounting and financial management. It should be noted that, despite the great advantage of outsourced accounting in comparison to a full-time service, outsourcing, depending on the specifics of the activity, may be recommended to some enterprises more than to others. Outsourcing would be an optimal variant if the business entity is:

- a startup, since the managers of such companies focus their efforts almost entirely on business processes and try to get less distracted by non-core functions;
- a foreign enterprise, the owners of which do not deem it necessary to deepen their knowledge of the legislation of the country where the activity is conducted;
- a small enterprise, where it is impractical to create an accounting service, and the services of freelancers are dubious;
- a holding, where both accounting matters and individual tasks can be outsourced;
- a company with a very specific activity, where accounting requires a very niche area of knowledge;
- a seasonal company (hotel and tourism business, food enterprise, agricultural company), for which

there is no point in keeping an accountant on the job all year long.

One of the spheres of activity in which outsourcing services are advised is the agricultural sector, which is the basis of Ukrainian economy. A full-scale invasion by the Russian army in early 2022 has left many areas unfit for growing crops and raising animals. However, the need to restore and develop the country prompts the search for innovative solutions and new opportunities in this area (Berxolli *et al.*, 2023). Many foreign companies are interested in investing in the development of the agricultural sector, however, during the war period, like other areas of the economy, this sector has experienced difficulties in development and needs to reduce costs and improve the efficiency of operations. The use of accounting outsourcing services can ensure optimization of costs and improvement of management of financial activities of agricultural enterprises. Among the outsourcing companies specializing in the agricultural sector, such companies as "Agrooblik", "Mazars", Ante Consulting Group, Solvency, are well-experienced in providing accounting outsourcing, tax and financial consulting services to agricultural companies taking into account their specific needs.

Taking into account the cost for the set of accounting services of individual companies, it is possible to analyze how much profitable it would be for the company to use outsourcing services in comparison with the cost of maintaining full-time accountants. The average cost for a set of accounting services from the company Ante Consulting Group per month is 15,000 UAH, and from Solvency the standard set of services for legal entities paying VAT (value added tax) costs 11,800 UAH (Top accountants and..., 2023). The economic benefit of using outsourcing accounting services is evident, when assessing the costs that may be incurred by the enterprise if accounting functions are performed by full-time employees of the enterprise (Table 4).

Table 4. *An approximate list of the company's current expenses for maintaining one full-time accountant*

Expenditure	Amount per year, UAH
Workplace maintenance costs:	
Organization of the workplace for the accountant (devices for work and communication: mobile phone, computer, printer, laptop; refilling cartridges, paper for printing documents, stationery)	5,000-50,000
Software (support, license updates)	2,000-5,000
Equipment and workplace maintenance (system administrator services, costs for electricity supply, water supply, room cleaning and security)	20,000-50,000
Provision of current professional periodicals, detergents, drinking water	4,000-20,000
Salary (estimated 9,000-12,000 UAH per month)	108,000-144,000
Total	**139,000-269,000**
Average value	**204,000**

Source: *compiled by authors*

The data in Table 4 shows that for one full-time employee who performs accounting operations at the enterprise, the average annual costs can amount to more than 200,000 UAH, and if there are two or three employees, then, according to the data given in Table 4, the amount of costs may reach 400-600 thousand UAH. Moreover, the full-time employee of the company's accounting service does not necessarily have a higher qualification level and a responsible attitude to their duties, thus is likely to make mistakes, which can lead to the imposition of fines on the company, adding to the costs. With the example of agricultural enterprises using accounting outsourcing services, it is possible to evaluate their economic profitability. According to the information of "BDO" LLC, which offers a wide range of services, for agricultural enterprises of Ukraine as well, their accounting outsourcing services are used, in particular, by Farm "Organic Systems", PAE "AF "Rodnichok" and ALLC "AF "Korsun" (BDO, 2022). According to the data of the indicated agricultural enterprises, it is possible to compare the annual amount of expenses for accounting tasks performed by full-time employees and expenses for accounting outsourcing (Table 5).

Table 5. *Comparison of the annual amount of the company's expenses for maintaining the full-time accounting service and paying for outsourcing services*

Name of the enterprise	Expenses for the accounting service, thousands UAH	Outsourcing costs, thousands UAH	Saved with outsourcing
Farm "Organic Systems"	1,600.5	240.3	1,360.2
PAE "AF "Rodnichok"	1,350.8	215.3	1,135.5
ALLC "AF "Korsun"	1,760.4	265.1	1,495.3

Source: *based on BDO (2022)*

In Table 5, the amount of savings from the application of accounting outsourcing is estimated as the difference between the costs of maintaining the full-time accounting service and the costs of keeping records by the outsourcing company. As can be seen from the data of Table 5, the amount of savings due to switching from full-time accounting to outsourcing services is significant for each enterprise. The way those cost savings affect the volume of administrative expenses for the years 2020-2022 of agricultural enterprises can be demonstrated graphically (Fig. 1).

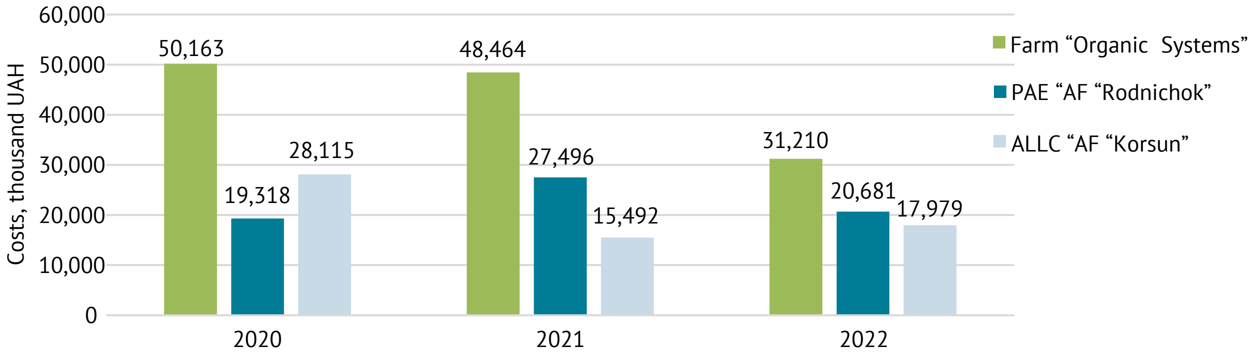

Figure 1. *Dynamics of administrative costs of individual agricultural enterprises for 2020-2022*
Source: *compiled by authors*

The data in Figure 1 shows that the administrative expenses (expenses for maintenance of management personnel, fixed assets that are in their use) of agricultural enterprises during 2020-2022 have been in flux precisely during the period using accounting outsourcing services more actively. Thus, in 2022, Farm "Organic Systems" began to more actively apply accounting outsourcing by transferring its full-time employees to outsourcing, which contributed to a reduction of administrative costs by 35.6%. PAE "AF "Rodnichok" has been using outsourcing for 6 years, so a sharp decrease in administrative costs has not been noticed. ALLC "AF "Korsun" began to move more actively to outsourcing in 2021, which, along with other factors, led to a decrease in administrative costs by almost 45%. Since accounting outsourcing is an effective tool for improving work efficiency, managers of agricultural enterprises should expand the practice of using outsourcing services, evaluating all its advantages and disadvantages. At the same time, managers of outsourcing companies should spread more information about their services and prove the economic feasibility of cooperating with them, as well as work on increasing trust in outsourcing companies of enterprises of various areas and forms of activity.

Therefore, the results of analyzing the use of accounting outsourcing services showed that giving preference to such a form of cooperation with specialists who conduct accounting at the enterprise is more profitable and effective for the enterprise, which is manifested mainly in reducing costs and increasing the responsibility of employees. The analysis of foreign experience made it possible to formulate valuable proposals for Ukraine. Despite the fact that the cost of services of outsourcing companies in Ukraine is 2-3 times lower than in the CIS, European countries and others, Ukrainian enterprises are not actively enough switching to cooperation with outsourcing companies. The use of accounting outsourcing for agricultural enterprises is appropriate given the specifics of their activities. The economic profitability and efficiency of the use of outsourcing services, demonstrated in the form of a comparison of the costs of a full-time accountant and an outsourcing employee, gives grounds for asserting the feasibility of further expanding the cooperation of agricultural enterprises with outsourcing companies.

DISCUSSION

Analysis of the use of accounting outsourcing services proves it to be more economically beneficial for the enterprise than conducting accounting operations by a full-time employee. Modern trends in the world economy development and requirements for reducing the costs of enterprises for higher profitability cause the need to review the approaches to the work process organization, especially in regards to agricultural enterprises. The results obtained during the research show that the use of outsourcing for accounting operations would optimize of the company's costs and increase the responsibility and efficiency of employees' performance. The study emphasizes on the positive impact of using accounting outsourcing by the enterprise, which consists in focusing the solely on the core functions, which bolsters the future development. Meanwhile, S.J. Anderson & D. McKenzie (2021) studied how to improve business practices in small companies and emphasized that many small companies lack the financial and marketing skills essential for growth, a reasonable solution to which can be outsourcing employees with the required qualifications.

The analysis of the study shows that the company's choice of whether to use accounting outsourcing services should depend on the specifics of said company's activities, as not all business entities are suitable for transferring functions to other specialists. The outsourcing of accounting functions is mainly suggested for enterprises operating in the area of small and medium-sized businesses, as well as in the public sector. The practice of outsourcing in the public sector as a strategy to save costs, to focus on the institution's core functions and to improve the quality of public services was studied by E.F. Mabonesho (2022) on the example of Tanzania and A. Dadzie *et al*. (2022) on the example of African institutions. However, it should be noted that outsourcing for budget institutions and organizations allows them to focus on their core, to reduce the costs of maintaining the institution and to improve their work productivity. As it was emphasized, the application of accounting outsourcing is quite effective for small and medium-sized enterprises. Confirming this point of view, F. Cahyaningtyas & M.N. Ningtyas (2020) studied the factors which influence the decision of small and medium-sized business managers to use accounting outsourcing, as well as the impact of their use on business performance. A similar study was conducted by D. Mohammed & R. Adamu (2020) who studied how the use of accounting outsourcing effects the financial performance overall and the performance of small and medium enterprises in the Nigerian manufacturing sector.

Fully supporting the point of view of A. Rogosic (2019), it should be noted that accounting is a management information system, with the purpose to provide relevant information for enterprise managers. Most small and medium-sized enterprises outsource accounting because of their full-time managers' lack of professionalism in this area and small need for accounting information in everyday business. However, it is worth mentioning that even when accounting operations are outsourced, the professionalism of the company's management in accounting and reporting information should be sufficient for timely management decisions. The application of accounting outsourcing was analyzed by scientists on the example of individual spheres of activity, taking into account their specifics, which deserves its own and more detailed study of the advantages and disadvantages of outsourcing. The relationship between outsourcing and organizational performance in a gas company was studied by Y. Nikkhah (2022), who aptly noted that the use of outsourcing services has an impact on the company's organizational performance, emphasizing the mediating role of organizational flexibility.

The use of outsourcing in the agricultural area is a fairly common problem that is considered in the scientific world. Thus, an overview of the phenomenon of outsourcing in agriculture, which has been developing since the beginning of the 2000s, was considered by G. Nguyen *et al*. (2022) who highlighted different aspects of this phenomenon, starting from the outsourcing a few tasks to full delegation of functions, which is a non-traditional practice. Analyzing the development of outsourcing in agriculture, S. Chen *et al*. (2022) emphasized on the evident impact of outsourcing of production services on non-point pollution of agricultural production in China, namely: on the reduction of excess nitrogen and the bolstering the implementation of ecological technologies of agricultural production. In support of the opinion on the need to encourage small farmers to transfer agricultural production activities to service organizations, one should emphasize the feasibility of transferring not only production, but also management functions, accounting in particular.

Though most of the studies point out the positive impact of outsourcing on various aspects of enterprises and companies, some scientists note negative impacts. R.M. Mahboub (2021) noted that outsourcing has become an essential aspect of a reasonable careful strategy. However, this area is understudied in developing countries such as Lebanon, particularly in the industrial sector. The analysis showed that the specificity of industry assets and behavioral uncertainty have a significant negative impact. At the same time, accounting competence has a positive effect on the outsourcing of accounting functions. Attitudes towards the outsourcing of accounting functions among farms of various sizes were studied by R. Rieg *et al.* (2022), who also highlighted that large firms are less likely to outsource financial and managerial accounting, but smaller firms with greater stakeholder influence are less likely to outsource.

A more in-depth study from the point of view of the customers' psychological attitude towards outsourcing services was studied by J. Juntunen *et al.* (2022), who divided outsourcing users into three latent classes: thrivers (have a positive attitude toward accounting outsourcing and associate competitiveness with mediating the relationship from outsourcing benefits to firm performance); dissatisfied (not satisfied with the accounting service, but see the advantages of outsourcing in competitive opportunities); contempt (satisfied with the accounting service and do not associate the benefits of outsourcing with the company's capabilities or performance). In support of this point of view, it is worth mentioning that reasoning the decisions of users opens up the possibility of studying and expanding the market of outsourcing services.

Considering different opinions on the use of accounting outsourcing, some scientists also highlight the negative attitude amongst clients. Thus, C. Hurl (2022) pointed out the issue of opposition to outsourcing in the London district (Great Britain) during the period when the city council transferred the main part of its services to an outsourcing service, which led to a series of complex contractual management mechanisms. The scholar demonstrated how local residents developed strategies to confirm the claims about efficiency and identify institutional problems in service performance. It is reasonable to agree that the outsourcing of accounting functions should satisfy not only the management of the enterprise, but also its employees, who should , for example, feel no problems with salaries or delayed accrual for vacations. Factors affecting the quality of accounting services and the search for possible solutions for its improvement were studied by R. Sneidere *et al.* (2013). Moreover, the risks of accounting outsourcing were investigated by E.M. Amaka & F. Alio (2020), who emphasized that companies engaging in accounting outsourcing should avoid problems that can spoil relationships with service providers and reduce the return on investment in acquiring these services.

Therefore, the analysis of the scientisic research results in regards of outsourcing services, in particular for the organization of accounting functions at an enterprise (either company or small business) shows that in theory this issue is handled in a way of highlighting the main advantages of outsourcing, the attitude of business entity's representatives towards transferring of functions to others companies and its application in various areas of activity. The main conclusions of this work are similar and correspond to those expressed in the works of other authors.

CONCLUSIONS

The research shows that the transfer of the accounting functions of an enterprise to the company, which specializes in this particular area, is a reasonable solution if the specifics of the enterprise's core functions are not related to accounting, which enables it to focus their resources on the main development. The goal set in this work and the analysis of the main factors that influence the application of outsourcing of accounting functions made it possible to formulate the following proposals.

It was found that accounting outsourcing services are used in Ukraine by a third less than in European countries (86%) and the USA (92%). The experience of the USA, Germany and Poland in outsourcing accounting functions is analyzed and approaches that can be applied in Ukraine are proposed, in particular: enshrining in national legislation the procedure for applying outsourcing; increasing the transparency of outsourcing companies' activities by publishing the information about their clients. During a comparative analysis of the performance of accounting functions by employees involved in different conditions of cooperation (full-time, freelance and outsourced), it was determined that outsourcing services have the most advantages, such as lower costs for maintaining workplace, a greater degree of responsibility and a more effective solution to urgent issues. It is concluded that companies in Ukraine, the USA, Poland, Great Britain, and Germany have a different price range for their services, while the list of said services is mostly the same, and consists of performing the main accounting functions and reporting. It was emphasized that accounting outsourcing is quite suitable for enterprises of the agricultural sector, considering whether their activity is seasonal and the fact that a large number of them are holdings. The economic profitability of accounting outsourcing for agricultural enterprises is substantiated on the basis of comparing the potential annual payment for full-time employees of the accounting service and the for outsourcing. It was proven that accounting outsourcing in the agricultural sector is an effective tool for optimizing enterprise costs, improving the quality of accounting and reporting, focusing efforts on expanding the main areas of activity, which is extremely important for the development of the agricultural sector of Ukraine during the war and in a post-war period. In this case, the main course of further research would be an in-depth analysis of accounting outsourcing from the perspective of the possible risks in order to minimize them, while increasing the trust of company managers in outsourcing.

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CONFLICT OF INTEREST

None.

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Бухгалтерський аутсорсинг як ефективний інструмент управління підприємством в сучасних умовах

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Анотація. Актуальність дослідження зумовлена необхідністю обґрунтування економічної вигідності для агропромислових підприємств застосування бухгалтерського аутсорсингу. Метою роботи є аналіз основних переваг делегування бухгалтерських функцій підприємства спеціалізованій компанії та доведення економічної доцільності аутсорсингу. Основу методологічного підходу складає: аналіз даних щодо рівня застосування аутсорсингу, метод середніх величин, метод порівняння, графічний метод, метод узагальнення. В межах статті було розкрито сутність, види, основні переваги та недоліки аутсорсингу та порівняно особливості організації робочого місця та оплати праці для штатного, позаштатного працівника та аутсорсингової компанії. Також було вивчено досвід США, Німеччини й Польщі та виокремлено підходи, які можна застосувати в Україні, а саме: закріплення у законодавстві порядку надання аутсорсингових послуг; оприлюднення аутсорсинговими компаніями інформації про клієнтів; визначення орієнтовного розміру фінансових витрат на утримання штатного працівника, що виконує обов'язки бухгалтера. У ході роботи було співставлено обсяги витрат на утримання бухгалтерської служби підприємства і на оплату за послуги аутсорсингової компанії та визначено розмір економічної вигідності від застосування бухгалтерського аутсорсингу, проаналізовано динаміки адміністративних витрат аграрних підприємств до та після передачі бухгалтерських функцій на аутсорсинг та обґрунтовано доцільність використання бухгалтерського аутсорсингу на підприємствах аграрної сфери як інструменту для зменшення адміністративних витрат і підвищення ефективності виконання бухгалтерських функцій на підприємстві. Результати дослідження надають пропозиції щодо розширення практики використання бухгалтерського аутсорсингу, зокрема шляхом підвищення довіри підприємств до аутсорсингових компаній, а також мають практичну значимість для аграрних підприємств при організації виконання бухгалтерських функцій та аутсорсингових компаній, наприклад, при розробці маркетингової політики просування послуг

Ключові слова: витрати; економічна вигідність; ефективне управління; штатний працівник; аграрна сфера

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Spatiotemporal patterns and vegetation forecasting of sunflower hybrids in soil and climatic conditions of the Ukrainian Steppe zone

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Abstract. Long-term studies of tillage and crop management are essential in finding out which crop production practices would contribute to sustainable yields and profits. In the conditions of climate change, such issues as selection, forecasting and adjustment of crop cultivation systems in the zone of moisture deficit and agricultural risk management are especially relevant. Therefore, the aim of the study was to establish spatiotemporal patterns of vegetative development of sunflower hybrids and predict their productivity in the soil and climatic conditions of the Ukrainian Steppe. A detailed analysis of seasonal changes in the values of the normalized difference vegetation index in sunflower hybrid crops during the 2019-2021 time period was carried out with the help of space images from the Sentinel 2 satellite device, and then processed with the ArcGis 10.6 licensed software product. The credibility of the achieved results of the condition of crops in different phases of plant vegetation on the basis of *NDVI* and the possibility of their use for forecasting the yield of agricultural crops have been proven. The adjustment capabilities of various sunflower hybrids to the STeppe soil and climate conditions were determined, particularly in regards of such hybrids as Oplot, Hektor, DSL403, P64GE133, 8X477KL. A model of the yield forecasting function for each sunflower hybrid was developed according to the annual level of moisture supply. The level of data approximation of the forecasting models was 97.2-99.9%. It is suggested to use system functional models

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developed specifically for different moisture supply and plant nutrition conditions in order to forecast of the yield of sunflower hybrids according to a particular situation. The results can be used to improve the methodology of researching the vegetation of agricultural crops, to validate crop rotation, to choose the best practical ways for the use of multifunctional growth-regulating substances, to define the climatic adjustment of cultivars and hybrids, to manage resources, to develop adaptive climate technologies in agriculture and crop production, to calculate their efficiency, to forecast the yield and to ensure the profitability of agricultural production in the moisture deficit zone and managing a high-risk farming

Keywords: crop production; climate; remote sensing; satellite images; modeling

INTRODUCTION

Intensive agriculture has greatly increased crop yields but simplified the production due less diverse farming systems, higher genetic homogeneity, and more uniform farming landscapes in recent decades. It should be noted that the system of relations between natural and man-made causes has changed significantly, which leads to a larger number of abnormal climatic conditions and the risks of their negative effects on the conditions for growing agricultural crops. The main result of the global warming is a decreasing moisture supply. Moisture has become a limiting factor for soils in various climatic zones. Therefore, the preservation of soil moisture, increasing the plant stress resistance to moisture deficit, adaptation of cultivars and hybrids to new climatic conditions, the need to adjust crop rotations and agro-technological operations, and the use of effective multifunctional growth-regulating substances have become an urgent issue.

The Steppe as a physico-geographical area characterized with high temperatures, and scarce, unstable and uneven distribution of atmospheric precipitation (Dudiak *et al*., 2019; Zhang *et al.*, 2019a), which causes high-risk farming conditions with a possibility of insufficient harvest of agricultural crops (Pichura *et al.*, 2021; Mateo-Sanchis *et al*., 2021). Since the 2000s, the number of abnormal climatic conditions has tripled, which caused a rise in the average annual temperature by 2.6°C and a higher number of torrential precipitations in the spring-summer period (Pichura *et al.*, 2022). This results in: a decreasing precipitation-productivity (Lisetskii *et al.*, 2020; Oti *et al.*, 2020), an increase in wind erosion (Dudiak *et al.*, 2021), local torrential precipitations and water erosion processes (Özşahin, 2023), as well as higher risks of terrestrial runoff, disruption in transpiration and increased evaporation of moisture in the summer-autumn period, water deficiency for agrocenoses (Assan *et al.*, 2020). Under such extreme climatic conditions, moisture is a limiting factor in the productivity of agricultural crops (Török *et al.*, 2020), therefore the agrotechnological conservation of pre-sowing soil moisture and the effective use of its reserves during the vegetation period of plants are utterly important (Domaratskiy *et al.*, 2020; 2022).

One of the promising areas of agricultural science research is the use of the remote sensing data to study the state of the crops based on the normalized difference vegetation index (*NDVI*) (Ding *et al.*, 2022; Essaadia *et al*., 2022). Spatiotemporal differentiation of the agrocenoses vegetation index indicates the state of plant development in different phenological stages depending on the natural and climatic conditions, the scope and kind of precipitation, the degree of agrotechnical measures. This makes it possible to define the level of adjustment of the hybrids to specific climatic conditions of certain physical and geographical zones and to evaluate the yield of agricultural crops.

Therefore, the purpose of the study was to forecast the yield to bolster the agricultural profitability, and to increase the level regional and national food security by rationalizing the optimal complex of agrotechnical measures, the choice of adjustable cultivars and hybrids considering the soil and climatic conditions of the Steppe zone.

LITERATURE REVIEW

Sunflower is the main Ukrainian oil crop, which takes about 25-28% in the structure of farm rotations. The seeds of modern zoned cultivars and hybrids contain 50-52% of oil, and the seeds of selective varieties - up to 60% (Shakalij *et al.*, 2019). In comparison to other oil crops, the sunflower provides the highest oil yield per unit area. Sunflower oil makes up for 98% of total oil production in Ukraine. Scientists S.D. Koutroubas *et al*. (2020), A.U. Jan *et al*. (2022) explained that ensuring a high level of oil content in crops requires a high level of moisture supply in the cultivation territory. Y. Cheng *et al.* (2023) found that in arid regions, soil moisture and nitrogen concentration are key indicators of plant development and productivity. During the growing season, the level of water consumption for sunflower changes (Domaratskiy *et al.*, 2020): from the emergence emergence to the inflorescence process, plants consume about 20% of growing water; during the phenological stages of fruit formation and flowering, the consumption of total vegetation moisture is 60%. In particular, the studies of V. Giannini *et al.* (2022) established that under the conditions of using standard agrotechnical measures on non-irrigated lands of the Steppe zone, the sunflower yield would not exceed 50% of its biological potential. Scientists I.V. Aksionov *et al.* (2021) emphasized that one of the ways to successfully solve the problem of a high and stable yield is the wide implementation of forecasting methods and programming the yield of agricultural crops. In turn, V.G. Didora *et al.* (2013) in their studies explained the need to use forecasting methods as a tool for solving the task of optimizing agricultural production, including the production of oil crops, as a way of considering and reducing weather risks on the agrocenoses productivity. Scientists P. Kamath *et al.* (2021) and R.J. Chitsiko *et al.* (2022) emphasized that forecasting and planning are among the most accurate measures and methods of scientific prediction, which sums up all types of activities related to defining the state of the agrocenosis of a cultivar or hybrid in future prospect in ways specific for these methods. P. Debaeke *et al.* (2023) notes that crop forecasting several weeks before harvest is strategically important for cooperatives that collect, store and sell grain. Scientific works of Y. Zhang *et al.* (2019b) and G. Ronchetti *et al.* (2023) in particular prove that using of satellite images provides relevant and crucial information, which is used to develop the yield forecasting models regardless of the scope of the research area and crop rotation based on *NDVI* calculation. In modern science, the application of Sentinel satellites has provided a number of new possibilities for yield forecasting due to its spatial resolution and revisit time (Desloires *et al.*, 2023; Zhang *et al.*, 2023).

Based on the results of the analysis of recent studies, it was established that it is important to develop a model for predicting the yield of agrocenoses, including sunflower, based on the *NDVI* index by using the data on the distribution of water consumption and plant nutrients on various development stages.

MATERIALS AND METHODS

The study of the development and productivity of sunflower hybrids in the soil and climatic conditions of the Steppe zone of Ukraine was conducted in the period from 2019 to 2021 at the experimental field of the Mykolaiv State Agricultural Research Station of The Institute of Climate-Smart Agriculture of The National Academy of Agrarian Sciences of Ukraine (Fig. 1). Experiments were conducted without irrigation. The total area of experiments: 2019 – 1.9 ha, 2020 – 8.4 ha, 2021 – 0.75 ha.

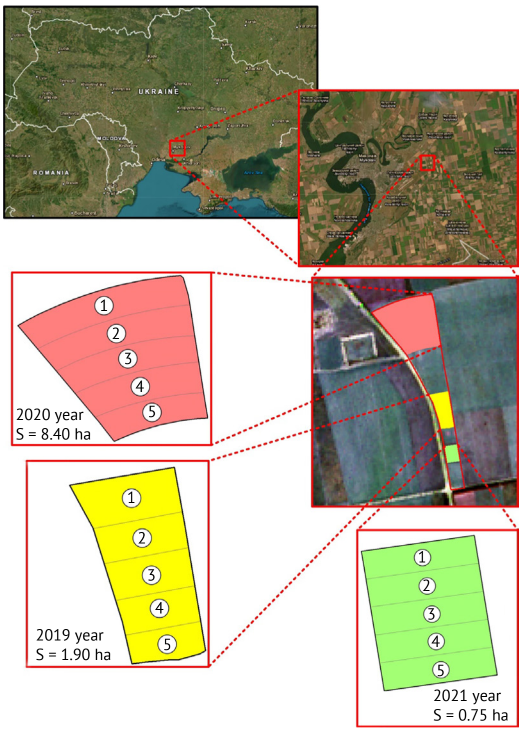

Figure 1. *The location of the experimental fields and the arrangement of sunflower hybrid sowing in the period of 2019-2021*

Notes: *1 – Oplot; 2 – Hector; 3 – DSL403; 4 – P64GE133; 5 – 8X477KL*

Source: *compiled by authors*

The experimental areas are located on low-humus southern chernozems with a loam that has a high level of dust in its granulometric composition. The content of humus in soils varies from 2.7 to 3.1%, the depth of the humus horizon is 30-40 cm. The reaction of the soil solution is close to neutral (pH 6.5-6.8), hydrolytic acidity is within 2.00-2.52 mg equiv. per 100 g of soil. The amount of absorbed bases is 32-35 mg equiv. per 100 g of soil, the degree of saturation with bases is 95.7%. According to the content of mobile nutrients, the soil of the experimental area is characterized by an average content of nitrate-nitrogen in the soil layer 0…20 cm – 30.0 mg/kg, 100 mg/kg of mobile phosphorus and a very high content of exchangeable potassium – 300.0 mg/kg of soil. The data on actual surface air temperature data (*T*, °C) and the amount of atmospheric precipitation (*P*, mm) for the growing season in 2019, 2020 and 2021 was used in the study, while the climatic norms for the research area were based on the data of the Mykolaiv meteorological station for the period of 1970-2020.

Program of scientific research. A field experiment was established in order to study the vegetation process based on the *NDVI* index and establish the climatic adjustment of high-oleic sunflower hybrids of Ukrainian and French selection. The Ukrainian selection included sunflower hybrids Hektor and Oplot (originator – V.Ya. Yuryev Institute of Crop Science). French selection consisted of DSL403 and P64GE133 (produced by Corteva, Brevant) and 8X477KL (produced by Dow Seeds). The experiments were repeated in 2019, 2020 and 2021. In 2019, the sowing date is 04/24, the harvest is 08/26; in 2020: sowing – 29/04, harvesting – 22/08; in 2021: sowing – 10/05, harvesting – 12/09. Every year, sunflower hybrids grew in the same sequence within typical soil and climatic conditions, in an area where the winter wheat used to grow before (Fig. 1). The sown area of the first order lot was 168 m^2, the testing lot was 120 m^2. Sowing was carried out with a UPS-8 pneumatic precision seeder, the seeding rate was 48.7 thousand units/ha. Accounting and observation were carried out according to the methodology of scientific research in agronomy (Ermantraut *et al.*, 2008; Didora *et al.*, 2013), methodological recommendations of The Plant Production Institute named after V.YA. Yuriev of National Academy of Agrarian Sciences of Ukraine (Kyrychenko *et al.*, 2014), DSTU 6068:2008 (2009) and DSTU 7011:2009 (2010). The level of soil moisture was determined by the thermogravimetric analysis during sowing and harvesting (Papish, 2001). The seed yield was recorded manually, with the subsequent calculation of the yield in tons from 1 hectare of the sown area with 8% seed moisture and 100% seed purity.

Methods of deciphering space images and spatial analysis. Spatial-temporal differentiation of the vegetation of sunflower hybrids was determined on the basis of the calculation of *NDVI* (Beyer *et al.*, 2023) based on the data of decoded Sentinel 2 space images with a spatial resolution of 10×10 m per pixel.

The *NDVI* value is calculated by the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}, \qquad (1)$$

where *NIR* – the visible and near-infrared range (Sentinel 2 – Band 8); *Red* – the red range of the electromagnetic spectrum (Sentinel 2 – Band 4).

The *NDVI* value ranges from 0 to 1.0. Open field soil is characterized by *NDVI* values from 0.05 to 0.15. At the beginning of the sowing the value of *NDVI* was 0.15 each year. In the period of active vegetation from the macrostages of "flower bud development" (*BBCH* 51-59) to the end of the "blooming" macrostage (*BBCH* 61-69), the *NDVI* value reflects the state of crop development, namely: < 0.15 open soil; 0.15-0.2 – sparse vegetation; 0.2-0.3 – suppressed vegetation; 0.3-0.4 – very poor condition; 0.4-0.55 – satisfactory condition; 0.55-0.7 – good condition; > 0.7 – very good plant condition.

Space photographs with no overcast over the experimental field were used in the research. The frequency of image processing was 10-16 days, which made it possible to determine the *NDVI* value for the main phenological stages of the development of sunflower hybrids, namely: seedlings (*BBCH* 00-09), the first pair of true leaves (*BBCH* 10-12), inflorescence formation (*BBCH* 14-59), flowering (*BBCH* 61-69), ripening (*BBCH* 71-99). The calculation of *NDVI* at all phenological stages made it possible to study the development process of sunflower hybrid crops and establish changes in the terms of the phenological stages of plants in regards to the climatic conditions of the year: dry, moderately humid and wet year. Space images were processed considering the sowing and harvesting dates in 2019, 2020, 2021.

In order to improve the quality of the visualization of maps of the spatiotemporal distribution of *NDVI* values and to increase both the accuracy of the interpretation of the vegetation index within individual plots and the characteristics of the heterogeneity of the vegetation of sunflower hybrids, the interpolation of the values obtained on the basis of the decoding of the Sentinel 2 space images was carried out. The interpolation was carried out using the method of geostatistical analysis with a radial basis function (Chen *et al.*, 2023; Pichura *et al.*, 2023). This method allows to establish an accurate interpolation of surface changes in *NDVI* values while preserving the input raster data.

The raster calculator of the ArcGis 10.6 software was used to calculate the generalized map of $NDVI_{year}$ values of sunflower hybrids based on the *NDVI* raster surfaces of the main phenological stages of vegetation and the formation of plant productivity. The correlation and regression analysis (Grover & Kaur, 2021) was used to develop functions for predicting the yield of sunflower hybrids depending on the spatial-temporal differentiation of the values of the vegetation index.

Space images processing, cartograms constructing, spatiotemporal and correlation and regression analysis were carried out with the licensed software product ArcGis 10.6 and Microsoft Excel 2010. The conducted research complies with all ethical norms according to The Convention on Biological Diversity (2022).

RESULTS AND DISCUSSION

Analysis of climatic research conditions. Climatic conditions of the studied area are characterized as medium-arid. The average statistical value of the normal (in period of 1970-2020) air temperature during the growing season was 18.0°C (Fig. 2a), the standard deviation was 4.9°C, and the level of variation was 27.3%. In particular, the average value of the air temperature during the growing season in the dry year (2020) was 19.0°C, the standard deviation was 6.3°C, and the level of variation was 33.3%. In a moderately humid year (2019), the average air temperature during the growing season was 20.4°C, the standard deviation was 5.5°C, and the level of variation was 27.0%. In the wet year (2021), the average air temperature during the growing season was 18.4°C, the standard deviation was 6.6°C, and the level of variation was 35.8%.

It has been established that over the past 10-15 years, the frequency of abnormal climatic conditions of a torrential nature has increased (Pichura *et al.*, 2022). In July 2020 (Fig. 2b), a drastic rise in the vegetation index was observed during the flowering period (*BBCH* 61-69), but the torrential nature of atmospheric precipitation had no positive outcome or prolonged effect on the formation of the productivity of sunflower hybrids. In particular, in the dry year (2020), a high value of the standard error (84.1 mm) and the level of variation of seasonal changes in atmospheric precipitation (139.7%) were recorded, which confirms their anomaly during the growing season.

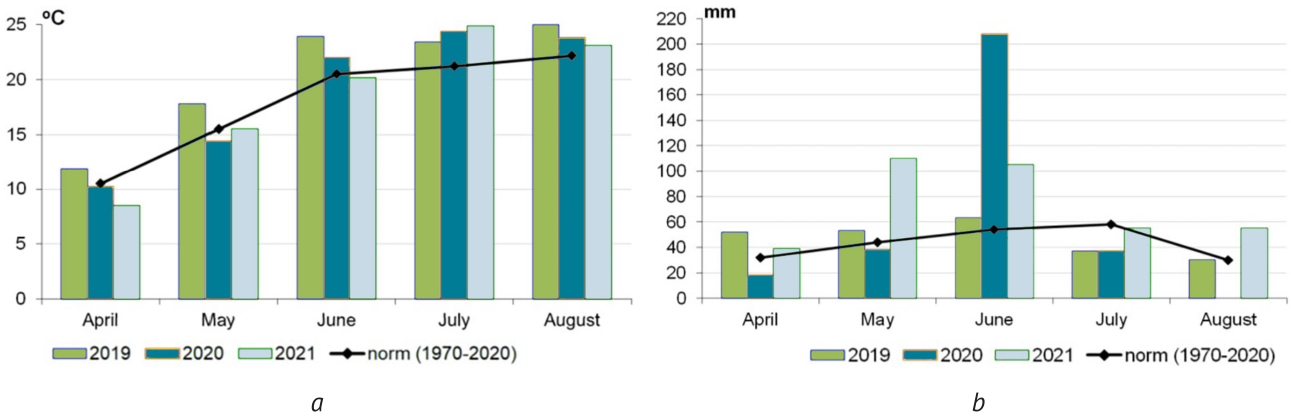

Figure 2. *Climatic conditions during the sunflower growing season for 2019-2021: a – average monthly air temperature (°C); b – amount of precipitation (mm)*
Source: *compiled by authors, based on the data of the Mykolaiv meteorological station*

The average monthly value of atmospheric precipitation during the growing season for 50 years (1970-2020) had been 43.6 mm (Fig. 2b), with the standard deviation 12.6 mm, and the level of variation 28.9%. The year 2019 was close to typical (normal) climatic conditions, the average monthly precipitation during the growing season was 47.0 mm, the standard deviation was 13.3 mm, and the level of variation was 28.3%. A typical wet year of 2021 in the Steppe zone is characterized by an average monthly precipitation of 72.8 mm, a standard deviation of 32.4 mm, and a high level of variation of 44.5%.

Well-developed sunflower crops consume from 500 mm to 600 mm of water during the growing season (Kohan, 2021) (the minimum water requirement is met with 300-400 mm of atmospheric precipitation). During the growing season of 2019, the amount of atmospheric precipitation was 235 mm, in 2020 – 295 mm (in July, an unusually abnormal amount of precipitation was estimated to nake 70.5% of the share of the growing season, being an unproductive precipitation of a torrential nature), in 2021 – 364 mm.

In the arid conditions of the Ukrainian Steppe, the level of soil moisture is a factor that determines the productivity of agrocenoses. It was estimated that 60-70% of the total sunflower water consumption during the growing season are provided by atmospheric precipitation, while 30-40% – by the soil moisture supply (Domaratskiy *et al.*, 2020). Using the thermostatic-weight method, it was established that the pre-sowing moisture reserves in a meter-long soil layer of the experimental fields in the dry year of 2020 amounted to 41 mm, in the moderately humid year of 2019 – 69 mm, and in the wet year of 2021 – 89 mm.

The second half of the growing season in 2019 was characterized by a moisture deficit, being 23.9% less than normal atmospheric humidity, as well as an increase in temperature by 11.5%, which mainly caused stress in plants with a subsequent decrease in productivity. In a dry year of 2020 sunflower hybrids were constantly under stress, caused by a significant deficit of soil and atmospheric moisture in combination with anomalous unproductive rainfall of a torrential nature in July as a result of high air temperature. Peculiarly, in the wet year of 2021, there were no signs of stressful weather conditions and a productive precipitation was recorded during the budding and flowering period (*BBCH* 51-69), which is the defining phenological stage of plant development in crop formation. Therefore, in the conditions of extreme agriculture of the Steppe zone, agrotechnological measures are aimed at preserving moisture.

Studying the state of sunflower hybrid crops. A change in the activity of the plant's photosynthetic processes and the production of chlorophyll content at a certain macrostage and phenological phase are indicators of plant development. The study of changes in the photosynthetic activity of sunflower hybrids was carried out based on the analysis of *NDVI* values, which is common in forecasting the productivity of agrocenoses.

The value of the *NDVI* index within the experimental fields, during 2019, 2020 and 2021, was calculated on the basis of data from satellite images from the Sentinel 2 spacecraft. Using the images, the state of the green mass of plants, which absorbs electromagnetic waves in the visible red range and reflects them in the near infrared was determined. In particular, the maximum absorption of solar radiation by chlorophyll occurs in the red zone of the spectrum (central wavelength of Sentinel 2 – 665 nm), and in the near infrared zone (central wavelength of Sentinel 2 – 842 nm) – the maximum reflection of energy by the cellular structure of the leaf.

The moderately humid year (2019). By interpreting a series of satellite images in a moderately humid year at the beginning of the vegetation process (May 5, 12 days from the sowing date), young seedlings were recorded in sunflower hybrid crops with an average value of the *NDVI* index of 0.26 ± 0.03 and insignificant level of spatial variation – 8.1%. After foliar feeding of the hybrids, a heterogeneous reaction to multifunctional growth-regulating substances was observed, which was later confirmed by satellite images on May 30 (37 days from the sowing date). It should be noted that the growth of Oplot hybrid plants increased and the *NDVI* value varied within 0.54-0.77, the Hector hybrid *NDVI* value varied within 0.54-0.80 and the DSL403 hybrid – within 0.51-0.78. A downward reaction to re-regulating substances was observed in hybrid P64GE133 with an *NDVI* value of 0.41-0.67 and hybrid 8X477KL with an *NDVI* value of 0.43-0.62. At the end of the phenological phase of "inflorescence formation" on June 14 (52 days from the date of sowing) and the beginning of the "flowering" phase on June 19 (57 days from the date of sowing), good (0.55-0.70) and thriving state of vegetation was recorded of all sunflower hybrids (> 0.70). During this period, the average value of *NDVI* was 0.72 ± 0.06, the level of spatial heterogeneity was 8.2%.

The second half of the growing season of sunflower hybrids in 2019 includes the second half of the flowering phase (*BBCH* 67-69) and the macrostages of "fruit formation" (*BBCH* 71-79), "fruit and seed ripening" (*BBCH* 80-89) and "senescence" (*BBCH* 92-99), which are components of the phenological stage of ripening (*BBCH* 71-99). It should be noted that the second period of plant vegetation was characterized by stressful conditions caused by the lack of moisture and high temperatures. This led to the sharp deterioration of photosynthetic processes and the shortening of the "fruit formation" period. On July 4 (72 days from the date of sowing), the average value of *NDVI* was recorded – 0.63 ± 0.09 with noticeable manifestations of heterogeneity in the formation of productivity of sunflower hybrids, the level of spatial variation – 14.1%. During the vegetation period on the "fruit and seed ripening" macrostage, on July 24 and August 13, rapid seed maturation of P64GE133 and 8X477KL hybrids was recorded. In the macro stage of "senescence" from the period of full ripeness (seed moisture about 10%, *BBCH* 92) to harvest (August 23), the average *NDVI* value was 0.37, on August 26 it was 0.30.

The dry year (2020). In 2020, the recorded conditions were extremely dry for the cultivation of sunflower hybrids, which caused a shorter growing season and the terms of individual phenological phases of plants. In particular, the beginning of the growing season in 2020 was characterized by a low level of soil moisture and a small amount of precipitation. This resulted in weaker plant seedlings and a critically low level of photosynthetic processes at the beginning of the phenological phase of inflorescence formation. After the cultivation of crops when the 6-8 true leaves were formed, the delayed reactions of all hybrids to the action of multi-functional re-regulating substances were recorded, as a result of stressful climatic conditions. According to the satellite image decoding data for May 19 (21 days after sowing), a low level of *NDVI* value was calculated - 0.23±0.02 with an insignificant level of variation - 8.2%. The lack of precipitation caused further suppression of plant development, which was confirmed by the results of interpreting the satellite image from June 8 (41 days after sowing), the *NDVI* value was 0.36±0.04 with a significant level of variation - 10.3%. June 2020 was characterized by heavy rainfall, which improved photosynthetic processes in sunflower hybrids. At the beginning of the flowering phase, on June 23 (56 days after sowing), the *NDVI* value was 0.70±0.03 with a slight variation of 4.9% (Fig. 3; Fig. 4).

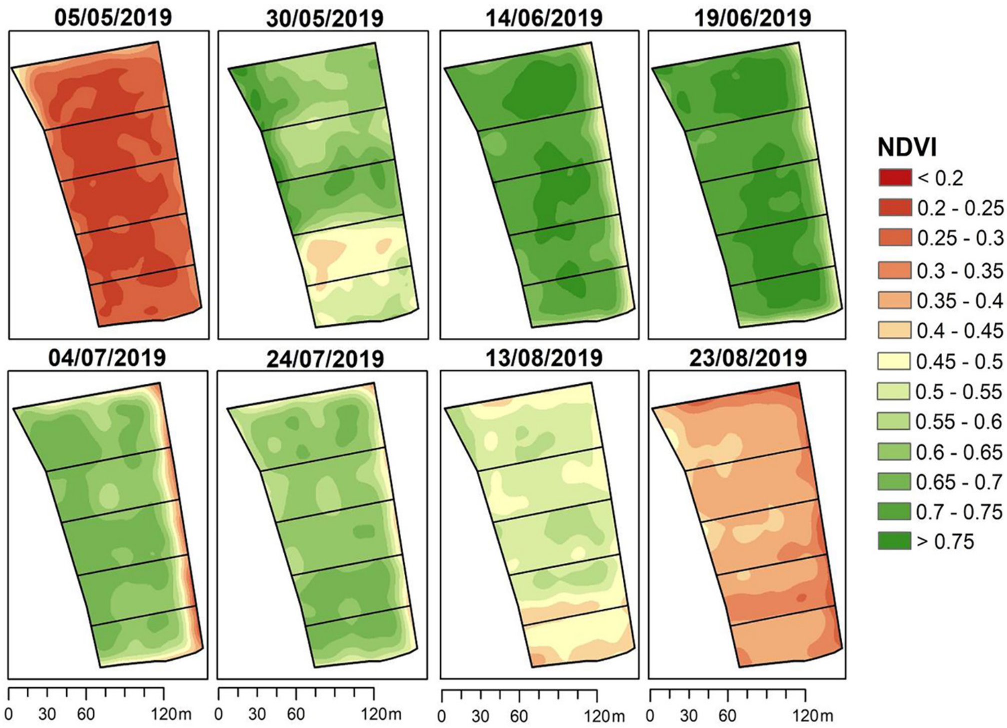

Figure 3. *Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2019)*
Source: *compiled by authors*

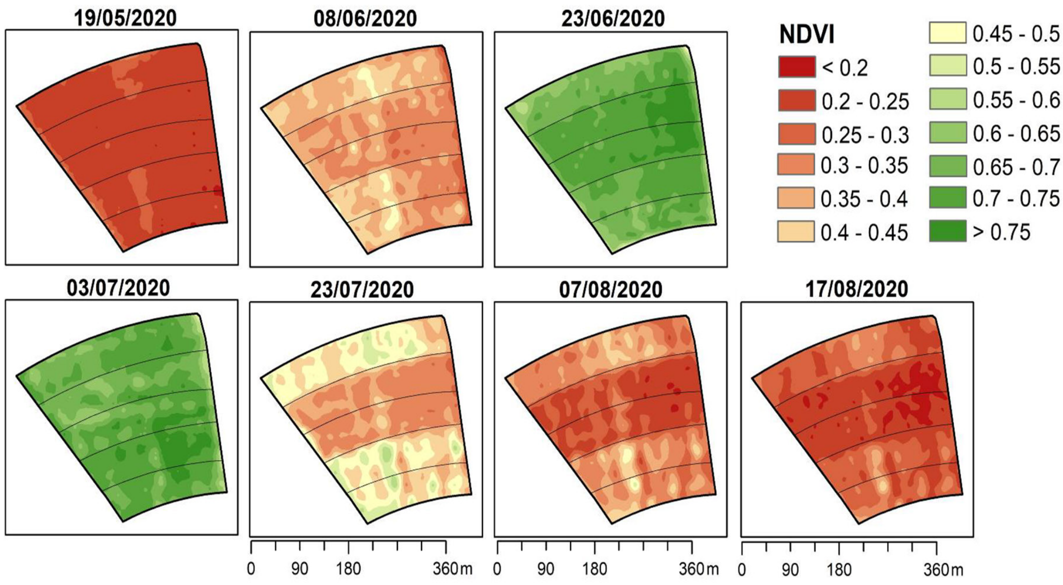

Figure 4. *Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2020)*
Source: *compiled by authors*

The end of the flowering phase in July 3 (56 days after sowing), was also characterized by high *NDVI* values of 0.69 ± 0.03 with a variation level of 9.8%. The lack of atmospheric and soil moisture supply in the second half of the plant growing season caused a sharp decrease in the photosynthetic activity of sunflower hybrids and, with a corresponding reduction in the term of the "fruit formation" (*BBCH* 71-79), stimulated the acceleration of "fruit and seed ripening" (*BBCH* 80-89) and "senescence" (*BBCH* 92-99) of plants, on July 23 (86 days after sowing), the *NDVI* value was 0.41 ± 0.04 with a variation level of 9.8%. As of August 7 (101 days after sowing), the *NDVI* value was 0.30 ± 0.04 with a high level of variation – 12.2%.

On August 17-18 (112 days after sowing), during the "senescence" macrostage, the *NDVI* value was 0.25 ± 0.03 with a high level of spatial variation – 11.6%. High spatial variation was caused by significant spatial heterogeneity of plants as a result of stress caused by climatic conditions. It was found that Hektor and DSL403 sunflower hybrids matured faster in dry periods. The lack of moisture caused the deterioration of photosynthetic processes, a significant decrease in the content of chlorophyll in plants, a shortening of the terms of important phenological phases and the vegetation period of sunflower hybrids as a whole.

The wet year (2021). The beginning of the growing season in 2021 was characterized by favorable climatic conditions in the pre-sowing period, which ensured a high level of soil moisture during the sowing period. This determined the high energy and uniformity of seedlings, recorded on May 14 (5 days from the sowing date), the value of the NDVI index – 0.25 ± 0.03, the level of spatial variation – 6.2% (Fig. 5).

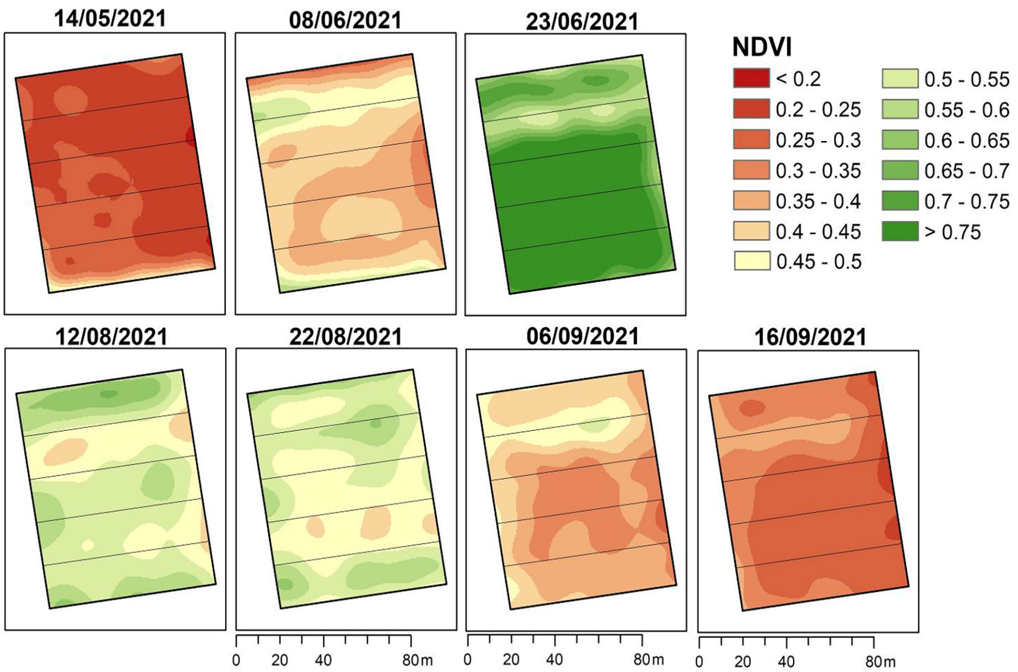

***Figure 5.** Seasonal distribution of NDVI of sunflower hybrids on the experimental field (2021)*
***Source:** compiled by authors*

On June 8 (21 days from the date of sowing), after processing the crops, a high heterogeneity of the response of the hybrids to multifunctional re-regulating substances was observed, this is due to the redistribution of moisture in the field and the hybrids' adjustment to the climatic conditions of the Steppe. The value of NDVI was 0.42 ± 0.04 with a high level of spatial variation of 14.0%. During this period, the high photosynthetic capacity of the Oplot hybrid was recorded, the *NDVI* value reached the level of 0.56. Hybrids DSL403 (*NDVI* – 0.39) and P64GE133 (*NDVI* – 0.40) had a relatively low level of photosynthesis.

On June 23 (45 days after sowing), during the flowering phenological stage, all the sunflower hybrids were characterized by a high level of photosynthetic processes, the *NDVI* value was 0.75 ± 0.06 with a spatial variation of 8.5%. Systematic and productive atmospheric precipitation and high soil moisture supply in the first part of the vegetation period led to the prolongation of the phenological stage of flowering, which contributed to the increase in plant productivity. In 2021 the flowering phase had lasted for 33 days, which is 2.3 times longer than in the previous two years. The maximum value of *NDVI* during the flowering period is 0.89-0.93. A high level of *NDVI* was recorded in the phenological stage of the "fruit formation" macrostage – 0.74 (76 days from the date of sowing) and the macrostage of "fruit and seed ripening" – 0.54 (95 days from the date of sowing).

A high level of moisture supply, the extension of the duration of the flowering phase provided favorable conditions for the formation of fruits and ripening of sunflower seeds. On September 6 (119 days after sowing), at the end of the "ripening fruit and seed" macro-stage, the *NDVI* value was 0.39; on September 12, in the "senescence" and harvest macro-phase, the *NDVI* value was 0.32. Spatial variation during the growing season of plants was caused by spatial differentiation of soil moisture and different levels of plasticity of hybrids to the climatic conditions of the Steppe zone.

Forecasting the yield of sunflower hybrids. Sunflower has a deep root system and the ability to consume water from a depth of 2 to 4 meters in dry years, however it still needs moisture supply. In different periods of the phenological stages of development, the sunflower consumes moisture unevenly, most actively during the phase of intensive growth, flowering and seeding. From the seedlings emergence (*BBCH* 09) to the inflorescence formation (*BBCH* 15), plants consume about 20% of vegetation moisture; during the phenological phases of inflorescence formation (*BBCH* 16-59) and flowering (*BBCH* 61-69), the consumption of total vegetation moisture is 60%, this period is crucial in the formation of productivity; on the other hand, 20% of vegetation moisture is consumed during the fruit formation and at the beginning of ripening (*BBCH* 71-80).

Defining the *NDVI* index during the main stages of sunflowers' moisture supply and mineral nutrition provided the possibility of creating a general cartogram of the spatial distribution of the vegetation index values in 2019, 2020 and 2021. Generalized cartograms of $NDVI_{year}$ values are the sum of raster surfaces of differentiation in NDVI values in the main periods of plant vegetation. The first raster surface in particular identifies the NDVI values at the beginning of the formation of embryo baskets in the macrophase *BBCH* 16-19, the second raster surface contains the *NDVI* values of the characteristics of the macrophases *BBCH* 61-67, the third raster surface contains the distribution of *NDVI* values of the macrophase *BBCH* 79-80. The corresponding *NDVI* raster is assigned a weighting factor of the cumulative influence of the values of vegetation moisture consumption and mineral nutrition elements on the formation of crop yield. Thus, the values of the raster surface $NDVI_{BBCH\ 16\text{-}19}$ are assigned a weighting factor of 0.2, the values of $NDVI_{BBCH\ 61\text{-}67}$ are assigned a weighting factor of 0.6 and the values of the raster surface $NDVI_{BBCH\ 79\text{-}80}$ are assigned a factor of 0.2.

The generalized map of *NDVI* values is created by the formula:

$$NDVI_{year} = 0.2NDVI_{BBCH\ 16\text{-}19} + 0.6NDVI_{BBCH\ 61\text{-}67} + 0.2NDVI_{BBCH\ 79\text{-}80}. \quad (2)$$

Spatial differentiation of $NDVI_{year}$ values, which are functionally correlated with spatial variation of yield of sunflower hybrids, was calculated using a raster calculator (Fig. 6). It was determined that in the moderately humid year of 2019, the value of $NDVI_{year}$ varied within 0.57-0.69, in the dry year of 2020 – 0.48-0.59, in the wet year of 2021 – 0.49-0.71. It was established that the values of the vegetation index reflect photosynthetic processes and the production of chlorophyll content, which depend on the conditions of moisture supply of the year and the amount of mineral nutrients, but do not identify the overall features and hybrids' adjustment to the soil and climatic conditions of physiographic zones. Therefore, in order to clarify the correlation between $NDVI_{year}$ values to the productivity of individual hybrids, the generalization of $NDVI_{year}$ values was carried out by mathematically relating the raster values of the vegetation index to its average value of the corresponding year.

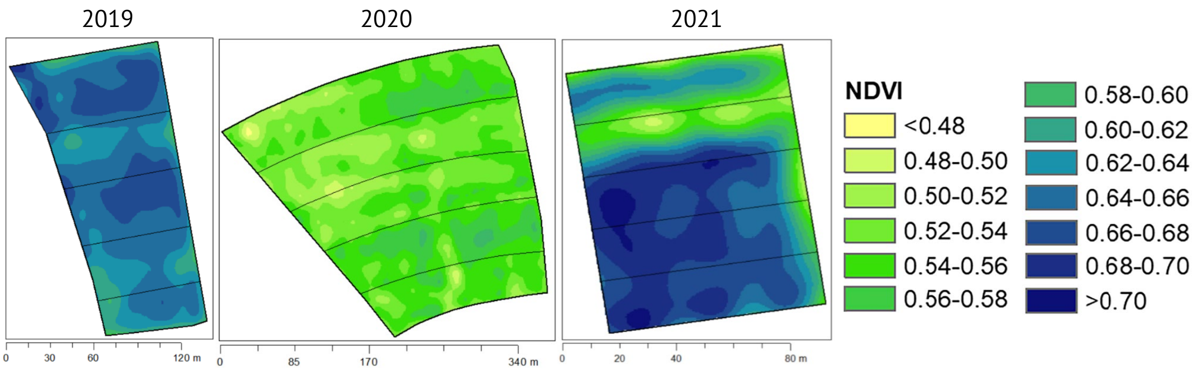

Figure 6. *Spatial differentiation of generalized* $NDVI_{year}$ *values of sunflower hybrids in 2019-2021*
Source: *compiled by authors*

With the calculations, raster surfaces were created, where the value "1" corresponds to the average value of $NDVI_{year}$ for each particular year. Thus, the average value of $NDVI_{year}$ of a separate lot corresponds to the average yield value of the respective sunflower hybrid. Next, the average yield of each sunflower hybrid was calculated: Oplot in 2019 – 3.0 t/ha, in 2020 – 2.01 t/ha, in 2021 – 3.04 t/ha; Hector in 2019 – 2.05 t/ha, in 2020 – 1.65 t/ha, in 2021 – 2.16 t/ha; DSL 403 in 2019 – 2.53 t/ha, in 2020 – 1.88 t/ha, in 2021 – 2.77 t/ha; P64GE133 in 2019 – 2.83 t/ha, in 2020 – 1.96 t/ha, in 2021 – 3.02 t/ha; 8X477KL in 2019 – 2.32 t/ha, in 2020 – 1.71 t/ha, in 2021 – 2.82 t/ha.

Based on the aforementioned data, cartograms of the spatial differentiation of yield of sunflower hybrids were constructed (Fig. 7), correlating to the distribution of generalized $NDVI_{year}$ values according to the formula:

$$CY_{year} = \frac{NDVIi_{year}}{Aver(NDVIi_{year})} \cdot Aver(CY_i), \qquad (3)$$

where $NDVI_{iyear}$ – the value of the vegetation index within the experimental lot of a separate cultivar or hybrid of a culture; $Aver\ (NDVI_{iyear})$ – the average value of the vegetation index within the experimental plot of a separate variety or hybrid of a culture; $Aver(CY_i)$ – the average value of the productivity of a separate variety or hybrid of a culture within the experimental area.

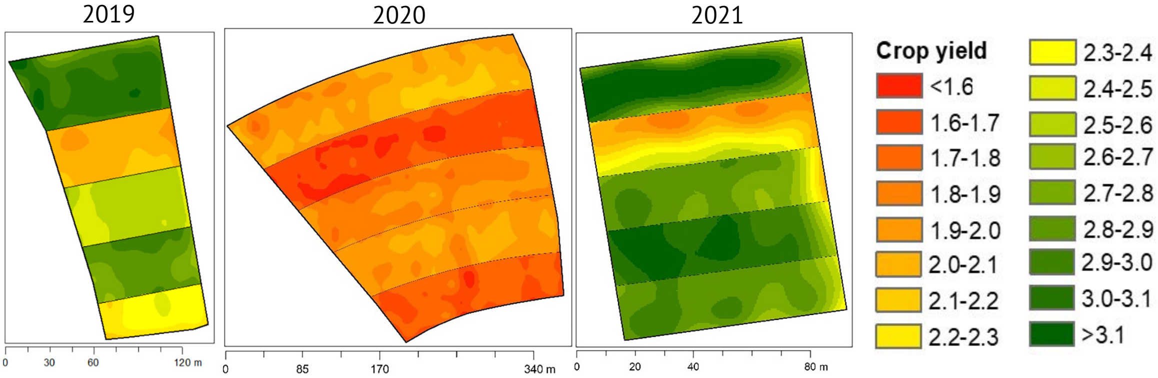

Figure 7. *Cartograms of the distribution of the yield of sunflower hybrids in 2019-2021*

Source: *compiled by authors*

Yield cartograms make it possible to establish the spatiotemporal heterogeneity of the productivity for an individual sunflower hybrid depending on the climatic conditions in 2019, 2020 and 2021. In the average humid year (2019), the yield of sunflower hybrids ranged from 1.86 to 3.18 t/ha. The minimum yield values were recorded for Hector hybrids were 1.86-2.15 t/ha, for 8X477KL – 2.10-2.42 t/ha, average yield levels for DSL 403 – 2.44-2.60 t/ha, while other have reached their maximum yield: Oplot – 2.70-3.18 t/ha and P64GE133 – 2.65-2.92 t/ha. In the dry year (2020), hybrids Hektor – 1.53-1.76 t/ha and 8X477KL – 1.58-1.81 t/ha had the minimum yield values, hybrids DSL 403 – 1.75-2.00 t/ha, P64GE133 – 1.80-2.06 t/ha and Oplot – 1.85-2.16 t/ha. In the wet year (2021), the Hektor hybrid had the minimum yield value – 1.82-2.56 t/ha, the average yield level was recorded in the hybrids DSL 403 – 2.65-2.93 t/ha and 8X477KL – 2.50-2.98 t/ha, the maximum level was achieved by hybrids Oplot – 2.60-3.37 t/ha and P64GE133 – 2.80-3.17 t/ha. It was established that each sunflower hybrid has individual genetic features of plant adjustment to the soil and climatic conditions of the Steppe, which determines the yields. Therefore, a model of the yield prediction function was developed for each hybrid (Table 1).

Table 1. *Forecasting functions and graphs of the normal yield distribution of sunflower hybrids according to the 2019-2021 data*

Oplot
2019 (the average humid year) $Y = 0.914NDVI_1 + 2.739NDVI_2 + 0.923NDVI_3$, $r^2 = 0.996$ 2020 (the dry year) $Y = 0.745NDVI_1 + 2.235NDVI_2 + 0.745NDVI_3$, $r^2 = 0.999$ 2021 (the wet year) $Y = 1.038NDVI_1 + 3.114NDVI_2 + 1.038NDVI_3$, $r^2 = 0.999$

Table 1, Continued

Hector
2019 (the average humid year)
$Y = 0.628NDVI_1 + 1.807NDVI_2 + 0.731NDVI_3$, $r^2 = 0.988$
2020 (the dry year)
$Y = 0.585NDVI_1 + 1.841NDVI_2 + 0.624NDVI_3$, $r^2 = 0.972$
2021 (the wet year)
$Y = 0.619NDVI_1 + 2.166NDVI_2 + 0.795NDVI_3$, $r^2 = 0.996$
DSL 403
2019 (the average humid year)
$Y = 0.758NDVI_1 + 2.220NDVI_2 + 0.798NDVI_3$, $r^2 = 0.989$
2020 (the dry year)
$Y = 0.701NDVI_1 + 2.107NDVI_2 + 0.703NDVI_3$, $r^2 = 0.999$
2021 (the wet year)
$Y = 0.839NDVI_1 + 2.464NDVI_2 + 0.833NDVI_3$, $r^2 = 0.987$
P64GE133
2019 (the average humid year)
$Y = 0.857NDVI_1 + 2.644NDVI_2 + 0.974NDVI_3$, $r^2 = 0.999$
2020 (the dry year)
$Y = 0.704NDVI_1 + 2.111NDVI_2 + 0.704NDVI_3$, $r^2 = 0.999$
2021 (the wet year)
$Y = 0.878NDVI_1 + 2.706NDVI_2 + 0.917NDVI_3$, $r^2 = 0.980$
8X477KL
2019 (the average humid year)
$Y = 0.944NDVI_1 + 2.140NDVI_2 + 0.583NDVI_3$, $r^2 = 0.990$
2020 (the dry year)
$Y = 0.629NDVI_1 + 1.887NDVI_2 + 0.629NDVI_3$, $r^2 = 0.999$
2021 (the wet year)
$Y = 0.845NDVI_1 + 2.535NDVI_2 + 0.845NDVI_3$, $r^2 = 0.999$

Source: *compiled by authors*

Functions with a high level of approximation (r^2) describe the spatiotemporal processes of vegetation formation of yield for each individual sunflower hybrids according to the level of moisture supply during the year. Function models were created on the basis of three raster periods of water supply and mineral nutrition of plants. The $NDVI_1$ value contains the average value or the raster surface of the spatial distribution of the vegetation index of sunflower hybrids in the macrophase of the formation of the embryo inflorescences of the *BBCH* 16-19 plant, the $NDVI_2$ value contains the average value or the raster surface of the spatial distribution of the vegetation index of sunflower hybrids in the flowering macrophase of *BBCH* 61-67, the $NDVI_3$ value contains the average value or raster surface of the spatial distribution of the vegetation index of sunflower hybrids at the end of the macrophase of fruit formation and the beginning of seed ripening (*BBCH* 79-80). These functions provide a level of approximation of actual data with 97.2-99.9% level of data approximation, which confirms the high accuracy of predicting the yield of sunflower hybrids.

It should be mentioned that the scientific research in the field of agriculture and crop production S.M. Shakalij *et al.* (2019) and S.D. Koutroubas *et al.* (2020) are approximated and do not take into account the causality of the spatiotemporal differences in the vegetation of varieties and hybrids of crops in regards to the unified *BBCH* scale. Therefore, the researchsuggests to take into account the peculiarities of the vegetative development of different sunflower hydrides according to the unified *BBCH* scale. This made it possible to establish regularities in the formation of the productivity of agrocenoses depending on their development in the main phenological phases and to determine the genetic features of the climatic plasticity of each sunflower hybrid to the conditions of their cultivation in the Steppe zone of Ukraine.

In the studies by I.V. Aksionov *et al.* (2021) and P. Kamath *et al.* (2021) forecasting the yield of agricultural crops was carried out on the basis of correlation and regression analysis, which involves determining the influence of individual natural and agrotechnical factors and further developing regression models of correlation between the actual yield and production factors. Such models are based on field, experimental and official data of institutions monitoring the natural and climatic conditions of the research region and do not take into account the spatiotemporal patterns of plant development in separate phenological phases of their development. Therefore, the author's approach to the development of regression models for predicting sunflower yield based on the new *NDVI* according to the unified *BBCH* scale is proposed. This would allow to quickly react to the changes on the plant vegetation state and to make adjustments to agrotechnical processes in order to increase the productivity of agrocenoses.

In the scientific works of G. Ronchetti *et al*. (2023) and Desloires *et al*. (2023) prove the relevance of using satellite images for forecasting and improving the mechanism of managing the agrocenoses development within a separate field. Thus, taking into account the existing developments, the approaches of using a series of satellite images for detailed research and establishment of spatiotemporal regularities in vegetation and the formation of agrocenoses productivity, considering their genetic features, zonal phytopotential, soil, local nature and climate conditions and elements of varietal agricultural technology, has developed and improved significantly.

The previous scientific works and the original research confirm the scientific and practical value of using modern technologies of remote sensing to improve the monitoring of crops, manage and determine the efficiency of agrotechnical measures, increase the reliability of forecasting the agrocenoses productivity within a specific field or the area of individual agricultural producers. The presented results are particularly aimed at determining the sunflower cultivars and hybrids, which would be the most adjustable to the soil and climatic conditions of the Steppe zone, and defining the specific features and effective ways to use chemical and biological multifunctional re-regulating substances to increase the plants' stress resistance to climate changes and moisture deficit. This enables the land users to adjust the system of growing agricultural crops in the zone of moisture deficit and to manage high-risk farming in order to ensure the profitability of production.

CONCLUSIONS

By interpreting the Sentinel 2 satellite images and analyzing of seasonal changes in *NDVI* values, the spatiotemporal patterns of the sunflower hybrids vegetation and their adjustment to the soil and climatic conditions of Ukrainian Steppe zone were established. A series of maps of with the differentiation of *NDVI* values at every phenological stage was developed, which made it possible to study the development process of sunflower hybrid crops and to establish changes in the length of the phenological stages of plants according to the climatic conditions of the respective year: the dry, the average humid and the wet year. In the average humid (2019), favorable conditions for plant development were recorded in the first half of the growing season, while the second half of the growing season was characterized by a decrease in soil moisture and a shortening in the flowering stage of sunflower hybrids. It was proved that in the dry year (2020) there was a reduction in the length of the flowering stage of sunflower hybrids, a low level of the *NDVI* vegetation index was recorded in the phase of inflorescence formation (0.22-0.40) and the ripping stage (0.30-0.40). In the wet year (2021), a prolongation of the flowering stage and a high value of the vegetation index during all the phenological stages of plant development were recorded. It was established that each sunflower hybrid has individual genetic features of plant adjustment to the Steppe soil and climatic conditions, which determines the yield of the crop. A high level of adjustment was observed in: sunflower hybrid Oplot with an average annual yield of 2.01 to 3.04 t/ha and hybrid P64GE133 with a yield in the range of 1.96-3.02 t/ha. The hybrid DSL 403 had an average level of plasticity, its yield was 1.88-2.77 t/ha. A low level of plasticity was recorded in the 8X477KL hybrid with a yield of 1.71-2.82 t/ha and the Hector hybrid with a yield of 1.65-2.16 t/ha. The water consumption of sunflower hybrids for the formation of a yield unit (t/ha) was calculated for each year of the study: the dry year – 927 ± 80 m^3/ha, the average humid year – 1106 ± 163 m^3/ha, the wet year – 1540 ± 232 m^3/ha. A yield prediction function model was developed for each hybrid. Functions with a high level of approximation describe the spatiotemporal processes of yield vegetative formation for individual sunflower hybrids according to the level of moisture supply of the year. The function models were based on the raster models of the spatial distribution of *NDVI* values in the most active periods of intensive growth, flowering and seeding. For situational forecasting of the yield of sunflower hybrids, it is recommended to use a system of function models developed for different conditions of the crop's moisture supply and mineral nutrition. The proposed functions provide the 97.2-99.9% level of data approximation, which confirms the high accuracy of predicting the yield of sunflower hybrids. The research results are a relative for improving the methodology of vegetation research of agricultural crops, validating crop rotation, determining the effectiveness of agrotechnical measures, correct selection of varietal and hybrid composition, forecasting the yield of sunflower hybrids in the soil and climatic conditions of the Steppe zone.

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CONFLICT OF INTEREST

None.

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Просторово-часові закономірності та прогнозування вегетації гібридів соняшнику в ґрунтово-кліматичних умовах зони Степу України

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Анотація. Довгострокові дослідження обробітку ґрунту та управління сільськогосподарськими культурами є важливими для визначення практик виробництва сільськогосподарських культур, які сприяють забезпеченню сталої врожайності та прибутку. Зокрема, в умовах зміни клімату актуальним питанням залишається вибір, прогнозування та коригування систем вирощування сільськогосподарських культур в зоні дефіциту вологи та ведення ризикового землеробства. Тому метою дослідження було встановлення просторово-часових закономірностей вегетаційного розвитку гібридів соняшнику та прогнозування їх продуктивності в ґрунтово-кліматичних умовах зони Степу України. Проведено детальний аналіз сезонних змін значень нормалізованого диференційного вегетаційного індексу у посівах гібридів соняшнику за період 2019-2021 рр. із використанням космічних знімків супутникового апарату Sentinel 2, оброблених із застосуванням ліцензійного програмного продукту ArcGis 10.6. Доведено достовірність результатів дослідження стану посівів у різні фази вегетації рослин на основі *NDVI* та можливість їх використання для прогнозування врожайності сільськогосподарських культур. Визначено пластичність різних гібридів соняшнику до ґрунтово-кліматичних умов зони Степу, зокрема гібридів Оплот, Гектор, ДСЛ403, П64ГЕ133, 8Х477КЛ. Розроблено модель функції прогнозування врожайності для кожного гібрида соняшнику відповідно до рівня вологозабезпечення року. Достовірність моделей прогнозування склала 97,2-99,9 %. Рекомендовано використання системи моделей функцій, розроблених для різних умов вологозабезпечення та підживлення з метою ситуаційного прогнозування врожайності гібридів соняшнику. Отримані результати досліджень можуть бути використані для удосконалення методики дослідження вегетації сільськогосподарських культур, обґрунтування сівозміни, вибору кращих практик застосування багатофункціональних ріст регулюючих препаратів, вставлення кліматичної пластичності сортів та гібридів, управління ресурсами, розробки адаптивно-кліматичних технологій у землеробстві та рослинництві, розрахунку їх ефективності, прогнозування урожайності та забезпечення прибутковості агровиробництва у зоні дефіциту вологи та ведення ризикового землеробства

Ключові слова: рослинництво; клімат; дистанційне зондування; супутникові знімки; моделювання

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The problem of nitrogen in modern agriculture

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Abstract. Optimal nitrogen supply to plants, in conditions of sufficient moisture, allows for high crop productivity with high-quality indicators. The aim of this article was to summarize and analyze statistical data on the dynamics of nitrogen input and expenditure from arable land worldwide and in Ukraine, as well as provide practical recommendations for addressing the nitrogen issue in modern agriculture. The research utilized theoretical generalization, comparative analysis, graphical, abstract-logical methods and statistical data from FAOSTAT for the period of 2000-2020. The research results have shown that nitrogen input from mineral fertilizers has been constantly increasing both globally and in Ukraine. In contrast to global indicators, there has been a significant reduction in nitrogen input from manure in Ukraine, as well as a decrease in nitrogen input from atmospheric precipitation and through biological fixation by leguminous crops. The components of nitrogen balance, such as leaching, evaporation, and denitrification, play a significant role in nitrogen expenditure. These expenditure components tend to increase both globally and in Ukraine. The largest share in the expenditure component of all countries worldwide, including Ukraine, is occupied by nitrogen removal by cultivated crops. Calculations showed that the nitrogen balance on arable land, both globally and in most countries across different continents for the researched period, was positive. However, in Ukraine, it was negative for 18 out of 21 years. To solve this problem, practical recommendations are proposed using the best practices and developments of economically developed countries worldwide

Keywords: mineral fertilizers; organic fertilizers; biological fixation; nitrogen removal; leaching; evaporation; nitrogen balance

INTRODUCTION

Of all the elements of nutrition that are known to modern science, one of the most important is nitrogen. It, together with other nutrients, provides the highest yield gains on most types of soils known in world agriculture (Bavar *et al.*, 2016; Pandit *et al.*, 2022). In addition, it is a component of atmospheric air, which contains about 78% nitrogen.

The nitrogen cycle is the most complex, since this element of nutrition is quite mobile, it has the property of moving from one form to another, migrating and

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redistributing along the soil profile, being lost in the process of denitrification, binding to atmospheric nitrogen by legumes by symbiotic fixation, etc. (Moreau *et al.*, 2019; Wang *et al.*, 2021; Stepanov *et al.*, 2021).

In general, the development of agriculture and obtaining appropriate crop yield levels are determined precisely by the amount of nitrogen available to plants in the soil. In the Southern steppe of Ukraine, the first place in the formation of plant productivity among the totality of all factors is occupied by their moisture supply, and the second pone is the content of available (mobile) forms of nitrogen (Vozhegova *et al.*, 2021; Zayets *et al.*, 2022).

This element of nutrition prolongs the duration of vegetation, increases the accumulation of more aboveground biomass of plants, increases their habit and, accordingly, the area of the assimilation surface, and therefore contributes to the strengthening of photosynthetic activity, intensive formation of dry matter and yield growth in general (Andrews *et al.*, 2019; Wang *et al.*, 2020). In addition, the formation of an optimal amount of aboveground biomass obscures the field surface well and prevents excessive and unproductive evaporation of moisture (Naorem *et al.*, 2023).

The aim of this article was to summarize statistical data, review literature sources, conduct analytical research on the dynamics of nitrogen input and expenditure on arable land worldwide and in Ukraine, and formulate and justify practical recommendations for achieving a positive nitrogen balance in the modern conditions of the agricultural sector using the advanced experience of economically developed countries worldwide.

MATERIALS AND METHODS

In the process of scientific research to achieve this goal, the following general scientific methods were used: methods of theoretical generalization (abstraction and formalization), method of comparative analysis, graphical and abstract-logical methods. The method of theoretical generalization (abstraction and formalization) was used to formulate an approach to understanding the essence of the nitrogen problem in modern agriculture, taking into account its dynamics over a 20-year period in the regions of the world and Ukraine. The method of comparative analysis was used to compare factual data on the dynamics of nitrogen in the agricultural sector of the world, world regions, and Ukraine for individual years and overall, for a 20-year period. The results of the research were visually represented in the form of diagrams using the graphical method. The abstract-logical method was used in the process of forming theoretical generalizations and formulating conclusions.

The information base of the study was statistical data from FAOSTAT (2022). Time coverage is from 1961 to the most recent data available (2020). Monographic, periodic and reference publications, results of author's research and calculations also compose and supple the information base of the study. According to the formulated goal, the stages of the study were as follows: study of the theoretical foundations of the problem of nitrogen, analysis of statistical data, justification of practical recommendations.

At the first stage, the theoretical foundations of the nitrogen problem in modern agriculture were investigated, and its dynamics in terms of major income and expenditure items were determined. The theoretical foundations of the research reveal the importance of the problem and allow other researchers to understand it; provide tools for critical analysis and help the researcher distinguish what is relevant and what is not.

Subsequently, an analysis of statistical data on the dynamics of nitrogen in the modern conditions of the agricultural sector of the world regions and Ukraine was conducted. Analysis is a method of cognition that allows dividing research objects into component parts. Direct or empirical analysis was used (to identify characteristics and properties from global indicators, separate regional indicators for Ukraine); reverse or elementary-theoretical analysis (theoretical reasoning regarding the cause-effect relationship of the studied phenomena, identification of their regularities); structural-genetic analysis (identification of individual elements that had a decisive impact on the studied indicators).

In the final stage, the ways to create a positive nitrogen balance in the current conditions of economic activity were substantiated. The methodology used contributed to solving the problem and substantiating practical recommendations for solving the problem of nitrogen as the main element of nutrition for plants, using the best practices of leading countries of the world.

RESULTS AND DISCUSSION

It is known that the balance of any element of nutrition and its losses or growth under a particular crop or over a certain period is determined by the difference between its entry into the soil and costs (Ullah *et al.*, 2019; Putra *et al.*, 2020). The results of the conducted research demonstrate the state of the nitrogen balance in the world and in Ukraine.

According to FAOSTAT (2022), 107.4 million tons of nitrogen were added worldwide in 2020 year. Of the total amount, 59.9% of the total global application was applied in Asia, 4.1% was applied in Africa, 13.8% was applied in Europe and 1.2% was applied in Oceania. It should be noted that since 2000, when the use of nitrogen in the world amounted up to 76.9 million tons, the application of nitrogen fertilizers in the subsequent period was constantly increased, which can be clearly traced according to Table 1 data.

Nitrogen fertilizer applications in Ukraine also grew with a similar dependence: from 0.350 million tons in 2000 year up to 1.689 million tons in 2020 year (Fig. 1).

Table 1. *Dynamics of nitrogen applied mineral fertilizers on arable land*

Year	Regions of the world										World deposit of nitrogen, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	
2000	46.802	60.9	14.935	19.4	2.384	3.1	11.855	15.4	0.887	1.2	76.863
2001	46.970	60.5	15.063	19.4	2.482	3.2	12.128	15.6	0.968	1.2	77.611
2002	49.915	62.2	15.125	18.9	2.609	3.3	11.658	14.5	0.924	1.2	80.231
2003	50.365	61.4	16.420	20.0	2.527	3.1	11.851	14.4	0.885	1.1	82.049
2004	53.122	62.6	16.117	19.0	2.868	3.4	11.804	13.9	1.010	1.2	84.923
2005	54.621	63.9	15.627	18.3	2.744	3.2	11.558	13.5	0.912	1.1	85.462
2006	57.386	64.3	16.620	18.6	2.828	3.2	11.586	13.0	0.819	0.9	89.240
2007	58.168	63.6	17.415	19.0	2.632	2.9	12.494	13.7	0.813	0.9	91.521
2008	57.853	64.9	15.828	17,8	2.796	3.1	11.829	13.3	0.804	0.9	89.109
2009	62.042	66.3	16.258	17.4	2.843	3.0	11.657	12.5	0.818	0.9	93.619
2010	61.342	64.2	17.659	18.5	3.253	3.4	12.291	12.9	0.939	1.0	95.484
2011	63.623	63.8	19.358	19.4	3.101	3.1	12.545	12.6	1.042	1.0	99.670
2012	63.737	63.7	19.362	19.3	3.046	3.0	12.928	12.9	1.058	1.1	100.132
2013	64.934	63,4	19.756	19.3	3.366	3.3	13.133	12.8	1.202	1.2	102.390
2014	63.439	62.5	20.030	19.7	3.454	3.4	13.269	13.1	1.328	1.3	101.519
2015	64.162	63.3	18.976	18.7	3.395	3.3	13.551	13.4	1.263	1.2	101.346
2016	63.018	61.7	19.823	19.4	3.782	3.7	14.139	13.8	1.414	1.4	102.176
2017	61.609	60.3	20.441	20.0	4.358	4.3	14.391	14.1	1.440	1.4	102.239
2018	61.627	60.7	20.436	20.1	4.183	4.1	13.989	13.8	1.275	1.3	101.509
2019	62.808	60.7	20.904	20.2	4.106	4.0	14.356	13.9	1.278	1.2	103.452
2020	64.342	59.9	22.489	20.9	4.412	4.1	14.816	13.8	1.314	1.2	107.373

Source: *compiled by authors based on the data from FAOSTAT (2022)*

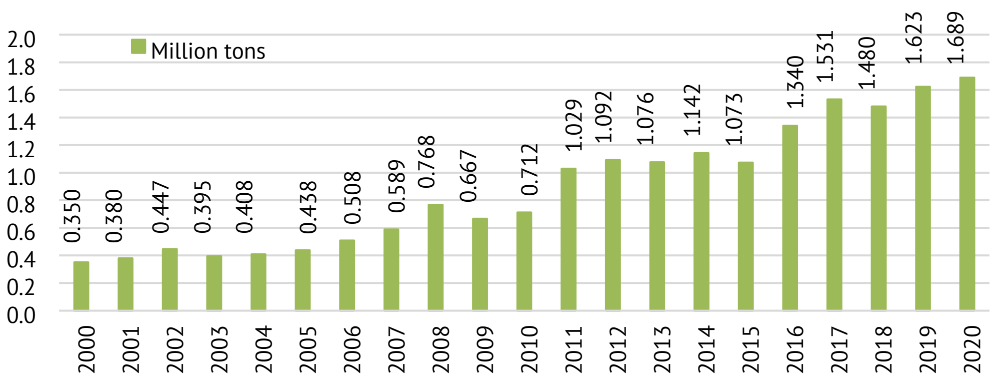

Figure 1. *Dynamics of nitrogen applied mineral fertilizers in Ukraine, million tons*

Source: *compiled by authors based on the data from FAOSTAT (2022)*

At the same time, it should be noted that the share of nitrogen introduced with mineral fertilizers in Ukraine to the total volume of nitrogen in the world in 2020 was 1.6%, and in European countries it was 11.4%. And a significant share of nitrogen introduced on arable land in the world was satisfied by embedding manure in the soil. According to FAOSTAT (2022), from 2000 year to 2020 year, the amount of nitrogen used with manure increased from 22.85 up to 26.20 million tons. The increase was due to Asian countries (from 9.66 to 12.54 million tons). In Europe, the volume of nitrogen application due to manure over a 20-year period, on the contrary, decreased from 7.19 down to 6.26 million tons, in Oceania they practically did not change (0.162 and 0.156 million tons, respectively, in 2000 year and 2020 year).

In Ukraine, the amount of nitrogen introduced with manure on arable land almost halved over the same 20-year period. So, if in 2000 its volumes were 520.9, then in 2020 year they were 264.9 thousand tons (Fig. 2). This negative state of manure use in Ukraine is explained by a significant decrease in the number of animals in the public sector. It should be noted that the application of manure to the fields served not only as a source of soil enrichment with nitrogen, but also with phosphorus, potassium, trace elements, and most importantly – enriched the soil with organic matter, and later (after its mineralization) with humus, improved the structure, water permeability, microbiological state, etc. Organic-fertilized soil preserves the main components of fertility elements, retains moisture well, it ensures optimal development of the root system of plants, its respiration, and so on. The maximum yield levels of all agricultural crops with high quality indicators are formed precisely by the organo-mineral fertilizer system in crop rotation. The effectiveness of manure application was monitored for several consecutive years (Action and aftereffect) until its final decomposition in the soil. Thus, the introduction of manure provided a fairly significant contribution to the overall nitrogen balance.

Atmospheric precipitation also accounts for a significant share in ensuring the nitrogen balance, that is, a certain amount of nitrogen gets to the fields with rain. Changes in this nitrogen supply to the soil over the past 20 years in the world are shown in Table 2.

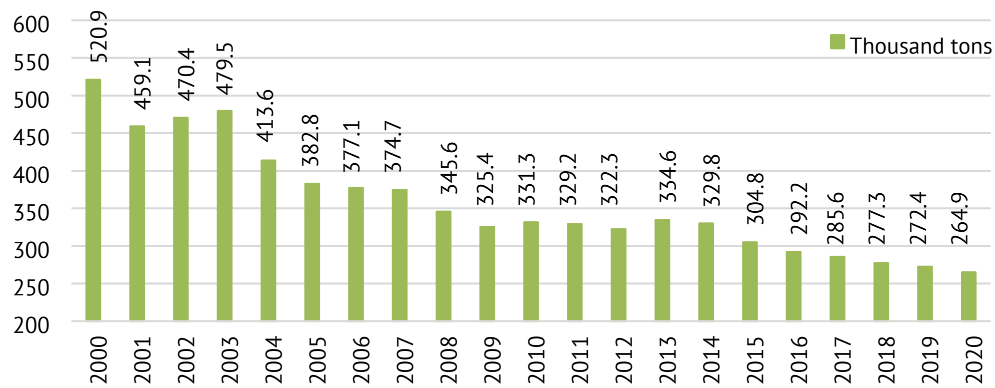

Figure 2. *Dynamics of nitrogen introduced with manure on arable land in Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Table 2. *Dynamics of nitrogen entering the soil with precipitation*

Year	Regions of the world										Global nitrogen supply, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	
2000	7.581	55.5	2.594	19.0	1.214	8.9	2.212	16.2	0.048	0.4	13.649
2001	7.563	55.7	2.525	18.6	1.250	9.2	2.191	16.1	0.048	0.4	13.577
2002	7.911	56.9	2.549	18.3	1.264	9.1	2.138	15.4	0.044	0.3	13.906
2003	8.002	57.5	2.487	17.9	1.348	9.7	2.039	14.6	0.052	0.4	13.928
2004	8.194	57.8	2.489	17.5	1.366	9.6	2.087	14.7	0.049	0.3	14.184
2005	8.481	57.9	2.534	17.3	1.475	10.1	2.101	14.4	0.049	0.3	14.640
2006	8.764	59.1	2.470	16.7	1.412	9.5	2.123	14.3	0.052	0.4	14.820

Table 2, Continued

Year	Regions of the world										Global nitrogen supply, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	
2007	8.788	59.2	2.517	17.0	1.470	9.9	2.024	13.6	0.046	0.3	14.845
2008	8.845	59.8	2.389	16.1	1.459	9.9	2.059	13.9	0.045	0.3	14.797
2009	9.235	61.2	2.338	15.5	1.474	9.8	1.988	13.2	0.055	0.4	15.090
2010	9.204	60.6	2.436	16.0	1.521	10.0	1.985	13.1	0.051	0.3	15.197
2011	9.287	61.2	2.378	15.7	1.539	10.1	1.900	12.5	0.066	0.4	15.169
2012	9.526	61.6	2.365	15.3	1.580	10.2	1.923	12.4	0.060	0.4	15.455
2013	9.544	61.7	2.338	15.1	1.595	10.3	1.919	12.4	0.061	0.4	15.456
2014	9.386	60.9	2.375	15.4	1.616	10.5	1.980	12.8	0.063	0.4	15.421
2015	9.414	60.9	2.370	15.3	1.626	10.5	1.981	12.8	0.061	0.4	15.452
2016	9.386	60.9	2.356	15.3	1.646	10.7	1.973	12.8	0.059	0.4	15.419
2017	9.401	60.7	2.383	15.4	1.663	10.7	1.983	12.8	0.061	0.4	15.491
2018	9.477	60.9	2.378	15.3	1.677	10.8	1.975	12.7	0.060	0.4	15.566
2019	9.475	60.9	2.375	15.3	1.677	10.8	1.979	12.7	0.060	0.4	15.566
2020	9.484	60.9	2.369	15.2	1.686	10.8	1.970	12.7	0.060	0.4	15.569

Source: *compiled by authors based on the data from FAOSTAT (2022)*

According to Table 2, the supply of nitrogen with precipitation in the world in 2000 was 13.65, and by 2020 it increased up to 15.57 million tons. Some growth in this nitrogen supply was mainly due to countries in Asia and Africa. In the countries of America and Europe, nitrogen intake with precipitation, on the contrary, slightly decreased during this period. As for Ukraine, the supply of nitrogen to the soil with snow or rain for the period from 2000 year to 2020 year practically did not change, although in dry years nitrogen was received somewhat less (Fig. 3). At the same time, the share of Ukraine in the total volume of nitrogen entering the soil with precipitation in 2020 year, according to FAOSTAT (2022) data, in Europe was 12.4%, and in the world volume, it was 1.6%.

In the positive part of the nitrogen balance, the main place belongs to the arrival of this element of nutrition due to biological fixation by legumes. Over a 20-year period, the amount of nitrogen entering the soil due to symbiotic fixation of air nitrogen by plant nodule bacteria increased significantly. So, if the global fixation of biological nitrogen in 2000 was 23.36 million tons, then in 2020 this figure increased up to 39.2 million tons (Table 3).

Figure 3. *Dynamics of nitrogen entering the soil with precipitation on arable land of Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

__Table 3.__ Dynamics of biological nitrogen fixation on arable land

Year	Asia		America		Africa		Europe		Oceania		World biological nitrogen fixation, mln tons
	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	
2000	9.673	41.4	11.364	48.6	1.531	6.6	0.567	2.4	0.225	1.0	23.359
2001	9.602	39.7	12.122	50.1	1.607	6.6	0.617	2.6	0.247	1.0	24.195
2002	9.439	38.5	12.596	51.4	1.690	6.9	0.621	2.5	0.159	0.6	24.505
2003	9.768	38.2	13.320	52.1	1.663	6.5	0.619	2.4	0.209	0.8	25.580
2004	9.960	36.9	14.458	53.6	1.688	6.3	0.692	2.6	0.175	0.6	26.973
2005	10.165	36.7	14.871	53.7	1.778	6.4	0.659	2.4	0.231	0.8	27.704
2006	9.946	35.8	15.215	54.8	1.825	6.6	0.667	2.4	0.131	0.5	27.784
2007	10.265	37.1	14.884	53.8	1.829	6.6	0.513	1.9	0.158	0.6	27.649
2008	10.439	36.1	15.831	54.8	1.939	6.7	0.529	1.8	0.158	0.5	28.896
2009	10.243	35.7	15.660	54.5	2.034	7.1	0.595	2.1	0.194	0.7	28.727
2010	10.759	34.1	17.552	55.6	2.282	7.2	0.732	2.3	0.228	0.7	31.554
2011	10.828	34.3	17.403	55.2	2.295	7.3	0.791	2.5	0.225	0.7	31.543
2012	10.630	34.3	16.881	54.5	2.511	8.1	0.769	2.5	0.199	0.6	30.990
2013	10.938	32.6	18.996	56.7	2.635	7.9	0.760	2.3	0.196	0.6	33.524
2014	10.698	30.4	20.596	58.5	2.729	7.8	0.962	2.7	0.196	0.6	35.181
2015	10.278	28.7	21.512	60.0	2.744	7.7	1.122	3.1	0.184	0.5	35.839
2016	10.709	28.9	21.953	59.3	2.856	7.7	1.213	3.3	0.266	0.7	36.997
2017	11.545	29.4	22.940	58.3	3.050	7.8	1.411	3.6	0.379	1.0	39.326
2018	11.514	29.9	22.262	57.7	3.173	8.2	1.327	3.4	0.276	0.7	38.552
2019	11.358	30.3	21.553	57.5	3.116	8.3	1.266	3.4	0.179	0.5	37.472
2020	11.875	30.3	22.743	58.0	3.161	8.1	1.244	3.2	0.172	0.4	39.196

Regions of the world (Asia, America, Africa, Europe, Oceania)

Source: *compiled by authors based on the data from FAOSTAT (2022)*

The largest share of nitrogen arrivals in the total world balance in the increase in this item was provided by the countries of America, Europe and Africa. To a lesser extent, this occurred in Asian countries, where, as a percentage of the global nitrogen fixation rate, this balance sheet item even decreased from 41.4% in 2000 down to 30.3% in 2020. Although in fact the increase in nitrogen was in Oceania countries, the dynamics of biological nitrogen fixation by legumes tended to decrease in both actual and percentage terms.

In Ukraine, since 2000, there was an increase in the amount of biologically fixed nitrogen by legumes (Fig. 4). Due to this, the nitrogen balance was met from 47.1 thousand tons in 2000 year and reached a maximum in 2017 year, when this figure in the state was 293.8 thousand tons. In subsequent years, the supply of nitrogen due to its biological fixation by legumes began to decrease and in 2020 amounted down to 191.6 thousand tons or compared to 2017 it decreased by 34.8%. The share of Ukraine in the total volume of fixed nitrogen in Europe in 2020 was 15.4%, and in the world, it was 0.49%. During 2012-2018 years, it was significantly larger and ranged from 20.8-24.8% relative to Europe and 0.68-0.75% of the world (FAOSTAT, 2022). This negative situation was again associated with a significant reduction in the number of animals in the public sector and a reduction in the area under perennial legumes, which were used to produce high-quality feed with a high protein content (hay, haylage, green mass, pellets, etc.). The trend of reducing the area under perennial grasses would continue in the coming years.

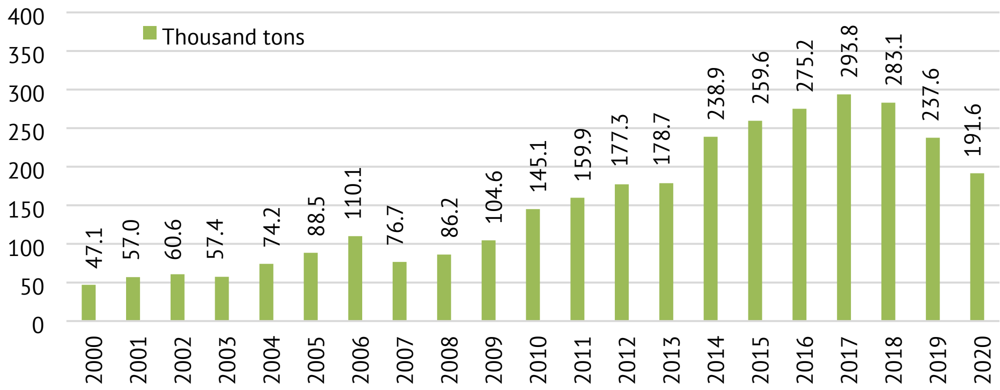

Figure 4. *Dynamics of biological nitrogen fixation on arable land in Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

So, the main indicators regarding the ways of nitrogen supply to the soil with various most important sources are given. Now it was necessary to indicate which were the components of losses of that extremely important element of nutrition that was known and widespread in nature. First of all, this was due to the process of leaching nitrogen from cultivated land. This was the process of washing nitrate nitrogen (NO_3) on irrigated, waterlogged soils or as a result of heavy rains, when the nitrogen of mineral fertilizers introduced into the upper layers of the soil was redistributed to much deeper horizons or to ground water, it became inaccessible to plants. At the same time, soil residues that were well enriched with organic matter and they had a high-water absorption capacity, on the contrary, they could contain significantly more water along with dissolved nitrate compounds. Nitrogen losses due to leaching over the analyzed 20-year period in the world as a whole were increasing. So, if this item of expenditure in 2000 accounted for 12.204, then in 2020 it was 16.038 million tons from the total area of arable land. In Asia, this figure increased from 53.9% up to 56.5%, in America it was from 20.3% up to 21.1%, in Africa it was from 3.4% up to 4.7%, in Oceania it did not change (1.0%), and in Europe, the number of actual leaching losses also remained virtually unchanged: 2.606 and 2.664 million tons, and as a percentage of total leaching in the world it decreased from 21.4% in 2000 down to 16.6% in the United States. 2020, respectively (FAOSTAT, 2022).

In Ukraine, this component of the balance sheet continued to grow (Fig. 5). Since 2000, in which leaching losses amounted to 139.2, by 2020 they increased up to 261.3 thousand tons, or almost doubled. At the same time, it should be noted that the area of large-scale irrigation of land during this period significantly decreased. Ukraine's share of total nitrogen losses from arable land in Europe due to leaching in 2020 was 9.8%, and world land it was 1.63% (FAOSTAT, 2022).

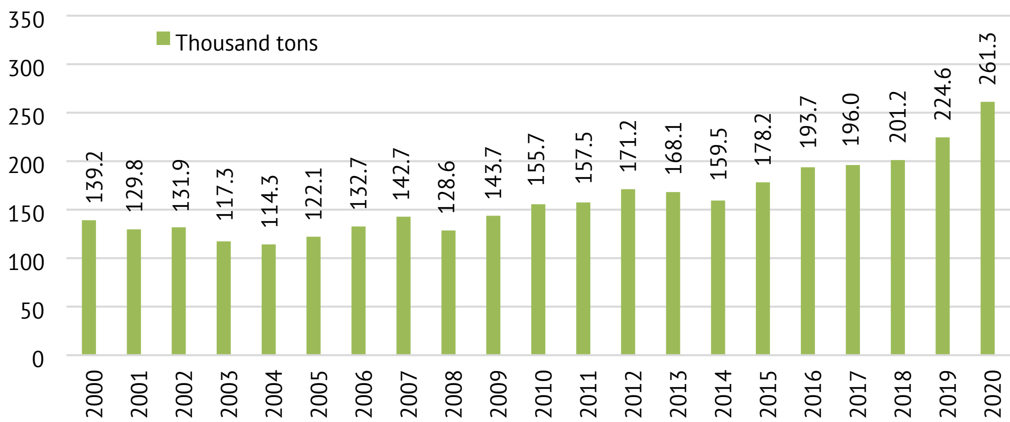

Figure 5. *Dynamics of nitrogen losses of arable land in Ukraine due to leaching, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Even greater were the nitrogen losses that occur during evaporation and denitrification of NO_3^-. This occurred during the conversion of nitrates by soil bacteria into gaseous oxides and molecular nitrogen. Nitrogen fertilizers were well soluble in water, their compounds were quite mobile, quickly redistribute along the soil profile in the presence of moisture and together with it evaporate from the field surface. Changes in nitrogen losses from arable land over a 20-year period were shown in Table 4. Its data show that during this period, nitrogen losses due to evaporation from arable land in the world increased significantly – from 29.758 in 2000 up to 40.253 million tons in 2020. The largest increase in this component of the nitrogen balance was typical for Asian and African countries. Much slower over the years, the rate of nitrogen loss to evaporation occurred in the countries of Oceania, Europe and America. In Ukraine, during the specified period of observations, nitrogen losses from arable land due to evaporation more than doubled (Fig. 6). It should be noted that in the total volume of nitrogen losses from arable land in Europe and the world due to evaporation in 2020, the share of Ukraine was 9.7 and 1.48%, respectively (FAOSTAT, 2022).

Table 4. *Dynamics of nitrogen losses of arable land due to evaporation*

Year	Regions of the world										World evaporation of arable land nitrogen, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	
2000	16.851	56.6	5.947	20.0	0.985	3.3	5.661	19.0	0.315	1.1	29.758
2001	16.940	56.5	6.027	20.1	0.997	3.3	5.677	18.9	0.340	1.1	29.981
2002	17.761	57.5	6.093	19.7	1.084	3.5	5.598	18.1	0.325	1.1	30.862
2003	18.109	57.3	6.462	20.4	1.063	3.4	5.658	17.9	0.314	1.0	31.605
2004	18.854	58.2	6.406	19.8	1.186	3.7	5.575	17.2	0.352	1.1	32.372
2005	19.410	59.4	6.326	19.4	1.162	3.6	5.434	16.6	0.323	1.0	32.655
2006	20.088	59.8	6.555	19.5	1.203	3.6	5.443	16.2	0.297	0.9	33.586
2007	20.527	59.3	6.941	20.0	1.142	3.3	5.730	16.5	0.295	0.9	34.635
2008	20.815	60.6	6.516	19.0	1.180	3.4	5.556	16.2	0.291	0.8	34.358
2009	21.792	61.9	6.522	18.5	1.207	3.4	5.362	15.2	0.295	0.8	35.179
2010	22.112	60.8	7.049	19.4	1.332	3.7	5.559	15.3	0.329	0.9	36.382
2011	22.429	60.0	7.678	20.5	1.305	3.5	5.592	15.0	0.363	1.0	37.366
2012	22.484	60.1	7.628	20.4	1.318	3.5	5.634	15.0	0.372	1.0	37.437
2013	22.715	59.8	7.696	20.3	1.380	3.6	5.763	15.2	0.399	1.1	37.954
2014	22.866	59.7	7.787	20.3	1.418	3.7	5.788	15.1	0.449	1.2	38.308
2015	22.928	60.3	7.362	19.4	1.436	3.8	5.864	15.4	0.422	1.1	38.012
2016	22.918	59.6	7.534	19.6	1.560	4.1	5.954	15.5	0.466	1.2	38.431
2017	23.056	58.9	7.798	19.9	1.744	4.5	6.089	15.5	0.475	1.2	39.162
2018	22.828	58.9	7.882	20.3	1.696	4.4	5.926	15.3	0.455	1.2	38.787
2019	22.665	58.5	7.953	20.5	1.716	4.4	5.982	15.4	0.434	1.1	38.750
2020	23.447	58.2	8.480	21.1	1.781	4.4	6.113	15.2	0.432	1.1	40.253

Source: *compiled by authors based on the data from FAOSTAT (2022)*

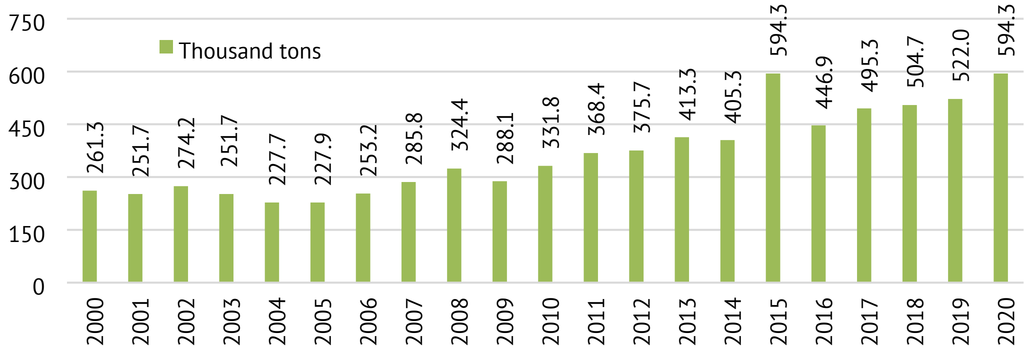

Figure 6. *Dynamics of nitrogen losses from arable land in Ukraine due to evaporation, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Most of all nitrogen from the soil and fertilizers was spent by agricultural crops on crop formation. The higher was the yield, the greater the amount of nitrogen removed. During the period from 2000 to 2020 years, nitrogen removal in all countries of the world increased: during the specified period, it increased from 64,433 up to 103,336 million tons (Table 5).

Table 5. *Dynamics of nitrogen removed from the soil by cultivated crops*

Year	Regions of the world										World nitrogen removal, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from world removal	mln tons	% from world removal	mln tons	% from world removal	mln tons	% from world removal	mln tons	% from world removal	
2000	28.811	44.0	21.615	33.0	4.126	6.3	9.650	14.7	1.232	1.9	65.433
2001	29.170	43.3	22.268	33.0	4.385	6.5	10.411	15.4	1.199	1.8	67.432
2002	29.133	43.3	21.834	32.5	4.479	6.7	10.573	15.7	1.234	1.8	67.253
2003	29.888	43.6	23.910	34.9	4.785	7.0	9.150	13.4	0.802	1.2	68.535
2004	30.994	41.8	25.630	34.5	4.896	6.6	11.375	15.3	1.301	1.8	74.195
2005	31.880	42.7	25.837	34.6	5.116	6.8	10.630	14.2	1.224	1.6	74.688
2006	32.835	43.4	25.885	34.2	5.360	7.1	10.254	13.6	1.265	1.7	75.599
2007	34.439	44.3	27.561	35.4	5.113	6.6	9.935	12.8	0.777	1.0	77.826
2008	34.931	42.4	28.918	35.1	5.424	6.6	12.257	14.9	0.929	1.1	82.460
2009	34.917	42.9	28.073	34.5	5.527	6.8	11.661	14.3	1.147	1.4	81.325
2010	36.173	43.0	30.541	36.3	5.859	7.0	10.398	12.4	1.151	1.4	84.122
2011	38.227	43.5	30.575	34.8	5.885	6.7	11.847	13.5	1.341	1.5	87.875
2012	38.742	44.8	29.390	33.9	6.217	7.2	10.750	12.4	1.471	1.7	86.569
2013	39.452	42.5	33.342	35.9	6.430	6.9	12.220	13.2	1.316	1.4	92.760
2014	39.426	41.3	34.836	36.5	6.637	6.9	13.295	13.9	1.364	1.4	95.559
2015	39.435	40.9	36.027	37.4	6.659	6.9	12.969	13.5	1.280	1.3	96.371
2016	40.013	40.5	37.503	38.0	6.682	6.8	13.221	13.4	1.271	1.3	98.690
2017	41.170	40.2	38.415	37.5	7.146	7.0	13.863	13.5	1.727	1.7	102.321
2018	41.702	41.3	37.315	37.0	7.417	7.4	13.096	13.0	1.330	1.3	100.861
2019	42.595	41.7	37.083	36.3	7.382	7.2	13.943	13.7	1.106	1.1	102.109
2020	43.099	41.7	38.428	37.2	7.467	7.2	13.373	12.9	0.970	0.9	103.336

Source: *compiled by authors based on the data from FAOSTAT (2022)*

Nitrogen removal with the crop of agricultural plants in Ukraine changed with an even greater trend (Fig. 7). So, if 657.6 thousand tons of nitrogen were used in 2000, then in 2019 they were 2044.9 thousand tons, or three times more. It should be noted that in 2019 year, this indicator was an item of negative balance-reached its maximum. Already in the next 2020 year, less nitrogen with the harvest was taken out as 1752.1 thousand tons. This had an exceptionally close relationship with the availability of years of growing crops with precipitation during the growing season, namely: the more favorable the year for climatic indicators, the higher the yield was formed, and therefore more plants used nitrogen for its formation. Such peaks and, conversely, insignificant nitrogen removals from the fields of Ukraine were clearly illustrated by Figure 7. In particular, 2000, 2003, 2007, 2010 and 2012 years were characterized by low harvest levels. The lower productivity of agricultural crops was formed in 2020 year, compared to 2019. Thus, the share of Ukraine in the total volume of nitrogen removed from the soil to European countries in 2019 was 14.7%, and in 2020 it was 13.1%, and in the world volume it was 2.0 and 1.7%, respectively.

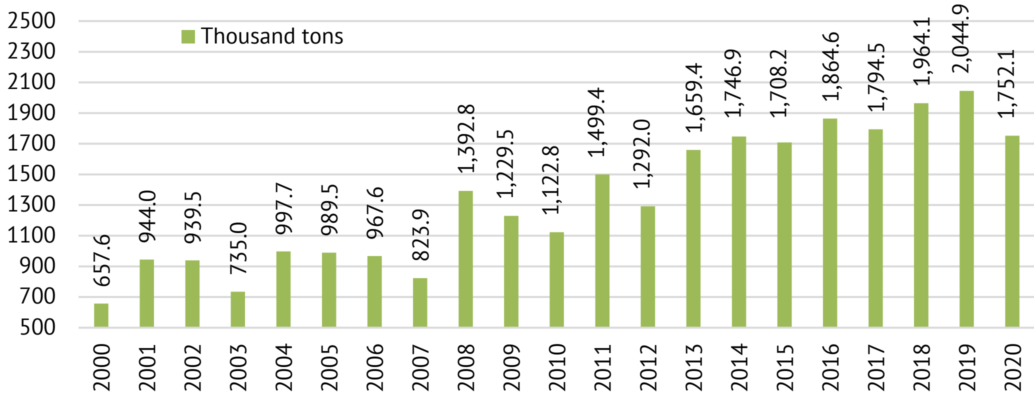

Figure 7. *Dynamics of nitrogen removed from the soil by cultivated crops in Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Based on the difference in incoming and outgoing parts relative to nitrogen, the overall balance of this battery was determined. Calculations showed that the nitrogen balance on arable land both in the world and in most countries of different continents for the period from 2000 to 2020 years was positive, which indicated that more nitrogen entered the soil compared to its total costs of plants for crop formation and other sources of costs (Table 6). The negative nitrogen balance for almost the entire period of definitions was only in Oceania (except for 2003, 2007 and 2020 years), whose share in the world balance was quite insignificant.

Table 6. *Nitrogen balance of arable land in the world by region (ratio of income and expenditure items), mln tons*

Year	World balance	Regions of the world				
		Asia	America	Africa	Europe	Oceania
2000	29.322	21.475	3.780	0.501	3.911	-0.346
2001	28.469	21.096	3.932	0.450	3.231	-0.240
2002	31.018	23.338	4.905	0.493	2.672	-0.391
2003	31.666	23.043	4.300	0.216	4.035	0.072
2004	29.639	24.289	3.553	0.355	1.830	-0.389
2005	30.703	24.878	3.510	0.268	2.365	-0.317
2006	32.834	26.045	4.491	0.069	2.735	-0.506
2007	31.583	25.065	2.843	0.316	3.357	0.001
2008	26.398	24.334	1.385	0.257	0.583	-0.161
2009	31.268	27.651	2.433	0.317	1.189	-0.323
2010	31.851	25.808	2.731	0.562	2.979	-0.229
2011	30.816	25.677	3.402	0.466	1.613	-0.341

Table 6, Continued

Year	World balance	Regions of the world				
		Asia	America	Africa	Europe	Oceania
2012	32.432	25.407	4.136	0.367	3.017	-0.496
2013	30.399	25.934	2.550	0.547	1.602	-0.235
2014	28.019	23.912	2.893	0.525	0.910	-0.221
2015	28.320	24.362	2.057	0.484	1.604	-0.188
2016	27.654	23.293	1.638	0.842	1.892	-0.012
2017	25.839	21.753	1.948	0.945	1.526	-0.333
2018	26.539	21.711	2.288	0.738	1.977	-0.175
2019	26.022	21.842	2.205	0.676	1.320	-0.020
2020	28.710	22.629	2.927	0.873	2.140	0.141

Source: *compiled by authors based on the data from FAOSTAT (2022)*

In Ukraine, during the analyzed period, out of the total number of years, only in extremely unfavorable precipitation in 2000, 2003 and 2007 years, the nitrogen balance was positive, and in 18 years out of 21 it was negative (Fig. 8). Moreover, significantly higher nitrogen consumption relative to its entry into the soil provided negative balance indicators in the most favorable years of crop cultivation for moisture, which was clearly illustrated by Figure 8.

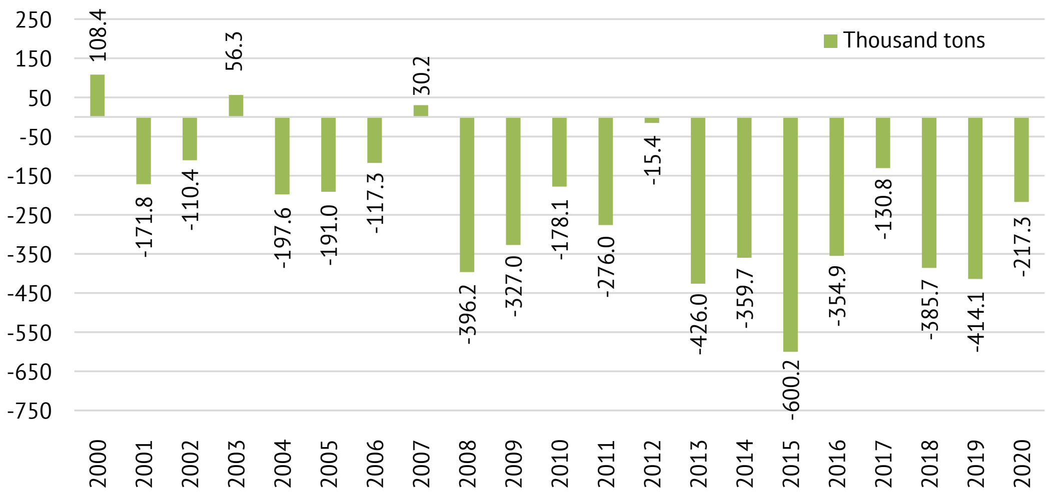

Figure 8. *Nitrogen balance of arable land in Ukraine (ratio of items of income and costs), thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

The most significant shortage of nitrogen nutrition on the cultivated soils of Ukraine was manifested in 2015 year and it amounted to 600.2 thousand tons. Such the lack of nitrogen in the soil caused by the already known, above-mentioned factors such as: a decrease in the volume of application of traditional organic fertilizer-semi-rotted manure, a violation of the reasonable alternation of crops in crop rotations, including excessive growth of areas under sunflower, which dried the soil and carried out a significant amount of nutrients, including nitrogen. At the same time, starting from the 90s of the 20th centuries, perennial grasses grown significantly less than necessary, which during three years of use were able to leave an average of 200 kg/ha or more of biologically fixed nitrogen after formation development, which was not washed out or lost from the soil and was free of charge. In many farms, even annual legumes or grass mixtures with them were not sown practically, which also provided replenishment of the soil with valuable crop-root residues and nitrogen (Gamajunova *et al.*, 2021). If this was not done, the soil would continue to lose the main signs of fertility, because for the formation of the crop, plants would use nutrients directly from humus and thus they impoverished and depleted the soil.

Previously, in Ukraine (1987-1990 years), about 150 kg of mineral fertilizers were applied for each hectare of arable area (in the amount of NRK), and on irrigated land – 325 kg/ha. In the composition of mineral fertilizers, the proportion of nitrogen fertilizers was significantly higher, which most increased the yield and affected its quality.

The same trend remains in the future. According to Pro-Consulting, in the structure of fertilizer use in agricultural enterprises of Ukraine, 68% of the total amount accounted for nitrogen. The share of potash was 3.7%, phosphorous one was 0.3%, and the complex one was 28%. The total amount of fertilizer application in 2018 it decreased from 4.4 to 2.3 million tons, but the share of nitrogen increased to 65% (Gamayunova *et al.*, 2020).

According to FAO, the actual level of mineral fertilizers applied in countries around the world varies significantly. Most of them were used in the Netherlands as 258 kg/ha, in Great Britain as 247, in Israel as 240, in Germany as 202 kg/ha. Slightly fewer mineral fertilizers are applied in Belarus as 194, in Poland as 176, in France as 169, in the Czech Republic as 157, in the USA as 137 kg/ha of active substance (Prokhopchuk, 2018).

The amount of nitrogen entered the soil with mineral fertilizers in the countries of the world for the years 2000-2020 was shown in Table 7. At the same time, it was quite positive that since 2000, when only 10.45 kg of nitrogen was applied to the cultivated hectare of soil in Ukraine, which was significantly less compared to the volume of application in the world, by 2020 this figure increased almost fivefold and it amounted to 50.02 kg/ha.

Table 7. *Dynamics of nitrogen entering the soil with mineral fertilizers, kg/ha of arable land*

Year	Regions of the world					World supply	Ukraine
	Asia	America	Africa	Europe	Oceania		
2000	83.30	40.35	10.37	39.02	33.19	51.50	10.45
2001	83.25	40.56	10.82	40.39	35.22	51.99	11.36
2002	88.34	40.94	11.23	39.13	35.56	53.82	13.35
2003	88.68	44.38	10.54	40.08	34.79	54.74	11.83
2004	93.00	43.52	11.92	40.03	36.14	56.43	12.21
2005	95.58	42.14	11.20	39.31	31.84	56.59	13.15
2006	100.44	44.81	11.46	39.64	30.99	59.19	15.25
2007	101.50	46.96	10.52	42.99	31.96	60.61	17.67
2008	101.11	43.01	11.03	40.60	30.41	58.96	23.01
2009	107.87	44.46	11.18	40.05	27.64	61.76	20.00
2010	106.53	48.07	12.53	42.38	33.40	62.78	21.34
2011	110.14	52.77	11.74	43.31	30.48	65.04	30.81
2012	110.01	52.80	11.23	44.54	31.00	64.95	32.69
2013	111.73	53.72	12.28	45.34	35.54	66.21	31.95
2014	108.97	54.56	12.57	45.83	38.43	65.58	33.94
2015	109.73	51.68	12.32	46.87	37.65	65.38	31.87
2016	107.15	54.20	13.60	48.99	43.42	65.79	39.79
2017	104.33	55.26	15.56	49.84	43.36	65.44	45.48
2018	104.27	55.42	14.91	48.53	38.09	64.98	43.84
2019	106.38	56.80	14.65	49.69	38.59	66.29	48.05
2020	108.82	61.24	15.66	51.44	39.61	68.76	50.02

Source: *compiled by authors based on the data from FAOSTAT (2022)*

If there is a lack of nitrogen for plant nutrition, in addition to a shortage of crops, the grown products would be formed with a low protein content. This is especially true for grain crops, as it is nitrogen which provides an increase in valuable protein fractions in grain (Hawkesford & Griffiths, 2019; Guerrini *et al.*, 2020). For this reason, at the beginning of the earing phase, foliar top dressing of winter cereals with urea is carried out at the rate of N_{30}. This measure makes it possible to increase the grain content to 6% gluten and, accordingly, to 2% or more protein in the optimal state of plants (Sydiakina & Gamayunova, 2020). In addition, such top dressing is combined with simultaneous protection of grain crops from the bug of the harmful turtle, which also provides an increase in the protein content in the grain (Tomchuk, 2020).

At the same time, high nitrogen rates lead to a decrease in the fat content in oilseeds due to the formation of greater protein content (Sydiakina & Pavlenko, 2021). The use of high standards of mineral nitrogen for vegetable crops can lead to a significant increase in nitrates in fruits. This occurs most intensively when the ratio of nitrogen with phosphorus and potassium is unbalanced and there is a lack of trace elements (Padilla *et al.*, 2020; Tei *et al.*, 2020).

Many researchers determined that the yield levels of agricultural crops and the quality of grown products was formed optimal with the combined application of organic and mineral fertilizers. In this case, even increased rates of nitrogen fertilizers will not negatively affect the main indicators of crop quality, as a certain part of nitrogen is partially fixed by soil microorganisms that decompose fresh organic matter. The nitrogen used by them will be fixed by the microbiota for a certain period of time and it will not be able to be "harmful". On the contrary, it acquires the properties of biological nitrogen: it is not lost from the soil and becomes available to plants after the death and decomposition of microorganisms (Lopusniak, 2011; Kerru *et al.*, 2020). This is an important sign of the activity of microorganisms in ensuring a favorable nitrogen regime of the soil and the full use of its compounds by plants without loss.

In modern agriculture, with a significant reduction in the volume of manure use, post-harvest and root residues are used as organic fertilizers after harvesting agricultural crops. To accelerate their decomposition, small rates of nitrogen fertilizers and stubble biodestructors, which include microorganisms, are used simultaneously with their sealing. It also has a positive effect on some increase in the content of nitrogen and other nutrients in the soil. In addition, most importantly, the soil is enriched with organic matter, its structure, water absorption capacity, etc. improves (Kovalenko, 2022; Panfilova & Byelov, 2022; Sydiakina, 2021). In soils with a sufficient content of organic matter, the introduced mineral nitrogen will be converted much faster from one form to another, unproductive losses of this element will significantly decrease due to temporary fixation by microorganisms (Yu *et al.*, 2020; Voltr *et al.*, 2021).

A significantly larger proportion of nitrogen in the nitrogen balance earlier, due to the conduct of scientifically based crop rotations (8-10-saw crops with alfalfa selection), is provided by systematic application of semi-rotted manure under row crops in the recommended standards, as well as by growing perennial grasses (D'Amours *et al.*, 2021; Oruj *et al.*, 2021). Now, due to the violation of the alternation of agricultural crops, the introduction of short-rotation crop rotations, insufficient saturation of their legumes, a significant reduction in the use of manure due to a reduction in the number of animals, the application of organic fertilizers is stopped practically. During this period, the saturation of soils with organic substances occurs only due to the embedding in the soil of post-harvest-root residues of cultivated crops, as well as straw of grain spikelet crops (Assefa & Tadesse, 2019; Kavun & Loboda, 2020; Gamajunova *et al.*, 2021).

So, it is necessary to incorporate all residues after crop harvesting into the soil with simultaneous addition of mineral nitrogen and stover biodegraders. Crop rotation should always include legume components, regardless of the number of fields. Nitrogen fertilizers should be applied in recommended norms for the zone, taking into account the predecessor and nitrogen content in the specific field's soil. This will ensure consistent yields with high quality indicators and maintain the nitrogen balance of soils in an optimal state.

CONCLUSIONS

The nitrogen balance in the soils of most countries of the world for the period from 2000 up to 2020 years is positive, that is, more of this element of nutrition enters the cultivated soils than it is lost and taken out by plants for crop formation. In Ukraine the nitrogen balance in soils is negative. This condition is explained by a number of reasons, which are as follows:

- non-compliance with scientifically based crop alternation in crop rotations;
- significant reduction of the area under perennial grasses and annual legumes;
- reducing the use of manure and mineral fertilizers per hectare of cultivated soil;
- limited use of the organo-mineral fertilizer system for cultivated crops in production conditions, despite the fact that many studies prove that the main indicators of soil fertility are preserved with the combined use of organo-mineral fertilizers in the recommended standards and with scientifically based alternation of agricultural crops in crop rotation.

The agricultural sector in Ukraine should be based on the use of scientifically based selection of agricultural crops in crop rotations (including legumes). This is the simplest and cheapest measure that allows you to maintain (even improve) soil fertility, enrich it with the optimal number of organic substances and free biological nitrogen. Due to crop rotation, the cost of growing crops is reduced by 15-20% (for fertilizers, plant protection products against weeds, pests and diseases). In addition to enriching the soil with nitrogen, legumes contribute to the dissolution of fixed phosphates in the soil, which also plays an important role in the nutrition system of agricultural plants.

Nitrogen nutrition plays an extremely important role in crop yield and quality formation, which requires maintaining its positive balance. To achieve this, it is necessary to systematically monitor the presence of this nutrient in the soil and follow recommendations for maintaining its positive balance, avoiding significant losses.

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CONFLICT OF INTEREST

None.

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Проблема азоту в сучасному сільському господарстві

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Анотація. Оптимальне азотне живлення рослин в умовах достатнього зволоження дозволяє отримати високу продуктивність сільськогосподарських культур з якісними показниками. Метою даної статті було узагальнення та аналіз статистичних даних щодо динаміки надходження та витрат азоту з ріллі у світі та в Україні, а також надання практичних рекомендацій щодо вирішення азотного питання в сучасному сільському господарстві. У дослідженні використано методи теоретичного узагальнення, порівняльного аналізу, графічний, абстрактно-логічний методи та статистичні дані FAOSTAT за період 2000-2020 рр. Результати дослідження показали, що надходження азоту з мінеральними добривами постійно зростає як у світі, так і в Україні. На відміну від світових показників, в Україні спостерігається значне скорочення надходження азоту з гноєм, а також зменшення надходження азоту з атмосферними опадами та за рахунок біологічної фіксації бобовими культурами. Такі компоненти азотного балансу як вилуговування, випаровування та денітрифікація, відіграють значну роль у витратах азоту. Ці компоненти витрат мають тенденцію до зростання як у світі, так і в Україні. Найбільшу частку у структурі витрат усіх країн світу, включаючи Україну, займає винос азоту сільськогосподарськими культурами. Розрахунки показали, що баланс азоту на орних землях як у світі, так і в більшості країн на різних континентах за досліджуваний період, складався позитивно. Проте в Україні він був від'ємним упродовж 18 з 21 року. Для вирішення цієї проблеми запропоновано практичні рекомендації з використанням кращих практик і напрацювань економічно розвинених країн світу

Ключові слова: мінеральні добрива; органічні добрива; біологічна фіксація; видалення азоту; вилуговування; випаровування; баланс азоту

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Prospects for the formation of investment support for the technological growth of the agricultural sector of the Ukrainian economy in the post-war period

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Abstract. During the war and after its end, Ukraine needs to restore its economy, in particular the agri-food sector, which is one of the key sectors of the national economy. Investment support for the technological growth of the agro-food sector can be of decisive importance for this, because it allows to achieve high productivity, competitiveness and sustainable development of this industry, which in turn will contribute to ensuring the food security of the country, raising the standard of living of the population and reducing the outflow of labor force abroad. The purpose of the article was to analyze and determine promising ways of attracting investments to support the technological development of the agro-food sector in post-war Ukraine. Using the analysis of literary sources and statistical data, the state of the agricultural sector of Ukraine in the pre-war and post-war periods is considered and analyzed. The structure and investment attractiveness of Ukrainian enterprises are investigated. The state of business subjects in the field of agriculture was analyzed and with the help of expert assessments, it was established that small entrepreneurship is the driving force of the development of the economy and economic relations, although it is risky for investment. Using statistical analysis, the structure of foreign investment is investigated and it is established that the main problem of attracting foreign investment is outdated equipment and technologies, so it is necessary to integrate innovations into agriculture. So, after analyzing the strengths and weaknesses, opportunities and threats, it was established that appropriate financing can help implement modern resource-saving technologies in agro-food production, promote the implementation of innovative approaches, namely the introduction of modern methods of soil treatment, the

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use of rational water use, the introduction of automation and mechanization of production processes, the use of drones and modern monitoring systems, as well as the introduction of modern methods of storage, processing and sales of products, which will ensure increased production efficiency, reduced environmental consequences and increased competitiveness of Ukrainian agricultural enterprises on the international market. The practical value of the research lies in the ability to provide recommendations on creating a favorable investment climate, improving legislation, ensuring the protection of investors' rights, as well as infrastructure development and support for research projects in the field of agro-food production

Keywords: resource-saving technologies; progressive development; small business; innovations; agriculture

INTRODUCTION

The agricultural sector is one of the most important elements of the economy of market economies, and its importance cannot be overestimated, as it forms the basis of the national economy and food security. The Ukraine Recovery Plan for 2022-2032 (n.d.), adopted at the Lugano conference in July 2022, identifies the agricultural sector of the national economy as a priority. Its further effective development is primarily associated with the restoration and reclamation of lands damaged as a result of military actions, the establishment of processing of produced agricultural products, the increase in the volume of value-added products and the increase in export batches of such products (Chumachenko *et al.*, 2022). According to preliminary estimates by experts, the restoration and restart of agricultural production requires 10-year investments in the amount of 37 billion dollars USA, as stated in the analytical report Kyiv Strategy Consulting (2022). According to the Minister of Environmental Protection and Natural Resources (2023), during the year of the full-scale war, experts of the State Environmental Inspection have already documented more than 2,300 crimes against nature. The amount of losses reaches almost 1.9 trillion hryvnias. Although in the pre-war period, Ukraine demonstrated rapid improvement in environmental indicators. Thus, according to the results of the evaluation of the comprehensive Index of Environmental Indicators, which shows how close the country is to achieving the goals of environmental policy, Ukraine took 60th place in 2020, and already in 2021 it took 52nd place (EPI Results, 2022).

Despite weather risks, war, logistics complications, and the energy crisis, agriculture remains the main sector of the Ukrainian economy, so there is a need to ensure its functioning and adaptation to difficult conditions. Agriculture has always been the backbone of the country in times of crisis, which shows the largest harvest in 2021 in the history of the country, compared to other sectors of the economy, which, on the contrary, reduced their pace (Ministry of Agrarian Policy and Food of Ukraine, 2022). Therefore, the solution to the problems in ensuring the development of the country's economy should be comprehensive and affect the political, economic, environmental, social and especially scientific and technological spheres. During the period of military operations, which is characterized, in particular, by a high degree of riskiness of investment activity, analysts note that the predominant investment is in strengthening working capital and preserving existing production capacities. Experts predict a slowdown in the pace of implementation of advanced technologies, justifying this both by a reduction in the amount of funds allocated for innovation, and by logistical and infrastructural problems related to the provision of agricultural production with the latest machinery, equipment, seeds, fertilizers, etc. At the same time, in those farms where innovative solutions have already been implemented, an important task is to continue them. It is believed that the increased investment risks of the agricultural business will be compensated to some extent by further growth in global food prices (Taran *et al.*, 2020). Ensuring economic development and the growth of agricultural production in difficult, modern conditions is impossible without adequate financial support, in which investments and innovations have a leading place. Investments largely determine the growth rate of production and are a powerful incentive for scientific and technological development. Investments aimed at the development of agricultural production are particularly important, since the development of all other sectors of the economy, the acceleration of reproduction processes and the improvement of its efficiency directly depend on it. It is obvious that the recovery of the agricultural sector of the Ukrainian economy is impossible without an increase in innovation and investment activity in the agricultural sector, prospects for technical re-equipment, modernization of production, etc. Solving the problem of increasing economic efficiency in agricultural enterprises of various sizes requires the introduction of technological innovations, the basis of which is the selection and application of resource-saving technologies depending on the optimal technological level (the optimality of the technology is determined by the requirements for the innovativeness of agricultural technology and the saving of material and other resources) (Taran *et al.*, 2020; Bashtannyk *et al.*, 2020). However, this requires additional financing for agricultural production, including credits from international organizations and partner countries.

The research was aimed at identifying problems and opportunities of the agro-food sector, assessing risks and obstacles, as well as developing recommendations for government bodies, investors and business structures regarding the direction of investments in the development of new technologies, infrastructure modernization, and product quality improvement.

MATERIALS AND METHODS

This scientific article is a theoretical research in the process of writing which general scientific research methods were used. The method of theoretical generalization was used to consider theoretical provisions on the essence of investment support for technological growth of the agro-food sector of the Ukrainian economy in the postwar period. Using the analysis of literary sources and statistical data, the state of the agricultural sector of Ukraine in the pre-war and post-war periods is considered and analyzed. The structure and investment attractiveness of Ukrainian enterprises are studied. The state of economic entities in the field of agriculture was analyzed with the help of expert assessments and, using statistical analysis, the structure of foreign investment was studied.

The main stages of work on the scientific article were as follows: the preparatory step, which covered the chosen topic, its understanding and justification of its relevance. The topic of the article was chosen taking into account the interest in the problem and the possibility of choosing analytical material and statistical data. The stages of the work included drawing up a plan and structure of the scientific article, conducting the research and summarizing its results. Based on the review of information sources and literature, the tasks set by the authors, the state of the problem under study was determined. The final stage involved processing and analyzing the results of the research conducted in accordance with the assignment, as well as formulating conclusions and compiling a list of references. The correctness of the article and the list of references was checked in accordance with the publisher's requirements.

RESULTS AND DISCUSSION

As of the beginning of 2022, the economic system of Ukraine could be characterized as a multi-sector, socially-oriented market economy, aimed at taking into account public needs, based on an innovation-investment model and the wide dissemination and implementation of the latest scientific and technical achievements.

The full-scale military invasion has become a new and determining factor in the formation of the investment climate in Ukraine, which, together with corruption and a weak judicial system, constitutes the top three negative factors. At the same time, there are opportunities for the business environment in granting Ukraine the status of a candidate for accession to the European Union, removing export restrictions, and a "transport visa-free regime" with the EU. After all, Ukraine is quite rightly called the breadbasket of Europe (Russia's war..., 2022), the country is the leader in the export of sunflower oil and grain, and thanks to this it receives quite a large amount of revenue, which allows the state to invest, although the percentage of funding from the budget should be higher, nevertheless, this is possible thanks to commodity producers and natural conditions (Fig. 1).

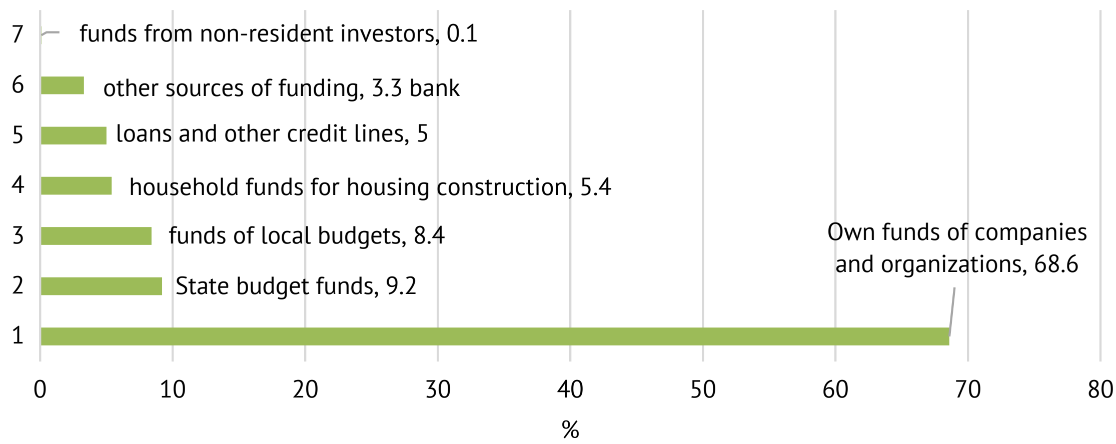

Figure 1. *Structure of capital investments by sources of financing in January-December 2021*
Source: *developed by the authors on the basis of State Statistics Service of Ukraine (2021)*

Thus, as shown in the Figure 1, the largest percentage, namely 68.6%, was directed to capital investments from the own funds of enterprises and organizations, which is 2.1% more than in 2020. Bank loans and other borrowings, although they tended to increase, still did not reach 10%. However, the weight of non-resident investors decreased by 0.3% compared to 2020, indicating the low investment attractiveness of Ukrainian enterprises. In general, a slight improvement in the investment climate is related to rising prices for agricultural products.

Capital investments in the agricultural sector of the national economy in 2021 were estimated at USD 2.3 billion. According to analysts' forecasts, in 2022, the sector was expected to show even higher results (Zakharchuk, 2022b). However, the military actions on the territory of Ukraine leveled this forecast.

According to research conducted by the European Business Association, the integral indicator of the Investment Attractiveness Index of Ukraine in the first half of 2022 was 2.17 points out of 5, which corresponds to the indicators of 2012-2013. For comparison, at the beginning of 2022, the indicator was 2.73 points, and during the "The Revolution of Dignity" – 1.8 points, with a rapid increase soon after, which is promising for similar dynamics in the post-war period (Kotsky, 2022).

Military operations are a significant obstacle to the realization of financial investments in the Ukrainian economy. However, already in 2022, a pilot project funded by the Multilateral Investment Guarantee Agency (MIGA), a member of the World Bank Group, was launched as part of the war risk insurance initiative, under which Ukraine received USD 30 million. In general, the country's investment potential is estimated at USD 43 billion, including USD 34 billion in the investment potential of the agricultural sector (Advantage Ukraine, n.d.).

Global experience and business practice indicate that the most important feature of a market economy is the presence and effective interaction of large, medium and small enterprises, as well as their optimal ratio (Table 1).

Table 1. *Number of large, medium, small and micro enterprises*

Year	Total, thousand units					Agriculture, forestry and fisheries				
	units	percent				units	percent			
		large	medium	small			large	medium	small	
					incl. micro enterprises					incl. micro enterprises
2010	378.88	0.2	5.5	94.3	79.3	50666	0.0	6.8	93.2	84.8
2015	343.44	0.1	4.4	95.5	82.8	46744	0.1	5.4	94.5	83.9
2017	338.25	0.1	4.4	95.5	82.2	50115	0.0	4.8	95.2	84.8
2018	355.87	0.1	4.5	95.4	82.3	50504	0.0	4.6	95.4	85.0
2019	380.59	0.1	4.7	95.2	82.3	50239	0.1	4.5	95.4	84.9
2020	373.81	0.1	4.7	95.2	82.4	49492	0.1	4.3	95.6	85.0
2021	370.83	0.2	4.7	95.1	82.2	47753	0.1	4.4	95.5	84.2
In % to 2010	97.8	100	85.5	101	103.6	94.2	-	64.7	102.5	99.3

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

The data in Table 1 show that the proportion of small enterprises is overwhelming and tends to grow, including agricultural enterprises. It has also been established and repeatedly proved (Pilevych, 2021; Babyna & Babyn, 2021) that small business is a driving force behind the development of the economy and economic relations. This is also evidenced by the increase in the volume of products sold from 2015 to 2021 by UAH 1639258.6 million, which in turn accounts for 18.9% of the total volume of sales of products (goods, services) by all enterprises in the country. But the fact that only profit and depreciation deductions are the main internal source of investment for small and medium-sized enterprises is, of course, insufficient for capital reproduction. And attracting external sources of investment is risky due to high credit rates, so government support is very important. The experience of European countries in attracting investments in high-tech agriculture is also important (Vasilevska *et al.*, 2019; Kiropoulos *et al.*, 2021).

Although Ukraine has created regulatory and legal regulation of small and medium-sized businesses, it is insufficient for successful innovative functioning, especially in the investment part, since funds are not distributed in favor of agricultural small and medium-sized enterprises, which introduces a certain economic imbalance of organizational and legal forms.

According to statistics, in 2020, the amount of support for the agro-industrial complex amounted to UAH 3.97 billion, and in 2022 – UAH 4.6 billion (Neuter *et al.*, 2022). That is, since 2020, state support has become more substantial and targeted, and other programs such as compensation for lost crops due to an emergency and others began to appear in 2021, but all this does not allow us to say that it is stable in terms of volume and structure, and the corruption factor is still in action. Thus, the reasons for the low investment attractiveness of the agricultural sector and credit risks are not only the size of enterprises and seasonal characteristics of the industry, but also the further worsening of the financial situation caused by the war in the country, the absence of liquid loans from debtors, and the disparity between the needs of agricultural enterprises for credit resources and the needs and opportunities of banks and investors (Pisarenko *et al.*, 2021).

There are also certain problems with foreign investment, primarily low returns on investment and their inefficient distribution by type of economic activity (Fig. 2).

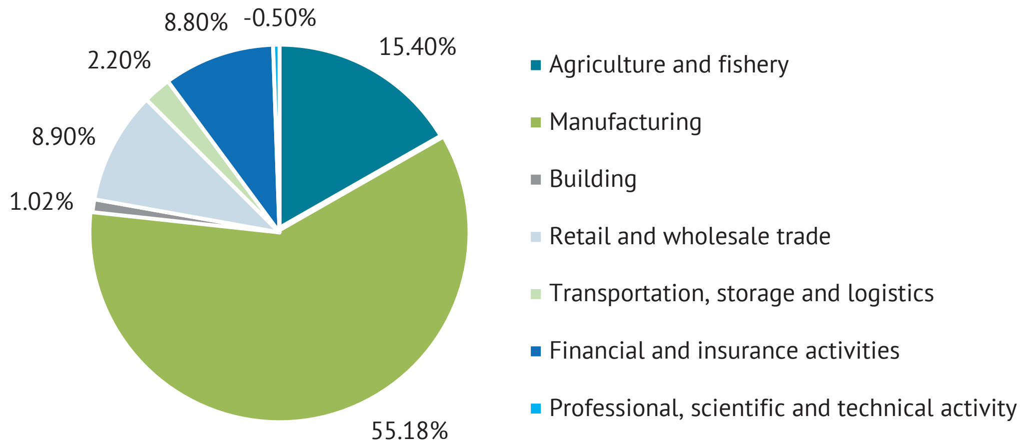

Figure 2. *Structure of foreign direct investment in Ukraine by type of economic activity in 2021*
Source: *developed by the authors based on State Statistics Service of Ukraine (2020)*

Thus, as can be seen from the Figure 2, the largest proportion in the structure of foreign investment in Ukraine is taken by industry (55.18%), the second place is occupied by agriculture (15.40%), and the third place is divided between financial and insurance activities and wholesale and retail trade (8.8% and 8.9%, respectively). It is worth noting that foreign investments is directed only to developed sectors.

And as mentioned above, one of the problems of attracting foreign investments is outdated equipment and technologies, therefore it is necessary to introduce innovations in agriculture. After all, technological renewal and development of the agro-industrial complex is a strategically priority direction of innovative activity of the state, and in 2020, the largest number of technologies was transferred in this direction, namely 55.6%, respectively, and the largest share of revenues was received – 77.2% (Pisarenko *et al.*, 2021). The foundation of innovative competitiveness is human capital, higher education, as well as knowledge and results of scientific research (Burkynskyi *et al.*, 2022; Lee & Keunhwan, 2022). Currently, there are many definitions of innovation, but the concept of agricultural innovation has not been sufficiently investigated. The authors share the interpretation of the Food and Agriculture Organization of the United Nations (FAO) on agricultural innovations (FAO, 2018) as a process in which individuals or organizations use new or existing products, processes or methods of organization for the first time in a particular context to improve efficiency, competitiveness, resilience to stress or environmental sustainability and thus contribute to food security and nutrition, economic development or sustainable management of natural resources.

The need to implement resource-saving innovations based on the rational use of resources in the activities of agricultural enterprises is objectively determined by the constant growth of prices for oil and gas, fertilizers, plant protection products, and seed. Ensuring the optimal level of costs for commodity and material resources included in the cost of production, while maximizing the growth of crop yields, allows to increase the profitability per 1 hectare of crop production. The use of such precision agriculture, which involves the optimal management of available land resources, opens up real opportunities for agricultural producers to grow quality products and preserve the environment (Koutsos & Menexes, 2019; Poertner *et al.*, 2022).

However, the effective implementation of innovative precision agriculture technologies and the solution of socio-economic tasks is impossible with the use of traditional mechanical equipment. Every year, the number of progressive agricultural market participants who recognize the need to actively involve the latest scientific and technological solutions in their production processes is growing. According to analytical data (The market…, 2022), the global precision agriculture market is poised to register a compound annual growth rate (CAGR) of 13% over the next ten years and reach USD 20.36 billion in 2032. Such forecasts are due to the increased demand for precision agricultural equipment caused by the lack of resources together with unpredictable weather conditions.

According to statistics, 70% of German farmers and more than 80% of US farmers use various elements of precision agriculture in their production process. In Europe, their use is noted even on areas of 0.5 hectares due to their high efficiency, which is due to a significant reduction in time and labor costs, which in turn reduces the investment payback period and contributes to the gradual expansion of the list of elements implemented (Zakharchuk, 2022a). As of the beginning of 2022, only 15% of Ukraine's agricultural land was covered by precision agriculture, mostly those used by agricultural holdings. The volume of the precision agriculture market in Ukraine, which includes equipment that comes with machinery, additional equipment, equipment sheds, services, software products, and drones, is estimated at more than USD 60 million. Currently, management systems that help ensure high vigilance in the implementation of production processes in agriculture, including safety, maintenance and prevention, account for more than 41% of the total market revenue. The complex implementation of precision agricultural systems has been realized on 5% of Ukraine's cultivated land, and on 20% of its individual elements (Zakharchuk, 2022a).

For Ukrainian producers, the use of resource-saving crop cultivation technologies that can increase production efficiency is becoming increasingly important. Such agricultural systems include, in particular, no-till, mini-till, strip-till, and verti-till, each of which has both advantages and disadvantages. When choosing the best technology for practical application in farming, it is necessary to take into account the field characteristics (mechanical composition and humus level; natural soil density, level of soil structure; relief; rainfall and annual temperature), availability of technical equipment; intensity of production technologies; existing crop rotations; and varietal characteristics of crops. The use of variable seeding rate technology (differentiated seeding), which is based on an precise calculation of plant growth density across the field, taking into account soil fertility, moisture reserves and topography, is highly effective, especially in heterogeneous fields. Spot spraying systems are widely used in Ukrainian agricultural enterprises. At the heart of these innovative products are modern optics and electronic computing systems that allow effective detection of weeds and their treatment with herbicides. Such spot use of herbicides provides savings of up to 90% (Zakharchuk, 2022a).

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P. Sabluk & I. Khomin (2020) substantiated the concept of reorientation of non-refundable budget allocations to revolving, but preferential crediting of commodity producers in the agricultural sector of Ukraine, which should encourage commodity producers to search for internal reserves, which is especially relevant for small and medium-sized agricultural enterprises in the post-war period. Such internal reserves, according to the authors, can become capital investments in technologies of precision agriculture, in particular. At the same time, the authors agree with the opinion of K.B. Voloshchuk *et al.* (2020), which emphasize the possibilities of achieving high productivity of agricultural producers in case of coordination and unification of efforts of business structures with state and local self-government bodies, solving problems and determining investment priorities according to the nature of strategic direction. V. Klochan & I. Klochan (2018) the improvement of the mechanism of state regulation of investments in innovative activities aimed at the development of the agricultural sector of the country is considered, in particular, due to the close integration of production and science, which fully allows to solve the task of finding internal reserves of agro-producing enterprises – through the application science-based management methods, innovative agricultural technologies, etc.

The latest achievements are the basis of various cultivation systems that provide cost savings. For example, the use of moldboardless technology saves about 27%, minimal tillage – 43%, and no-till technology –

86% of total fuel and lubricants costs for crop preparation. Improvements in the structure of the machine and tractor park, the optimal combination of tillage units during sowing, fertilization and pesticide application, etc. have a significant impact on the efficiency of crop production. The operation of combined units in combination with resource-saving technologies reduces total production costs by 15% compared to traditional technologies, and the introduction of precision agriculture and minimum tillage technologies reduces them by almost 20% (Taran *et al.*, 2020).

The implementation of resource-saving innovations, such as precision agriculture, is necessary for agricultural enterprises due to increasing costs for key resources and the need to maximize crop yields and profitability. It is critical to explore the internal reserves of agro-producers through innovative agricultural technologies, improved mechanisms for state regulation of investments, and closer integration of production and science; such strategies not only enhance the efficiency of crop production but also significantly reduce production costs.

CONCLUSIONS

The need for investment support for the technological growth of the agro-industrial sector of Ukraine's economy during the wartime period is critical, as the agro-industrial complex is one of the key sectors of the country's economy and plays an important role in providing food for the population and export potential. One of the most promising areas is attracting foreign investment, as Ukraine has great potential for this in the agri-food sector, in particular due to its natural resources, location on international transportation routes, the presence of a domestic market and growing demand for agricultural products. However, there is a need to provide financial support to small and medium-sized agribusinesses. This may include creating favorable conditions for access to loans and other financial resources, developing support programs aimed at developing technologies and innovations in the agri-food sector.

For example, today there are more and more problems related to the rational use of natural resources and environmental safety, lack of investment, especially in the context of rising costs of environmental protection measures and production expansion. In this regard, the state can no longer solve these problems on its own and needs a new approach to interacting with business in this area. One possible approach is to develop a new type of interaction between the state and business based on the principles of partnership and cooperation. This means that the state and business should cooperate on an equal footing, increasing mutual responsibility and equality, in order to achieve common goals of rational environmental management and environmental safety. This new type of interaction can be based on the following principles:

- Dialogue and consultation. The state and business should interact on the basis of open dialogue and consultation with the opinion of users and the views of all stakeholders, including public organizations and scientists.
- Joint decision-making. The state and business should jointly make decisions on environmental management, taking into account economic, social and environmental aspects. The decision must be balanced and not harm the interests of all stakeholders.

The authors see the study of the potential of innovative technologies that can be implemented in the agri-food sector, the study of financial instruments and investment mechanisms, and the study of the effectiveness of investment projects as promising directions for further research on the mentioned topic. Also in research, it would be advisable to conduct a more in-depth analysis of the prospects of attracting investments in terms of agricultural enterprises of different sizes, specialization, location, etc.

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CONFLICT OF INTEREST

None.

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Перспективи формування інвестиційного забезпечення технологічного зростання агропродовольчого сектора економіки України в повоєнний період

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Анотація. В період війни і після її завершення Україна потребує відновлення своєї економіки, зокрема агропродовольчого сектора, який є одним із ключових галузей національної економіки. Інвестиційне забезпечення технологічного зростання агропродовольчого сектора може мати вирішальне значення для цього, адже дозволяє досягти високої продуктивності, конкурентоспроможності та сталого розвитку цієї галузі, що в свою чергу сприятиме забезпеченню продовольчої безпеки країни, підвищенню життєвого рівня населення та зменшенню відтоку робочої сили за кордон. Метою статті було проаналізувати та визначити перспективні шляхи залучення інвестицій для підтримки технологічного розвитку агропродовольчого сектора в умовах післявоєнного періоду в Україні. Використовуючи аналіз літературних джерел та статистичних даних, розглянуто та проаналізовано стан галузі сільського господарства України в довоєнний і повоєнний період. Досліджено структуру і інвестиційну привабливість українських підприємств. Проаналізовано стан господарюючих суб'єктів в галузі сільського господарства і за допомогою експертних оцінок, встановлено, що саме мале підприємництво є рушійною силою розвитку економіки і економічних відносин, хоча і ризикованим для інвестування. За допомогою статистичного аналізу досліджено структуру іноземних інвестицій і встановлено, що основною проблемою залучення іноземних інвестицій є застаріла техніка і технології, тому є необхідним запроваджувати інновації в сільське господарство. Отже, проаналізувавши сильні й слабкі сторони, можливості і загрози, встановлено, що відповідне фінансування може допомогти впроваджувати сучасні ресурсоощадні технології в агропродовольчому виробництві, сприяти впровадженню інноваційних підходів, а саме – впровадження сучасних методів обробки грунту, використання раціонального водокористування, впровадження автоматизації та механізації процесів виробництва, використання дронів та сучасних систем моніторингу, а також впровадження сучасних методів зберігання, переробки та збуту продукції, що забезпечить підвищення ефективності виробництва, зниження екологічних наслідків та підвищення конкурентоспроможності українських аграрних підприємств на міжнародному ринку. Практична цінність дослідження полягає у можливості надати рекомендації щодо створення сприятливого інвестиційного клімату, удосконалення законодавства, забезпечення захисту прав інвесторів, а також розвитку інфраструктури і підтримки науково-дослідних проектів у сфері агропродовольчого виробництва

Ключові слова: ресурсоощадні технології; поступальний розвиток; мале підприємництво; інновації; сільське господарство

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Scientific basics to develop functional meat pâtés

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Abstract. The problems of providing consumers with healthy nutrition in sufficient quantities are typical for the entire modern world, and specialists are working hard to solve them, trying to harmonize the priorities of nutritional value with the basics of thrifty use of food resources. In this regard, it is important to develop functional food products, the composition and production technology of which rationally correspond to the nutritional needs of certain categories of consumers. The purpose of the article is to substantiate the use of the indicated vegetable raw materials in functional pâté products and to determine the quantitative parameters of their inclusion in formulations. To study the swelling and hydration of the samples, conventional laboratory methods were used, the water-retaining and fat-retaining capacities were determined by the Schoch method, the amino acid composition – by using the High-Performance Liquid Chromatography. The research has confirmed the feasibility of using plant flour and oils as sources of protein and fat to impart functional properties to meat products and to save valuable meat raw materials. Studies of the physical, chemical and functional-technological properties of flaxseed, rice, corn, sunflower flour showed that flaxseed and rice flour are the most suitable for creating formulations of functional meat products. The determination of the amino acid composition of these two types of flour showed a higher content of essential amino acids, including lysine, in flaxseed flour, which is very valuable for ensuring the proper functioning of the child's brain. For the rational conduct of research, a generalized scheme for planning formulations of functional pâté products was proposed, based on the properties of the used plant materials and the desired functional properties of these products. The practical value of the studies performed is that they made it possible to determine the necessary ratios of vegetable raw materials in the formulations of meat pâtés, which determine their functional properties

Keywords: functional food products; nutrients; meat products; flaxseed flour; rice flour; amino acid composition

INTRODUCTION

The Declaration of the Food and Agriculture Organization of the United Nations (1996) contains a provision that food security is ensured when all persons at all times have physical and economic access to safe and nutritious food, sufficient to satisfy their physiological needs and ensure an active and healthy life. An

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important role in this is played by functional foods, that is, foods, each of which is intended for systematic consumption as part of diets, and at the same time maintains and improves health, and also reduces the risk of developing nutrition-related diseases due to the presence of physiologically functional food ingredients in its formulation (Borsolyuk *et al.*, 2018).

The idea of producing foods with enhanced functionality by incorporating bioactive ingredients has prompted academia and the food industry to intensify research and development in functional foods. This suggests that dietary and lifestyle modification is a practical strategy to reduce the incidence of chronic diseases. Although there is no single definition worldwide, foods can only be considered functional if, in addition to their primary nutritional impact, they beneficially affect certain physiological functions in the human body, improving physical condition and / or reducing the risk of non-communicable diseases and chronic diseases (Ramírez Osorio *et al.*, 2021).

Some scholars have emphasized the importance of developing new biologically valuable ingredients from natural resources, as well as the positive therapeutic effect in the nutrition of patients with certain chronic diseases using functional foods and nutraceuticals their formulations including functional and biological substances. Biological ingredients (bioingredients) are substances that are used for food production or food preparation and are present (although possibly in a modified form) in the final product and have a pronounced biological activity in relation to the consumer's body. In the modern world, bioingredients play an important role in various areas of human life (Premkumar & Vasudevan, 2018).

The production of functional food products based on meat raw materials is developing in the direction of expanding the diversity of products, combining and optimizing their composition in order to achieve nutritional and biological value, preserve valuable components of raw materials, and compensate for the lack of a number of macro- and micronutrients by including functional ingredients in formulations. Regarding meat products, the efforts of specialists are mainly directed to their modification by changing the content of lipids and fatty acids and / or by adding a number of functional ingredients: fibers, vegetable proteins, monounsaturated or polyunsaturated fatty acids, vitamins, calcium, phytomaterials (Premkumar & Vasudevan, 2018). It is necessary that the combined meat products have a high biological value due to the combination of meat raw materials with food and protein supplements of animal and vegetable origin, characteristic for pronounced functional properties and the proper content of essential nutrients. For this purpose, proteins of plant, animal, microbiological origin, are used in the form of isolates, concentrates or flour. Examples of such natural proteins are blood, bone and milk proteins, wheat gluten, legume proteins and sunflower (Acosta *et al.*, 2021; McClements & Grossmann, 2021).

Functional foods contain functional ingredients their addition being beneficial to the health of consumers, namely probiotic bacteria, prebiotics, dietary fiber, synbiotics, antioxidants, polyunsaturated (ω-3) fatty acids, plant sterols, biologically active peptides, minerals and vitamins. The addition of functional ingredients to meat products should not change the properties of the said products. New ingredients should be present in the formulations in such quantities that have a positive impact on the health of consumers (Borsolyuk *et al.*, 2018). Often the functional properties of meat products are achieved by changing the content of lipids and fatty acids or adding fiber, vegetable proteins, monounsaturated or polyunsaturated fatty acids, vitamins, calcium, phytomaterials, etc. (Abzhanova *et al.*, 2022). It is relevant that the trend of using functional bioactive compounds in meat production is becoming more pronounced. Undoubtedly, these components can significantly affect human health, but the qualitative and quantitative composition of these substances must be correctly selected. In particular, an important question is whether the product will be processed and, if so, what processing will be applied (Pogorzelska-Nowicka *et al.*, 2018). Of no small importance in the development of functional meat products is also taking into account the deficiency of certain substances in the diet of specific consumer groups. The process of creating new meat products with functional properties is complex and depends not only on the influence of functional ingredients on the nutritional value of the final product, but also on the quality of its production (Borsolyuk *et al.*, 2018).

The information given above lets it possible formulating the goal of the research the said goal consisting in the study of the functional meat pâtés intended for the children of preschool and school age, substantiating plant raw materials used for the purpose and rational formulations of these pâtés.

LITERATURE REVIEW

The ability to develop functional foods aims to use strategies that can condition the presence of certain compounds, either by limiting the content of those that have negative consequences (for example, allergens or irritants) for the health of consumers, or by increasing the proportion of those that show beneficial effects (for example, fiber, polyphenols, flavonoids, carotenoids, vitamins and minerals) (Jiménez-Colmenero, 2013). In this context, food waste is an important source of bioactive components that can be used as ingredients or additives to develop functional foods (Kumar *et al.*, 2017).

In the scientific practice of Ukraine, the term "functional food products" refers to a wide range of food products: carriers of natural and organic substances, low-calorie and calorie-free products for weight control, foods enriched with vitamins and microelements, energy drinks, probiotic products, dairy products with specific properties. To maintain the health, performance and longevity of a person, it is very important to observe three basic principles of rational nutrition: balance of energy, meeting the needs of the body in the required quantity and ratio of nutrients and diet. Studies by medical scientists carried out in Ukraine have shown that recently there has been a decrease in protein in the diet of the population (Order of the Cabinet of Ministers of Ukraine No. 332-2004-r, 2020). At the same time, many people were found to be obese due to metabolic disorders. As of 2021, the average life expectancy of the population of Ukraine is 65.16 years for men and 74.36 years for women (State Statistics Service of Ukraine, 2022). For elderly category of consumers, the need to develop and produce special functional food products seems obvious. Another large group of consumers who need functional products are children and adolescents.

These are foods that contain biologically active components that have a nutritionally beneficial effect on one or more functions of the body, the purpose of which is to reduce the incidence of chronic non-communicable diseases. Among the specific elements or biologically active components in food systems, probiotics, biologically active peptides, carotenoids, vitamins, phenolic compounds, phytoestrogens, fatty acids or structured lipids are to be mentioned. According to statistics, globally, the production of these products is increasing by 48% annually because the addition of these components, either naturally or through modification, has been shown to provide great developmental health benefits every day, early growth, protection against oxidative stress, regulation of metabolic processes, physiology of the cardiovascular system and the gastrointestinal tract, mental, cognitive, physical and/or athletic performance (Fuentes *et al.*, 2015; Lamos *et al.*, 2018; Delgado Sánchez, 2019).

Among the fatty acids contained in the human diet, there are two groups, some of which are necessary for the body, while others are not. It is difficult for a person to produce the necessary substances on their own, so they come from food, being a good source of energy in case of deficiency – the examples are α-linolenic (ω-3) and linoleic (ω-6) acids (Lemahieu *et al.*, 2017). However, saturated or trans acids may pose a health risk to the consumer (Moghadasian & Shahidi, 2016). Therefore, polyunsaturated fatty acids (PUFAs) or volatile fatty acids have received a lot of interest lately, as they are found in varying amounts in mammalian cell membranes, among the most important being: docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), from the ω-3 family where seafood is the richest source of these components, while α-linoleic acid is found in vegetables such as seed oils, green leaves and legumes (Colussi *et al.*, 2016). These compounds contribute to a reduction in the number of people with cardiovascular disease and death from this cause, according to epidemiological studies (Baker *et al.*, 2016). Commercial blends of fats have been replaced by vegetable oils or oilseeds, fish oils, or combinations thereof, increasing the functional value of foods. On the other hand, in the poultry industry, interest has increased in enriching the diet of birds with fish, flaxseed or rapeseed oil due to the increase in the content of polyunsaturated fatty acids formed in meat. Studies have shown that levels of this type of acid increase, thus revealing higher levels of EPA and DHA in breast and thighs, as well as levels of linolenic acid where 100g of breast or thigh meat provides the body on average 33% and 15.5%, respectively, of the recommended human daily intake of EPA and DHA (Konieczka *et al.*, 2017).

Thus the numerous examples of scientific works including those mentioned in the above literature review confirm the beneficial effect of different plant raw materials in the course of supplying human organism with nutritionally valuable substances and compounds.

MATERIALS AND METHODS

The determination of the physical and chemical characteristics of the functional pâtés was carried out using a set of research methods. The following parameters of the functional pâtés were determined using the methods specified below:

- protein content (by mass) was determined according by the content of total nitrogen according to Kjeldahl with subsequent distillation of ammonia;
- water content (by mass) was determined by the thermogravimetric method using electronic moisture balance ADS-50 (AXIS) by drying the sample to constant weight at a temperature of 105°C;
- fat content (by mass) was determined using the Soxhlet method – extraction of samples with dichloroethane and drying to constant weight after evaporation of the solvent;
- carbohydrates content (by mass) was determined using the formula [100 - (protein + water + fat + ash)];
- moisture-binding capacity was determined by pressing according to E. Okuskhanova *et al.* (2017).

The swelling capacity of flour samples was determined by keeping a 1% aqueous suspension in a measuring cylinder for a day at a temperature of 18-20°C. Swelling was evaluated as the maximum amount of water that an object can absorb and retain until dynamic equilibrium, related to the weight of the sample. The level of hydration of flour samples was determined by the amount of bound water (product: water ratio). The water-retaining and fat-retaining capacity of flour samples was determined by the Schoch method with the addition of water (for WRC) or fat (for FRC), holding in a water bath and subsequent centrifugation for 15 minutes at 6000 rpm. The amino acid composition of flour proteins was studied according to the International Standard ISO 13903:2005 (2005). Amino acids were separated by ion-exchange chromatography, reacted with ninhydrin, and the content of amino acids was determined by the photometric method (wavelength 570 nm). The results of the studies were also statistically processed using the Microsoft® Office Excel 2003 software package. The experiments were repeated three times. The results were considered significant at a confidence level of P 0.05. Graphical processing of the results was carried out using the Microsoft® Office Excel 2003 software package.

RESULTS AND DISCUSSION

Regarding meat products, the efforts of specialists are mainly aimed at modifying them by changing the content of lipids and fatty acids and / or by adding a number of functional ingredients: fibers, vegetable proteins, monounsaturated or polyunsaturated fatty acids, vitamins, calcium, phytomaterials. The following basic requirements for the creation of specialized meat-based products are rational:

- ➥ the protein component of functional meat products must combine protein of animal and vegetable origin – this provides a more pronounced physiological effect;
- ➥ sources of animal protein in the product can be beef, pork, chicken and turkey meat;
- ➥ it is recommended to use chickpeas, soybean products, cereals and cereals as a source of vegetable protein;
- ➥ products should be enriched with vitamins, macro- and microelements at their optimal ratio, polyunsaturated fatty acids, dietary fiber, which reduce the risk of developing cardiovascular diseases;
- ➥ the fat component can be formed by the fat of meat raw materials and vegetable oils: sunflower, corn, flaxseed, soybean and others, as a source of polyunsaturated fatty acids;
- ➥ the source of carbohydrates should be vegetable products - cereals, vegetables containing sufficient dietary fiber and fiber;
- ➥ the energy value of 100 g of the product should be in the range of 150-200 kcal. Some researchers suggest using rice and corn flour or cereals for the production of meat products, which allows for a more rational use of protein resources (Bashtova, 2015).

Therefore, the partial replacement of meat in meat products with protein raw materials of plant origin is justified in the economic and technological sense, and is also useful in terms of improving the nutritional value of these products. Of the various forms of adding vegetable protein raw materials to the formulations of meat products, there are isolates that are inferior to flour in terms of their effect on the sensorial properties and suitability of products for storage. Raw meat is rich in ω-3 and ω-6 fatty acids, but a certain balance is needed between them, which determines the functionality of the product. To achieve good results in the balance of the fatty acid composition of meat products, the use of vegetable raw materials in their formulations, primarily vegetable oils, as well as flour (Borsolyuk *et al.*, 2017), makes it possible. As part of the research, an assessment was made of the nutritional, physical, chemical and technological properties of different types of flour used in the composition of functional pâté pâté products intended for feeding children of preschool and school age. The flow of technological processes is mainly determined by the functional and technological properties of the components, therefore, in order to rationally use various types of flour or their mixture in pâté formulations, a study of the functional and technological properties of the specified raw materials was carried out, the results of which are shown in Table 1.

Table 1. *Physical, chemical and technological parameters of flour samples*

Parameter	Flaxseed flour	Rice flour	Maize flour	Sunflower flour	Flour mix *
Water, %	6.93	9.80	7.85	5.69	8.57
Protein, %	26.11	6.50	7.27	31.97	19.15
Fat, %	14.62	2.17	2.38	9.89	8.19
Ash, %	5.86	81.02	0.26	6.83	3.12
Carbohydrates, %	46.48	0.51	82.24	45.62	61.0

Table 1, Continued

Parameter	Flaxseed flour	Rice flour	Maize flour	Sunflower flour	Flour mix *
Swelling, cm^3/g	12.2	3.6	0.54	1.0	7.4
Hydration level	1:6	1:7	1:6	1:3	1:7
Water retaining capacity, %	622.5	575	220.0	300.0	220.0
Fat retaining capacity, %	192.5	245	137.0	170.0	132.5

Notes: ** - mix of maize and flaxseed oils in the ratio of 1:1*
Source: *L. Borsolyuk et al. (2017)*

It is known that the amino acid composition indicates the quality of food protein. Essential amino acids are especially important, which are not synthesized in the human body and enter it with food. At this stage of the research, the amino acid composition of flaxseed and rice flour was analyzed, the results are shown in Table 2.

Table 2. *Amino acid content of flour samples*

Amino acid		Flaxseed flour		Rice flour	
		g/100 g of flour	g/100 g of protein	g/100 g of flour	g/100 g of protein
Protein content, %		26.11		6.5	
Essential:					
Arginine	Arg	2.539	9.77	0.516	7.94
Valin	Val	1.487	5.72	0.348	5.35
Histidine	His	0.802	3.10	0.149	2.29
Isoleucine	Ile	1.320	5.08	0.244	3.75
Leucine	Leu	1.580	6.08	0.488	7.51
Methionine	Met	0.587	2.26	0.144	2.22
Threonine	Thr	0.473	1.82	0.210	3.23
Phenylalanine	Phe	1.348	5.18	0.317	4.88
Lysine	Lys	1.259	4.84	0.207	3.18
Total essential:			43.83		40.35
Non-essential:					
Alanine	Ala	1.286	4.95	0.332	5.11
Aspartic acid	Asp.ac	2.052	7.89	0.549	8.45
Cysteine	Cys	0.473	1.82	0.107	1.65
Glycine	Gly	1.228	4.72	0.267	4.11
Glutamic acid	Glu.ac	3.123	12.01	1.097	16.88
Proline	Pro	1.179	4.53	0.278	4.28
Serene	Ser	1.148	4.42	0.310	4.77
Tyrosine	Tyr	0.737	2.83	0.314	4.83
Total non-essential:			43.18		50.06
Total:			83.64		90.42

Source: *L. Borsolyuk et al. (2017)*

As can be seen from the Table 2, the content of essential amino acids is higher in flaxseed flour. In particular, there is an advantage in the quantitative content of amino acids such as arginine, isoleucine, phenylalanine and lysine. In terms of the importance of ensuring the functional properties of the finished product, the most valuable amino acid is lysine, since this substance contributes to brain function, which is very important for children of primary school age.

To formulate a pâté intended for preschool and school children, a general approach was used to develop formulations of emulsion products with the necessary modifications. To draw up a generalized scheme (Fig. 1) for formulating a functional pâté product for these categories of consumers, the priority condition was precisely the proper functionality due to the chemical composition, bioavailability, proportions of components, processing method, degree of comminuting together with other physical and chemical parameters of the product (Borsolyuk *et al.*, 2018). In particular, vegetable oils were used in the composition, which have a pronounced antioxidant effect. They also effectively inhibit the growth of tumors, inactivate toxic substances and bacteria, and have anti-inflammatory and immunoprotective traits. To improve the fatty acid composition of meat products, it is advisable to add vegetable oils in the form of emulsions (Bal-Prylypko & Leonova, 2020).

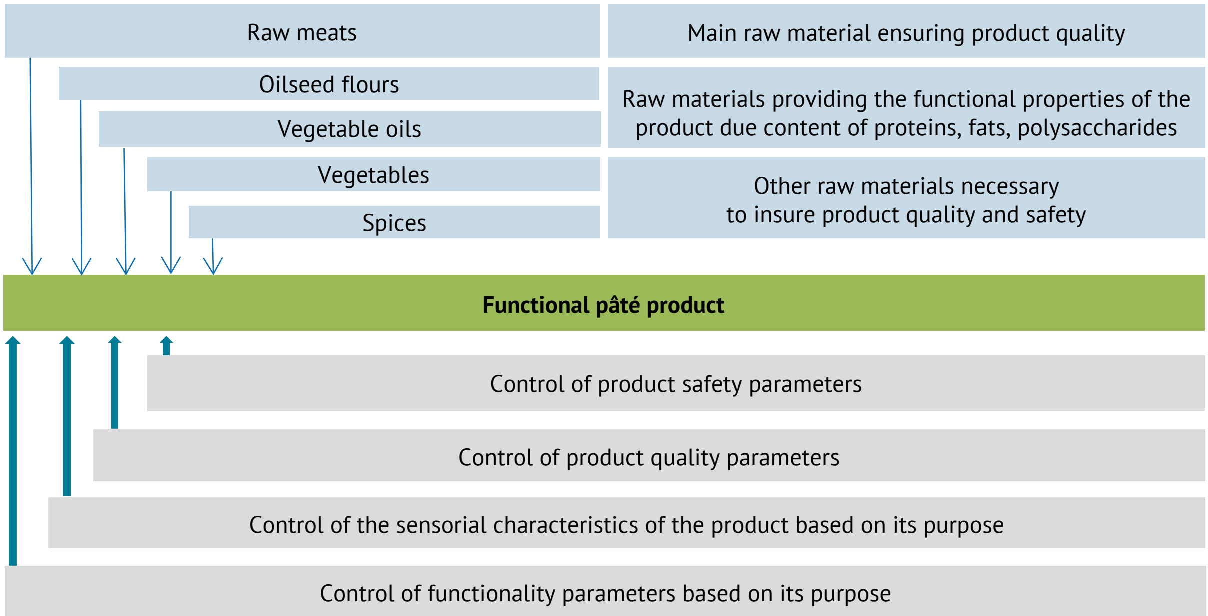

Figure 1. *Chart of formation of a functional pâté formulation*
Source: *authors' own development*

For the products of children nutrition, animal protein should make up 55% of the total amount of protein, vegetable fat – up to 30 % of the fat component of the product (Borsolyuk *et al.*, 2017). The ratio of polyunsaturated and monounsaturated fatty acids should be 1 : 1, the ratio of protein: fat should be 1.00 : 0.87. The liver is one of the best dietary sources of iron. It contains much more iron compounds such as hemoglobin and myoglobin than meat. Also, the liver is rich in vitamins of group B, PP, folic acid, contains minerals – potassium phosphorus, iron, manganese, copper, zinc (Gorneţ, 2016). Iron from the liver is well absorbed by the body, since it is in the form of heme. To enrich formulations of pâtés with ω-3 and ω-6 fatty acids, blends of vegetable oils: sunflower and flaxseed (90 : 10) and corn and flaxseed (85 : 15) were used. Corn flour, sunflower and flour mixture were included in the formulations of meat pâtés in order to enrich them with vegetable protein, carbohydrate component and create the desired consistency grade, to prevent separation of the liquid phase (broth). Carrots were used as a source of pectin substances, fiber, vitamins A, B, E, K, carotenoids, macro- and microelements.

There are also other possible solutions to provide the sufficient functionality of meat products. Thus scholars consider it rational adding flaxseed flour to the formulations in different forms – not additionally treated, fried, partially defatted and defatted. Experiments showed that fried not defatted flour was the best for the fat absorption capacity of the product, while the best water absorption capacity was characteristic for non-fried partially defatted flour (Hussain *et al.*, 2008). The flax flour the formulation of a minced lamb product promoted raising water-retaining capacity, sensorial acceptability, texture and shelf life of the product (Sharma *et al.*, 2014). The flaxseed flour as a functional ingredient to ground beef cutlets added in the amount of 3, 6, 9, 12 and 15% caused a decrease in moisture and protein content and increase in alpha-linolenic acid content. Experiments showed the ratio of ω-6 to ω-3 to decrease from 5.76 for the product with 10% fat to 0.36 for that with 15% flax flour. The addition of 3 or 6% flaxseed flour improved the sensorial characteristics of the product studied (Bilek & Turhan, 2009).

There is information that the fat component of the daily diet should provide no more than 30% of the energy requirement, including in equal amounts separate fractions of fatty acids, that is, saturated fatty acids : polyunsaturated fatty acids : monounsaturated fatty acids = 1 : 1 : 1 (Peshuk *et al.*, 2011). Such a composition of "ideal" fat is the basis for the development of norms for the physiological needs of for the basic nutrients and energy. Thus, the use of meat in the composition of pâtés for preschool and school children is necessary, since the meat contains biologically active substances that determine its functional properties: complete animal protein, bioactive peptides, minerals, vitamins, fatty acids, and for the enrichment of pâtés with fatty acids it is advisable to use vegetable oils, as well as corn and sunflower flour for enriching pâtés with vegetable protein and carbohydrates (Borsolyuk *et al.*, 2018).

To improve the content and lipid profile of meat pâtés, their formulation was changed, which reduced the total content of fat, cholesterol and improved the lipid profile by replacing part of the animal fat with more healthy lipids, the characteristics of which are more in line with scientific dietary recommendations. Vegetable oils belong to such substances (Freitas *et al.*, 2012). They contain sterols, which have an expressive antioxidant effect, inhibit the growth of tumors, inactivate toxic substances and bacteria, and have anti-inflammatory and immunoprotective properties.

It can be stated that the results obtained are sufficient in the terms of reaching the goal of this article. Somewhat different conclusions made by other authors do not contradict the said results but confirm the existence of numerous ways to improve functional and other important properties of the meat products studied.

CONCLUSIONS

For the manufacture of functional pâté products, a number of ingredients of plant origin are used, in particular, flour from the seeds of various crops and mixtures of various types of flour. The purpose of using flour in formulations of functional pâté products is, in particular, to enrich these products with proteins and polysaccharides. Comprehensive comparative studies of physical, chemical and technological properties of rice and flax flour showed significant advantages of the latter in terms of ensuring the proper functional properties of the finished product. Flaxseed flour, as a functional component, normalizes the work of the gastrointestinal tract, as a technological component, it helps to increase the moisture-binding capacity of the meat system. It is rational to replace up to 15% of meat raw materials with flax flour in the composition of functional pâtés. The use of sunflower flour allows you to get a product that is balanced in chemical composition and enriched with proteins necessary for the normal functioning of the body. Corn flour can be considered a promising raw material in the production of functional pâtés, useful in diseases of the liver, cardiovascular system, and gout. The inclusion of corn flour in the composition of functional pâtés helps to remove fat accumulations from the body, and the presence of such a microelement as silicon helps to increase the elasticity of blood vessels and strengthen teeth. Studies have shown that corn flour is significantly inferior to flaxseed and sunflower in terms of protein and fat content, but contains more carbohydrates – mainly due to the higher content of starch. So, a promising direction for creating formulations of functional pâté products is a combination of corn and flax flour. This allows to increase the protein content in the mixture due to flaxseed flour and enrich the mixture with polysaccharides due to corn flour. It is advisable to focus further research on the development of specific formulations of functional pies intended for various special categories of consumers – preschool and school-age children, the elderly people, as well as those suffering from certain diseases, military personnel and other consumers in extreme conditions.

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CONFLICT OF INTEREST

None.

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Наукові основи розробки функціональних м'ясних паштетів

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Анотація. Проблеми забезпечення споживачів здоровим харчуванням у достатній кількості характерні для всього сучасного світу, і фахівці наполегливо працюють над їх вирішенням, намагаючись гармонізувати пріоритети харчової цінності з основами ощадливого використання продовольчих ресурсів. У зв'язку з цим важливого значення набуває розробка функціональних харчових продуктів, склад і технологія виробництва яких раціонально відповідають харчовим потребам окремих категорій споживачів. Мета статті – обґрунтувати використання рослинної сировини у функціональних паштетних виробах та визначити кількісні параметри її долучення до рецептур. Для дослідження набухання та гідратації зразків було використано загальноприйняті лабораторні методи, водоутримуючу та жироутримуючу здатність було визначено за методом Шоха, амінокислотний склад – за допомогою високоефективної рідинної хроматографії. Проведені дослідження підтвердили доцільність використання рослинного борошна та олій як джерел білка та жиру для надання функціональних властивостей м'ясним виробам та економії цінної м'ясної сировини. Дослідження фізико-хімічних та функціонально-технологічних властивостей лляного, рисового, кукурудзяного, соняшникового борошна показали, що лляне та рисове борошно є найбільш придатними для створення рецептур функціональних м'ясних продуктів. Визначання амінокислотного складу цих двох видів борошна показало вищий вміст незамінних амінокислот, зокрема лізину, у лляному борошні, що є дуже цінним для забезпечення належного функціонування дитячого мозку. Для раціонального проведення досліджень запропоновано узагальнену схему планування рецептур функціональних паштетних виробів, виходячи з властивостей використаної рослинної сировини та бажаних функціональних властивостей цих виробів. Практична цінність проведених досліджень полягає в тому, що вони дозволили визначити раціональні співвідношення рослинної сировини в рецептурах м'ясних паштетів, які визначають їх функціональні властивості

Ключові слова: функціональні харчові продукти; поживні речовини; м'ясні продукти; лляне борошно; рисове борошно; амінокислотний склад

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The use of entropy and information analysis to estimate the milk productivity of the Black-and-White dairy breed cows depending on their lineal affiliation

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Abstract. In modern realities, an important place for the effective management of the cattle breeding industry is a properly implemented selection and breeding process with the sampling of cows that are marked by the highest indicators of a set of productive qualities. In this case, the application of entropy and information analysis is one of the most expedient, as it makes it possible to assess the economic and useful qualities of animals as fully as possible. The purpose of the study is to evaluate and analyze the degree of organization of the biological system of dairy cattle productive traits under the influence of hereditary factors such as the age and origin of cows. During the research, methods generally accepted in zootechnics and methods using information and entropy analysis, which are adapted and modified in animal husbandry, were used. The data obtained from the entropy and information analysis show that for cattle of the Black-and-White breed of different lineal affiliations, the level of organization of systems varies – R from 0.009 to 1.341 bits. Moreover, the most stable trait from the point of view of variability was the fat content in milk, the level of unconditional entropy in the section of lactations was equal to 3.333-4.550 bits, which indicates a smaller influence of disorganized factors on the level of manifestation of this trait, and a greater dependence on hereditary factors, i.e. origin. Although in general, a reliable influence of the lineal affiliation of cows on indicators of unconditional entropy and organization of the system was not established, the influence of the age factor on indicators of entropy was observed. Thus, the researched livestock is not characterized by uniformity and consolidation in terms of the main selection characteristics, except for the fat content in milk, which indicates a wide range of variability and serves as a flexible material both for selection and breeding work and for increasing the level of milk productivity. Therefore, the use of empirical data of information theory can be a kind of marker when predicting hereditary traits of a particular productivity, since entropy and information analysis provides wider and deeper values of trait variability

Keywords: information theory; milk yield; fat content in milk; entropy; organization of the system; measure of chaos

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INTRODUCTION

Since the 2000s, the use of entropy and information analysis (EIA) has attracted more and more attention in various areas of scientific practice, many publications can be found in biology, physiology, medicine, and since 2018, modeling and analysis of selection processes using information theory have been widely used in animal husbandry (Machado *et al.*, 2020; Chanda *et al.*, 2020; Mueller *et al.*, 2021).

Modeling the processes of system development becomes possible precisely due to the study of the mechanism of information transmission, which in turn, taking into account the degree of organization, orderliness and complexity, explains the essence of the mechanism of system progress (de Andrade *et al.*, 2022; Fuentes *et al.*, 2022).

The method of entropy analysis allows to increase the level of research of various indicators of economic and useful traits. When analyzing the dependencies between the entropy of nominal features and its expressiveness, the mutual information of natural descriptive statistics corresponds to the laws of information theory (Karatieieva *et al.*, 2021).

Entropy, as a logarithmic measure of disorder, characterizes the average degree of uncertainty of the state of the message source. The degree of uncertainty in information systems decreases due to the received information, therefore, in numerical terms, entropy is equal to the amount of information, that is, it acts as a quantitative measure of information. Entropy also has the feature of additivity, since the total entropy of several objects is equal to the sum of the entropy phenomena of individual objects (Pidpala *et al.*, 2018).

In agriculture, mathematical modeling methods are actively used to solve the following tasks: drawing up optimal animal feeding rations, determining the sexually mature structure of the herd, drawing up optimal timing of animal vaccination, drawing up lactation curves of milk yield, etc. However, for cattle breeding, they have a slightly different character, this is due to the fact that one of the most important components for these animals is the comprehensive assessment of cattle, for their further use in the selection and breeding process, and one of the advanced methods is precisely the method of mathematical modeling (Kramarenko *et al.* 2019).

The use of the method of entropy analysis makes it possible to identify natural and ecological consequences that significantly affect selection and production characteristics, as well as to choose the most compatible pairs for breeding, from the point of view of selection, and to eliminate from the selection process unsatisfactory animals that do not meet the requirements (Fuentes *et al.*, 2022). Therefore, the purpose of the research was to use information theory as an additional model for evaluating milk productivity of cows, determining the organization of the system as an indicator of the selection potential of a given herd.

LITERATURE REVIEW

The first works on information theory began to appear in mathematics and computer science. Thus, the American mathematician C. Shannon (1948) is the founder of the mathematical theory of information, and in his research, he used the concept of entropy in creating "codes resistant to interference" and in establishing the critical speed in information transmission. This approach, using statistical thermodynamics and the probabilistic function of entropy, turned out to be appropriate in the biological sciences as well (de Andrade *et al.*, 2022).

The concept of entropy for understanding biological systems was first applied by E. Schrödinger (1944a), using life phenomena, individual biological processes, and even human activities. Later, M. Delbrück (1962) continued his research, taking as a basis the nature of intermolecular forces observed in biological processes. T.P. Knowles *et al.* (2007) using entropy analysis elucidated the molecular origin of fibril material properties and showed that the main contribution to their stiffness comes from the general system of hydrogen bonds between backbones, which is modulated by various interactions of side chains.

Therefore, the probabilistic function of entropy allows to study all stages of the transition of a biological system from maximum disorganization, that is, a state of complete chaos, which is characterized by an equal value of probabilities and the maximum possible value of entropy itself, to a state of maximum permissible order of the system, in which the only possible state of segments of biological system would be observed (Landete-Castillejos & Gallego, 2000; Gray, 2011).

Many scientists consider a living organism, from the point of view of entropy, as a complex open system in which physical and chemical processes take place, which is in a disorganized, non-stationary state (Gray, 2011; Pidpala *et al.*, 2018; Kramarenko *et al.*, 2019). Therefore, the modeling process in biology is unique in its characteristics and at the same time quite complex, it is inextricably linked with such elements as: hypothesis, abstraction, analogy and others. This method is considered as a process of building, studying and applying mathematical models. If such an analysis is not carried out, there will be a significant decrease in indicators of animal husbandry development (Lemay *et al.*, 2009; Mueller *et al.*, 2021).

Since all exchange processes are balanced in living organisms, this causes a decrease in entropy and contributes to the maximum organization of the entire biological system. Therefore, thanks to entropy analysis, it is possible to provide a characteristic of the vital activity of a biological system or its element, which is not limited to a simple set of chemical and physical, microbiological, physiological processes, but is characterized by a number of other complex processes of self-regulation, which are given in the studies of various scientists (Erill, 2012; Ritchie & Van Steen, 2018; Fuentes *et al.*, 2022).

P.T. Krishnan *et al.* (2020) using entropy and information analysis established several correlations between differentially expressed genes and mental disorders. The authors used the Cell Signaling Network entropy approach, which consisted of the probability of gene interaction using matrix RNA (ribonucleic acid) quantification, calculating signal propagation within the network. The obtained data demonstrated a change in gene expression in disorders. However, the entropy of the cellular signaling network in each pathology showed no differences compared to the corresponding control values. In comparison, progenitor cells, stem cells, and tumor cells showed high entropy, meaning less information in cell signaling. Thus, the author concluded that the disturbance changes cell signaling in peripheral tissues, but supports cell differentiation and the amount of information (Krishnan *et al.*, 2020).

Similar studies were conducted by M.M. Breve *et al.* (2022) based on maximum entropy and using features extracted from graphs to classify mRNA and ncRNA sequences. The results showed the adequacy of the proposed methodology, achieving higher accuracy than in studies using variational statistics. In addition, the proposed method performed classification with less processing time, which indicates a reduction in complexity while maintaining confidence in classification.

The entropy-based method is more powerful than conventional methods and may be useful for detecting epistasis of rare genes, including in animal breeding (Schrödinger, 1944b; Nezhlukchenko, 1999; Pidpala *et al.*, 2018). Chinese scientists S. Liu *et al.* (2023) used a combination of hyperspectral imaging and the entropy method to comprehensively assess the activity of antioxidant enzymes in Tano lamb. The conducted studies indicate that entropy analysis may have great potential for future studies of various enzymes in meat.

Thus, the application of the technique of entropy analysis and information theory in breeding work with dairy cattle will provide more in-depth knowledge and form an understanding of the biological system from the point of view of variability according to the assessment indicators, based on the criteria of physiological factors, genetic factors and environmental factors that affect this biological system.

MATERIALS AND METHODS

The research was carried out on the basis of the agricultural production cooperative "Agrofirma "Myh-Servis-Ahro" of the Mykolaiv region, Ukraine, in the period 2019-2021. For the research in the experiment, an entropy and information analysis of the milk productivity of cows of the Black-and-White dairy breed was used depending on their lineal properties that come from three breeder bulls – Champion, Dragoon and Goliath.

At the first stage of research, for the perfect characterization of milk productivity of animals, biometric processing of the source information was carried out using the methods of variational statistics, and the method of N.A. Plokhinsky (1964) was used. Next, an entropy and informational analysis of the traits of milk productivity was carried out (in terms of 305 days of the first, second, third and higher lactations of cows using the method of K. Shannon (1983) in a modified version of O.S. Kramarenko *et al.* (2019). Based on the recommendations of Yu.G. Antamonov (1977) a classification of biological systems was carried out.

The intra-population value of the unconditional entropy of quantitative traits was determined using the formula:

$$H = -\sum_{i-1}^{k} (p_i \cdot log_2 \cdot p_i), \quad (1)$$

where H – the entropy of a specific statistical system; p_i – the probability (or frequency) of the variation of the characteristic according to the gradations of the variation series; k is the number of possible variants of the system (trait).

For this stage of the system at the maximum possible level, the theoretically determined entropy was calculated according to the formula:

$$H_{max} = log_2 \cdot k, \quad (2)$$

where H_{max} – maximum system uncertainty or degree of complexity; k – the maximum number of positions of the system of trait.

The level of absolute organization of the system was determined by the formula:

$$O = H_{max} - H. \quad (3)$$

The relative organization of the system and its level was calculated according to the formula:

$$R = 1 - H \div H. \quad (4)$$

It is when the entropy level is zero that the system has the highest level of organization. In deterministic systems, the value of relative entropy reaches its maximum and is up to 1. The indicator $R = 0$ occurs in completely disorganized systems.

In the study, the authors used the ARRIVE (n.d.) guidelines as a checklist and followed all relevant ethical norms.

RESULTS AND DISCUSSION

The use of diversity scores has a long history in population ecology, while population genetics has instead been dominated by measures based on variance, a technical gap that slows the breeding progress of a herd or breed. Using entropy in selection work, in contrast to variance, first a model of continuous chaotic diversity is constructed. And then a multiple nested division of diversity of alleles, individuals, populations, and species is created, each component of which engages in behavior of the corresponding diversity metrics, and then these components are converted into a scaled form of the system organization (Shannon, 1948). At the same time, non-parametric statistical tests of components within a population, breed or herd, and new tests of homogeneity of components of diversity within a population at any hierarchical level are also used (Schrödinger, 1944a; Narinc *et al.*, 2013; Liu *et al.* 2023).

The calculations that were performed determined that the limits of relative organization of the biosystem for the cows of the Champion line (Table 1) for the first three and higher lactations were $R = 0.027 – 0.679$. The age of cows was not a significant driving force in the change in the level of milk productivity in the conducted research, so this value was rather fluctuating. Significant indicators of unconditional entropy – $H = 3.612$ bits were observed during the first lactation. The level of unconditional entropy during the second lactation decreased its meaning to 1.688 bits, but it rose again during the third lactation – to 3.429 bits, it also showed a downward trend during the higher lactation – $H = 1.067$ bits, which indicates the level of entropy reduction, and accordingly the system becomes more ordered.

Examining the fat content in milk, the situation was characterized by significant stability, so the level of unconditional entropy in the first lactation was equal to $H = 4.222$ bits, during the second one it decreased slightly – 3.333 bits, the data from the third to higher lactations were identical – $H = 4.550$ bits. The amount of milk fat, which was also subject to research, did not show a significant manifestation of unconditional entropy and its positive correlation with the age of animals.

If analyzing the level of relative disorganization of the system (R), it should be noted that according to the classification of Yu. Antamonov (1977), this biological system was neither stable in terms of age nor productivity, and in most cases belonged to a stochastic ($R = 0.003 – 0.088$ bits) or quasi-deterministic (R=0.158-0.271 bits) system, only complete disorganization system was noted for milk yield at the age of the second and higher lactations ($R = 0.492 – 0.679$ bits). At that time, anentropy, regardless of age and productivity characteristics, acquired negative values, which reflects a higher degree of differentiation and heterogeneity of this biological system ($A = – 3.740 – 4.080$ bits).

Table 1. *EIA of milk productivity of the Black-and-White dairy breed of the Champion line*

Trait	*n*	Parameters of entropy and information analysis of a trait				
		$H \pm SE_H$	H_{max}	O	R	A
		first lactation				
Milk yield for 305 days, kg	20	3.615 ± 0.452	3.322	0.293	0.088	-3.939
Fat content in milk, %	20	4.222 ± 0.444	3.322	0.900	0.271	-3.935
Amount of milk fat, kg	20	3.846 ± 0.512	3.322	0.524	0.158	-3.980
		second lactation				
Milk yield for 305 days, kg	20	1.688 ± 0.048	3.322	1.634	0.492	-3.780
Fat content in milk, %	20	3.333 ± 0.319	3.322	0.011	0.003	-3.897
Amount of milk fat, kg	20	2.063 ± 0.095	3.322	1.259	0.379	-3.839
		third lactation				
Milk yield for 305 days, kg	20	3.429 ± 0.371	3.322	0.107	0.032	-3.939
Fat content in milk, %	20	4.550 ± 0.487	3.322	1.228	0.370	-3.747
Amount of milk fat, kg	20	3.231 ± 0.347	3.322	0.091	0.027	-3.797
		higher lactation				
Milk yield for 305 days, kg	20	1.067 ± 0.002	3.322	2.255	0.679	-3.780
Fat content in milk, %	20	4.550 ± 0.487	3.322	1.228	0.370	-3.747
Amount of milk fat, kg	20	3.563 ± 0.358	3.322	0.241	0.072	-4.080

Notes: *n is the number of animals to be studied*
Source: *authors' development*

Conducting an entropy and information analysis for cows of the Dragoon line (Table 2), it should be noted that the maximum possible entropy indicator reached H_{max} = 3.322 bits. And the maximum value of unconditional entropy was obtained by milk yield during the third lactation – with a value of H = 3.133 bits.

Table 2. *EIA of milk productivity of the Black-and-White dairy breed of the Dragoon line*

Trait	n	Parameters of entropy and information analysis of a trait				
		$H \pm SE_H$	H_{max}	O	R	A
first lactation						
Milk yield for 305 days, kg	20	2.000 ± 0.101	3.322	1.322	0.398	-3.839
Fat content in milk, %	20	2.647 ± 0.174	3.322	0.675	0.203	-3.971
Amount of milk fat, kg	20	1.000 ± 0.008	3.322	2.322	0.699	-3.622
second lactation						
Milk yield for 305 days, kg	20	3.059 ± 0.234	3.322	0.263	0.079	-3.997
Fat content in milk, %	20	3.813 ± 0.413	3.322	0.491	0.148	-4.030
Amount of milk fat, kg	20	2.067 ± 0.097	3.322	1.255	0.378	-3.822
third lactation						
Milk yield for 305 days, kg	20	3.133 ± 0.280	3.322	0.189	0.057	-3.922
Fat content in milk, %	20	1.133 ± 0.012	3.322	4.455	1.341	-3.522
Amount of milk fat, kg	20	2.000 ± 0.079	3.322	1.322	0.398	-3.839
higher lactation						
Milk yield for 305 days, kg	20	2.563 ± 0.168	3.322	0.759	0.229	-3.813
Fat content in milk, %	20	2.286 ± 0.138	3.322	1.036	0.312	-3.780
Amount of milk fat, kg	20	2.813 ± 0.205	3.322	0.509	0.153	3.839

Notes: *n is the number of animals to be studied*
Source: *authors' development*

Comparing the indicators of the first and second lactations in more detail, it can be seen that the entropy level decreased from H = 3.059 to H = 2.000 bits. The level of relative and absolute organization of the trait according to milk yield showed a clear dominance for the first lactation, for which their values were – O = 1.322; R = 0.398 respectively. At the same time, the level of unconditional entropy for higher lactation reached a value of H = 2.563 bits. Cows of the Dragoon line were characterized by milk yield as complex-stochastic systems (R = 0.0179 – 0.148 bits), but in the second and higher lactations they were simple-quasi-deterministic systems (R = 0.229 – 0.398 bits).

According to the content of fat in milk, the level of organization of the system compared to the value of milk yield had higher indicators and reached for the second and third lactation – O = 0.491 and O = 4.455 bits, respectively. And this, in turn, automatically reduced the level of unconditional entropy from H = 3.813 bits to H = 1.133 bits.

When studying the amount of milk fat, a tendency to increase the value of unconditional entropy was noted. So, for the first lactation, its indicator was H = 1.000 bits, and for the higher one, H = 2.813 bits. This contributed to the decrease with age of the index of conditional organization of the system – from O = 2.322 bits for the first lactation to O = 0.509 bits for higher lactation. Accordingly, there was a decrease in the indicator of the relative organization of the system. Thus, the level of relative entropy for the first lactation was R = 0.699 bits, which characterized this herd as a disorganized system. At the same time, with age, there was a tendency to decrease this parameter: R = 0.378 bits for the second lactation and R = 0.153 bits for higher lactation. This contributed to the gradual orderliness of the system and transferred the animals from a chaotic completely disorganized system, first to a quasi-deterministic system (R = 0.378 bits) – the second lactation, and then to a deterministic ordered system (R = 0.153 bits) – higher lactation.

Anentropy indicators from A = –3.522 bits to A = –4.030 bits were noted within the permissible values, regardless of the age of the animals and the selection trait, its negative values were observed. A similar trend is observed in the characteristics of the entropy of the breeding and productive traits of cows of the Goliath line (Table 3).

Table 3. *EIA of milk productivity of the Black-and-White dairy breed of the Goliath line*

Trait	*n*	Parameters of entropy and information analysis of a trait				
		$H\pm SE_H$	H_{max}	*O*	*R*	*A*
first lactation						
Milk yield for 305 days, kg	20	3.125 ± 0.256	3.322	0.197	0.059	-3.913
Fat content in milk, %	20	3.500 ± 0.298	3.322	0.178	0.054	-3.954
Amount of milk fat, kg	20	3.438 ± 0.322	3.322	0.116	0.035	-3.939
second lactation						
Milk yield for 305 days, kg	20	1.867 ± 0.072	3.322	1.455	0.438	-3.780
Fat content in milk, %	20	3.941 ± 0.410	3.322	0.619	0,186	-4.013
Amount of milk fat, kg	20	2.867 ± 0.221	3.322	0.455	0.137	-3.822
third lactation						
Milk yield for 305 days, kg	20	3.250 ± 0.279	3.322	0.072	0.022	-3.880
Fat content in milk, %	20	3.625 ± 0.355	3.322	0.303	0.091	-3.803
Amount of milk fat, kg	20	2.267 ± 0.118	3.322	1.055	0.318	-3.780
higher lactation						
Milk yield for 305 days, kg	20	3.000 ± 0.236	3.322	0.322	0.097	-3.813
Fat content in milk, %	20	1.667 ± 0.055	3.322	1.655	0.498	-3.739
Amount of milk fat, kg	20	3.353 ± 0.285	3.322	0.031	0.009	-3.913

Notes: *n is the number of animals to be studied*
Source: *authors' development*

Characterization of cows' milk yield connected with lactations determined a wave-like fluctuation of entropy with the age of cows. Thus, a significant decrease in the level of entropy by milk yield was observed at the age of the first and second lactations, and its level was $H = 3.125$ bits and $H = 1.867$ bits, respectively. During the third lactation, an increase in the value to 3.250 bits was noted, and during the higher lactation, its level decreased again to $H = 3.000$ bits.

The value of the absolute organization of the system was also characterized by relativity, as well as the indicator of the previous feature manifestation had a wave-like tendency. Namely, during the first lactation, the absolute organization of the system was $O = 0.197$ bits, at the age of the second lactation, its value increased to 1.455 bits and decreased again to $O = 0.072$ bits in the third lactation, and at the age of higher lactation, it reached its maximum value – $O = 0.322$ bits. At the same time, its relative organization had other indicators and had a tendency to gradually decrease $R = 0.059 - 0.022$ bits, excluding the second lactation – $R = 0.438$ bits. It characterized the investigated objects in the first case as a stochastic deterministic system, and in the second case as a completely disorganized one.

According to the level of unconditional entropy, the fat content in milk from the first to the third lactation was relatively stable – $H = 3.500 - 3.941$ 0 3.625 bits, respectively, and it decreased radically only at the age of higher lactation – $H = 1.667$ bits. It should be noted that according to the fat content in the milk the Goliath line cows were simple stochastic $R = 0.054 - 0.186$ bits, excluding higher lactation – R = 0.498 bits, where the studied cows turned into a chaotic system, which may be due to the fact that higher lactation is a fairly subjective indicator, since it includes cows of different ages. High determination of the feature is inherent in cows in all age periods – respectively $O = 0.178$; $O = 0.619$; $O = 0.303$; $O = 1.655$ bits. Also, it should be noted that the entropy of polygenes, which are responsible for the implementation of the milk fat feature, decreases with the age of cows.

Among the studied animals of this group, the indicator of the amount of milk fat was marked by a fairly stable level of unconditional entropy $H = 2.267 - 3.438$ bits. In general, according to the amount of milk fat, cows of the Goliath line at the age of the first and higher lactations were found to be complex stochastic systems, but at the age of the second lactation they were simple quasi-deterministic systems ($R = 0.035$ bit; $R = 0.009$ bit and $R = 0.137$ bit). This confirms the opinion that cows with age can sustainably and for rather a long period of time maintain a high productivity potential.

Similar works were also carried out by a number of scientists R. Fan *et al.* (2011), F.V. Lishout *et al.* (2013), M.D. Ritchie & K.V. Steen (2018), who used empirical data using entropy analysis to identify interactions between genes and the features they cause. The correlation between indicators of milk productivity and genes associated with it was studied by H. Dehghanzadeh *et al.* (2020). As a result of research of metabolic pathways of genes based on gene annotations, it was found that the proposed clustering method gives correct, logical and fast results.

A. Borowska *et al.* (2018) used information theory as an alternative statistical approach to identify sections of the genome and candidate genes associated with economically useful livestock traits. The results of the study showed that important sections of the genome and candidate genes that determine variable qualities of bull sperm are located on several chromosomes. The scientists proved the validity of the influence of Single Nucleotide Polymorphism (SNP) on some variable quality of Holstein-Friesian bulls by means of entropy analysis.

Basing on entropy, scientists O. Fukuda *et al.* (2013) built a Radial basis function (RBF) neural network model to predict the live weight of pigs based on the growth parameters of Landrace sows. The results showed that the modeling method based on the RBF neural network using entropy analysis was an effective way to build a pig live weight prediction model. Entropy eliminated the collinearity of the independent variables in the linear regression analysis and predicted pig live weight better than the linear regression model.

E. Karatieieva *et al.* (2021) confirmed that animals with a high level of order of systems by live weight will, accordingly, have a high level of order of systems represented by the main indicators of milk productivity. The expediency of using information theory is also confirmed by M.S. Kwon *et al.* (2014), they prove that the use of entropy analysis of gene interaction (GGI) can reveal a large part of the obscure heritability of complex traits.

Thus, the obtained results make it possible to state that the use of information theory in breeding work with animals can be used as an additional indicator of their evaluation according to the main economically useful characteristics, in particular, their milk productivity. It will allow to get a more accurate and complete assessment and to predict their future milk productivity even in the early stages of development.

CONCLUSIONS

Processes influencing the degree of determinism of the system of productive qualities of cows of different lineal affiliations depending on their age were studied. It was established that the actual degree of values of unconditional and conditional entropy shows the result of combinative variability between polygenes and the traits they control, and the change of the traits themselves in the process of ontogenesis is the effect of gene expression and their interaction with environmental factors. Thus, the calculations of entropy and information analysis demonstrate that Black-and-White cattle, in relation to the importance of the organization of biological systems, which were represented by the main traits of milk productivity, do not have an unambiguous level of manifestation of their organization. Wave-like dynamics of the level of unconditional entropy were observed for the studied cows, that is, it sometimes decreased, then increased, depending on certain characteristics, such as milk yield and the amount of milk fat. At the time when the fat content in milk showed a gradual decrease in the level of unconditional entropy, which can be caused by selection and breeding work and the effect of stabilizing selection in the herd. At the same time, no dependence was found between the origin of the cows and indicators of their orderliness or disorganization. That is, the entropy analysis did not confirm the influence of the hereditary factor – the origin of cows on the level of their organization of the system. At the same time, the studied animals, according to the main characteristics of selection, both in terms of age and in terms of lineal affiliation, are not of the same type and uniform. According to the degree of organization of the system, they belong to different classification groups: stochastic, quasi-deterministic, deterministic, simple and complex, this indicates a high degree of variability in this herd. This, in turn, is a good indicator, as the studied herd has a high potential and reserve, both for increasing the level of milk productivity and for further breeding work with this herd. Entropy and information analysis will be used for the comprehensive assessment of this herd in the future in order to investigate the influence of paratypic reproductive qualities, such as the age of first insemination and calving season on indicators of milk productivity. They are essential factors in the formation of breeding traits and they have a probable influence on the level of productive qualities.

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CONFLICT OF INTEREST

None.

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Використання ентропійно-інформаційного аналізу для оцінки молочної продуктивності корів чорно-рябої молочної породи залежно від їх лінійної приналежності

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Анотація. В сучасних реаліях важливе місце для ефективного ведення галузі скотарства є вірно здійснений селекційно-племінний процес з відбором корів, які відмічаються найвищими показниками сукупності продуктивних якостей. В даному випадку застосування ентропійно-інформаційного аналізу є одним із найбільш доцільних, оскільки дає можливість оцінити господарсько корисні якості тварин максимально повно. Мета дослідження полягає в оцінці та аналізі міри організованості біологічної системи продуктивних ознак молочної худоби під впливом спадкових факторів, таких як вік та походження корів. В ході дослідження були використані загальноприйняті в зоотехнії методики та методи з використанням інформаційно-ентропійного аналізу, які адаптовані та модифіковані у тваринництві. Одержані дані з проведення ентропійно-інформаційного аналізу демонструють, що для великої рогатої худоби чорно-рябої породи різної лінійної належності рівень організованості систем коливається – R від 0,009 до 1,341 біт. При чому, найбільш стабільною ознакою, з точки зору мінливості, виявився вміст жиру в молоці, рівень безумовної ентропії у розрізі лактацій дорівнював 3,333-4,550 біт, що вказує на менший вплив дезорганізованих факторів на рівень прояву даної ознаки, а більшу її залежність від спадкових чинників, тобто походження. Хоча в цілому достовірного впливу лінійної належності корів на показники безумовної ентропії та організованості системи не встановлено, але спостерігався вплив вікового фактора на показники ентропії. Таким чином, досліджуване поголів'я за основними селекційними ознаками, за виключенням вмісту жиру в молоці, не характеризується одноманітністю та консолідованістю, що вказує на широкий діапазон мінливості і слугує пластичним матеріалом як для селекційно-племінної роботи, так і для підвищення рівня молочної продуктивності. Використання емпіричних даних теорії інформації може бути своєрідним маркером при прогнозуванні спадкових ознак тієї чи іншої продуктивності, оскільки, ентропійно-інформаційний аналіз надає більш ширші та глибші значення мінливості ознаки

Ключові слова: теорія інформації; надій; вміст жиру в молоці; ентропія; організованість системи; міра хаосу

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Analysis of biogas production and prospects for the development of biogas technologies in Ukraine

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Abstract. The relevance of this study is determined by the fact that over the years the trend of finding new types of raw materials and technologies for their processing into biogas is growing rapidly. Not only people in European countries but all over the world tend towards the advantages of its production. For Ukraine, the development of infrastructure and a detailed study of this industry will later become a necessary stimulus for the reconstruction of the economy in the post-war period. The aim of the work is to analyze the biomass potential of fallen leaves for biogas production, taking into account the possibilities of technological development of this field in Ukraine. Several methods and approaches were used to achieve the goal. In particular, the physicochemical basis of the process of anaerobic fermentation of organic matter to obtain biogas was studied. A mathematical model of the process of obtaining biogas in a reactor from fallen leaves was also developed. And at the very end, the calculation of the economic efficiency of using a biogas plant for utilization of fallen leaves in a bioreactor was carried out. Summarizing the main results, it is possible to highlight the development of the patent-protected design of the bioreactor, the engineering methodology and the mathematical model for calculating the methane tank for the production of biogas from fallen leaves. First of all, the potential of biomass of plant origin for biogas production was analyzed and this led to the conclusion that the use of fallen leaves is a promising direction, but the significant advantages of using the raw material base are ignored. One of the main environmental problems of Ukraine remains the utilization of fallen leaves and other organic matter of plant origin. At the same time, the conducted research produces not only a number of solutions to this issue, but also turns the problem into an economically profitable solution and eliminates all ecologically unjustified processing methods

Keywords: gas holder; anaerobic fermentation; organic waste; raw materials; bioreactor

INTRODUCTION

The study of biogas technologies will create a powerful stimulus for the entire civilized world in the transition to renewable energy sources, since the production of biogas consists in processing waste of organic origin. At the same time, the entire raw material base is quite diverse and under normal conditions is absolutely not

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involved, and when decomposed in the usual environment, it has a negative environmental impact. Unlike exhaustible sources such as oil or coal, the use of agricultural waste, food waste and wastewater will contribute to the transition to a more sustainable energy sector.

The utilization of organic waste and its successful processing will allow solving a number of environmental issues closely related to global warming, the manifestations of which are increasingly being observed on the planet. First of all, the active use and installation of biogas plants will contribute to the reduction of greenhouse gas emissions, namely methane. This malignant formation is observed during the natural decomposition of organic materials. The use of biogas technologies that capture and use methane can significantly reduce its emissions into the atmosphere, helping to reduce the greenhouse effect. On the other hand, the development of such technologies makes it possible to use organic waste effectively, which earlier would simply have been thrown away or subjected to a long process of natural decomposition. Instead, organic matter can be turned into a valuable resource – biogas and organic fertilizers. This helps to reduce waste, improve the management of agricultural waste and ensure sustainable development.

The analysis of the latest publications, which have already dealt with the research of similar aspects in this field, helped to understand the topic better, as well as to find problems that require additional and more thorough study. A publication by N. Pryshliak (2019) notes that India has an important place in the research, development and propagation of renewable energy technologies. Biogas production turned out to be a promising technology for processing agricultural waste into energy, including livestock, industrial and municipal waste. In 2017, gas consumption by the population of Ukraine amounted to 11.2 billion m^3, while the potential value of biogas production from livestock waste is 1.5 billion m^3 (13% of all consumed by the population).

According to Y. Gontaruk (2022), given Ukraine's negative trade balance and the country's great potential in the agricultural sector, the situation can be improved by focusing on the production of biogas from agricultural waste. One of the main producers of biogas can be sugar factories, the production of which can be restructured by building biogas plants. If the by-products of sugar mills are fully processed, they could produce about 790 million m^3 based on their capacity in 2020, resulting in 473.7 million m^3 of biomethane. This would make it possible to reduce the import of natural gas and provide sugar factories with their own source of energy.

According to L. Sakun *et al.* (2020), the most productive types of raw materials for biogas power plants are waste from farms and agricultural enterprises (silage, pulp, manure, litterfall, etc.), wastewater and household waste from landfills. Ukraine has great potential due to high rates of development and low saturation of the agricultural market, which is the main source of bioenergy raw materials.

As noted by D. Tokarchuk *et al.* (2020), the use of biogas plants in Ukraine is effective for solving the problems of waste utilization, including crop production, improving the ecological situation, increasing soil fertility, reducing energy dependence and developing the economy locally. In addition, there is a significant group of raw materials in the perspective of application for biogas production, consisting of fresh grass, beet leaves, grass silage, corn and cereals, the output part of methane from which is from 270 to 330 l/kg.

Publication of M.K. Devi *et al.* (2022) is devoted to a review of recent advances in biogas production using agro-industrial waste. The work considers technical and economic aspects of this process. Biogas produced from agro-industrial waste can reduce greenhouse gas emissions, cumulative energy demand and environmental problems. During biogas production, some additives are added to the reactor to improve the biogas production process.

European scientists A. Sobczak *et al.* (2022) considered the economic conditions for biogas production on the example of Poland and Germany. Agricultural biogas plants that have been built in Western Europe, particularly in Germany, for over 20 years have been designed to use substrates derived from crops, mainly corn. Today, the trends have changed — the price of technologies that allow gas production mainly from agro-food industry waste is high. In general, the new plants will be more modern and better meet the objectives of the environmental policy of the European Union.

The purpose of this work was to study the peculiarities of the utilization of fallen tree leaves and the production of biogas from them as an alternative source of energy, as well as the development of the necessary technologies for the successful distribution of individual biogas equipment within Ukraine.

MATERIALS AND METHODS

The methodological basis of the researched topic was the application of theoretical and experimental regularities in the biochemical processes of anaerobic fermentation. During the multi-stage process of fermentation of organic compounds, the gradual destruction of carbon bonds occurs due to interaction with various groups of microorganisms.

In the process of biogas production research, an important aspect is the study of the materials involved in the researched object. That is why, for a deeper analysis, a comparison of the components of different types of organic waste was carried out, which will eventually become the necessary raw material base for the production of an alternative source of energy, namely, biogas. In particular, raw materials collected on the basis of farm waste, vegetation residues, animal manure, as well as other organic products in the form of fallen leaves, grass, and sawdust were considered. A biogas plant was described as a research object for a complete technological review. The type of plant is based on the anaerobic fermentation process, which takes place in a special reactor. An anaerobic reactor looks like a closed container in which optimal conditions are created for the decomposition of organic substances by microorganisms without air access. After the fermentation process, biogas, consisting mainly of methane and carbon dioxide, is collected in the reactor and fed to the collection system, where it is stored in special containers, gas holders, where it can be used later for energy production or other purposes.

The following theoretical methods of scientific knowledge were used in this study of biogas: analysis of theoretical models, system analysis, optimization methods, kinetic modeling, genomic sequencing, gas chromatography and thermodynamic modeling. While analyzing various theoretical models, it was possible to get an idea of the processes taking place in biogas plants. At the same time, for more accurate results, mathematical models, physico-chemical calculations and analytical methods were applied. System analysis made it possible to investigate production processes from the point of view of energy and mass balance, as well as to evaluate the efficiency of the system and the relationships between components. Its application included energy and mass balance analysis, as well as evaluation of the system's efficiency and the interconnections between its various components. The optimization method for process parameters is used to derive the optimal operating mode and maximize biogas production. Kinetic modeling helps to predict the speed and efficiency of biological processes depending on the studied parameters. In this study, it was involved in the development of mathematical models that essentially described the kinetics of biological processes, namely fermentation and methanogenesis in biogas plants. Genome sequencing allows studying microorganisms involved in the biogas process. Thanks to this method, it was possible to identify and categorize microbial communities and investigate their functional role in the biogas process. Gas chromatography (GCh) was used to analyze the composition of biogas and control the quality of production. In this work, the content of the following gases was investigated: methane, carbon dioxide, hydrogen. Thermodynamic modeling using thermodynamic models helped to study the thermal parameters and energy efficiency of biogas plants, as well as the conditions of optimal heat balance in biogas plants.

RESULTS

The key point affecting the rate of anaerobic fermentation is the conversion of acetic acid into methane during the decomposition of polymer-containing waste, which is limited to the hydrolysis stage. Figure 1 shows a scheme of methanogenesis, which shows the decomposition of organic substances.

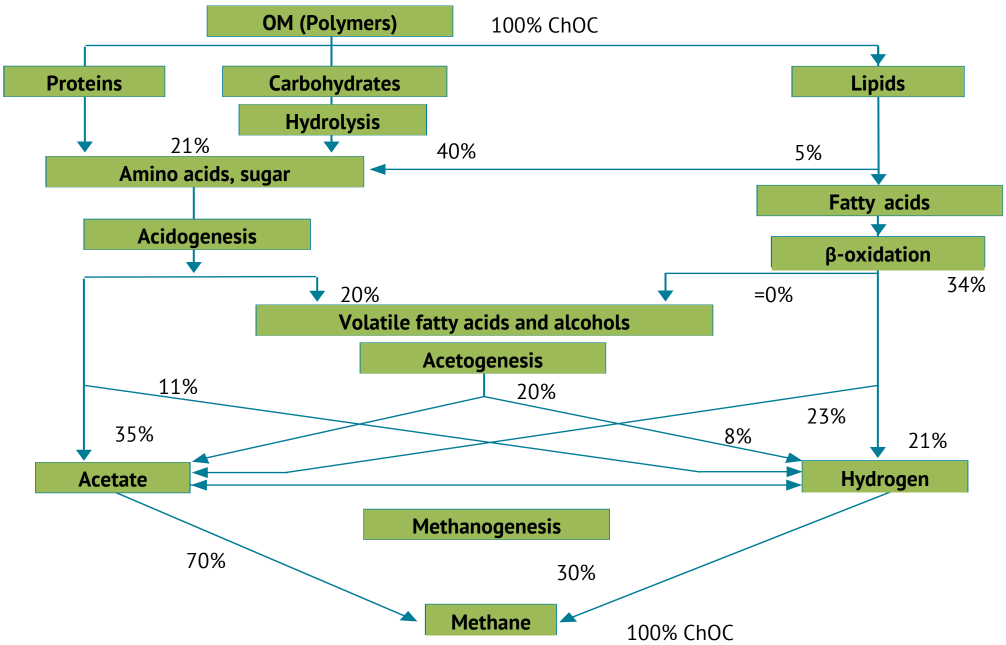

Figure 1. *Complete scheme of methanogenesis*

Note: *ChOC – chemical oxygen consumption*
Source: *developed by the authors*

To carry out the entire complex process of transformations, hundreds of types of microorganisms are involved, while the main role remains for bacteria. The quantitative and qualitative composition of microflora largely depends on the composition of fermented organic matter and environmental conditions. However, hydrolytic, fermentative, synthetic and methanogenic microflora predominate, which successively carry out the above-mentioned stages of anaerobic fermentation. In the course of studies of this process and design of plant models, empirical models of the process based on microbial kinetics and equations of the homeostat theory are used.

The Mono model is considered one of the most famous. It reflects the specific growth rate of microorganisms and the half-life of organic matter, which depend on many conditions of the fermentation process (1):

$$\frac{dx}{dl} = \frac{P_{max} \cdot X \cdot L}{K_1 + L};\ \frac{dl}{dt} = \frac{-P_{max} \cdot X \cdot L}{y(K_d + L)}, \quad (1)$$

where $y = dx/dt$ – mass conversion coefficient into biomaterial; dx/dl – growth of microorganisms, day^{-1}; X – microbial population density, kg/m^3; L – saturation of the substrate, kg/m; dl/dt – change in biomass density, day^{-1}; P_{max} – the highest rate of reproduction of microorganisms, day^{-1}; K_1 – the half-saturation threshold of the substrate concentration, at which the rate of the process reaches half the maximum level; K_d – indicator of biomaterial decomposition.

This model has limitations in working with different types of substrates. Another attempt to mathematically describe the process of methane fermentation is the model presented by Muyang (2):

$$P = \frac{L}{1 + 10^{(pK - pH)}} \cdot \left(\alpha - \beta \frac{K_\tau}{1 + K_\tau}\right), \frac{\text{Нм}^3}{\text{м}^3}, \quad (2)$$

where P – specific rate of biogas removal; L – list of initial organic compounds, kg; K_τ – period of complete interchange of initial material, day; α, β – coefficients that depend on the nature of the carbohydrate component, the type of substrates and the content of organic nitrogen in the waste; pK and pH – constants, depending on the temperature regime, day^{-1}.

The above Muyang model demonstrates the influence of the organic composition of the original substrate on the intensity of the fermentation process by distinguishing between the hydrocarbon fraction and the content of organic nitrogen compounds. For a wider class of input substrates, taking into account the volume rate of biogas and essential parameters of the methane fermentation process, the Kanto model (3) is used:

$$V = \frac{B_0 \cdot S}{T}\left(1 - \frac{K}{\mu \cdot T - 1 + K}\right), \frac{\text{Нм}^3}{\text{м}^3}, \quad (3)$$

where V – speed of the output volume of biogas, m^3/(m^3·day); B_o – the maximum amount of biogas release from a unit of organic matter of the established composition after an infinite duration of exposure, m^3/kg; S – concentration of organic matter in the source material, kg/m; T – exposure time, day; μ – the greatest growth of microorganisms during the fermentation process, day^{-1}; K – kinetics.

The highest growth of microorganisms (μ) is described by a linear dependence of temperature values from 30 to 60°C. In his research, Hashimoto derived an empirical formula that describes the dependence of the process temperature on the kinetic parameter K and the exposure time in regimes involving tolerant (T = 45°C) and thermophilic (T = 60°C) regimes (4):

$$K = [-0.95 - 0.51 + 0.01(T) + 0.0004(T2)]. \quad (4)$$

The calculation of biogas yield according to the Hashimoto model can be determined by formula (5):

$$\gamma \cdot V_{max} = \frac{B_0 \cdot S_0 \cdot M_n}{(1 + \sqrt{K})^2}, \quad (5)$$

where K – kinetic parameter; B_0 – the maximum output of biogas from a single given organic substance under the condition of an infinite exposure index, m^3/kg; S_o – initial content of organic matter in biomass, kg/m; M_n – growth rate of microorganisms in a given fermentation process, day^{-1}.

Then, in the initial substrate, the dependence of the values of the kinetic parameter on the concentrations of organic matter is described as follows (6):

$$K = 0.5 + 0.03\exp\ (0.058). \quad (6)$$

The balance of bacteria in the fermented substrate (7):

$$\frac{dx}{dt} = \mu \cdot x - D \cdot x, \quad (7)$$

where x – bacterial density, kg/m^3; D – rate of dying, day^{-1}; μ – rapid growth, day^{-1}.

In his work, Hill expanded the Kanto model by adding the coefficient K, which takes into account the loss of microorganisms in the fermentation process (8):

$$\gamma \cdot V = \frac{B_0 \cdot S_0}{\theta}\left[1 - \frac{K(1 + K_d \cdot \theta)}{\theta \cdot \mu - (1 - K\Delta\theta) - (1 - K)}\right], \quad (8)$$

where θ – time of exposure of the substrate in the methane tank; $\theta = \frac{V}{VS}$. The loading speed of the methane tank with organic matter is indicated $\frac{V}{VS}$, where VS – the period of obtaining volatile solids from the farm, which depends on the number of animals and their diet; V – methane tank capacity.

In the above mathematical models of anaerobic fermentation, there is a mathematical parameter S, which indicates the concentration of organic matter in the source material and gives the values of empirical coefficients that take into account individual cases of biogas extraction from the components of the source substance.

Empirical engineering and mathematical models are most often used in the production of biogas, provided that regression dependencies are derived taking into account the characteristics of a certain type of biomass. Therefore, when using these models, it is advisable to conduct experiments to determine empirical coefficients.

In order to implement the process of processing waste into gas inside the biogas plant, several important measures must be taken. First, it is necessary to ensure the access of nutrients to the bacteria, constant oxygen-free and temperature conditions, the correct ratio of solid particles in the substance and high-quality mixing. Secondly, monitor the ratio of carbon and nitrogen in the mass, the fermentation time and timely loading and unloading of raw materials, as well as the absence of inhibitor substances in the content.

During the multi-stage fermentation process of methanogenesis, the destruction of carbon bonds occurs. Various groups of microorganisms contribute to this, so the biogas production process is carried out in four stages:

- the stage at which complex molecules of biopolymers (proteins, lipids, polysaccharides) are hydrolyzed to simpler monomers (amino acids, carbohydrates, fatty acids);
- the stage at which the resulting monomers undergo fermentation to simpler substances, such as lower acids and alcohols, with the formation of carbon dioxide and hydrogen;
- acetic acid production stage: acid, hydrogen and carbon dioxide are produced, which in turn are direct precursors of methane;
- stage of methanogenesis: the decomposition of complex organic substances with the formation of methane as the final product (Abbasi *et al.*, 2012).

Anaerobic fermentation for the production of biogas is a complex biotechnological process, which requires interaction and fulfillment of the following conditions for the effective course of methane fermentation of organic substances: the appropriate temperature regime of the process; weak alkaline reaction of the environment; the presence of methane-forming bacteria; oxygen-free environment.

One of the important factors of an effective fermentation process is the temperature regime of the fermenting biomass. The natural release of biogas takes place at a temperature from 0°C to 98°C, taking into account the process of optimized processing of organic substances for the purpose of removing biogas and biofertilizer while maintaining three temperature regimes: psychrophilic (20-25°C); mesophilic temperature regime (25-40°C); thermophilic temperature regime (more than 40°C) (Mao *et al.*, 2015).

Depending on the selected mode, for a high-quality fermentation process in the bioreactor, the same temperature level should be maintained and biomass should be regularly mixed. Also, when choosing a thermophilic mode, it is worth considering its significant advantages compared to others – with accelerated decomposition of raw materials, the complete destruction of disease-causing bacteria, as well as obtaining a larger amount of biogas at the output. Disadvantages include high energy consumption, initial low-quality biofertilizer, and significant sensitivity to minimal temperature changes. Due to these negative factors, a mesophilic temperature range is used for European fermentation chambers.

Another important factor in methane fermentation is the dependence of the content of raw materials between nitrogen and carbon. A lack of nitrogen and an excessive indicator of the C/N ratio will lead to limitations in the process of methane formation (Table 1). At the same time, a small indicator of the mentioned ratio, in turn, will lead to the formation of a large amount of ammonia, which is toxic to bacteria. Experiments have shown that the level of the ratio of carbon and nitrogen from 10 to 20 (depending on the origin of the raw materials) stimulates to achieve the highest degree of gas formation (Kougias *et al.*, 2014).

Table 1. *C/N ratio of organic waste that can be a raw material for obtaining biogas*

Raw material for biogas	Nitrogen, %	The ratio of carbon to nitrogen, C/N
	Animal manure	
Cattle	1.7; 1.8	16-25
Chicken	4-6	7-10
Horse	2	25
Swine	4	6-12
Sheep	4	33
	Household waste	
Feces	6-7	6-10

Table 1, Continued

Raw material for biogas	Nitrogen, %	The ratio of carbon to nitrogen, C/N
	Household waste	
Kitchen waste	2	29
Potato peels	1.5	25
Cabbage	4	13
Tomatoes	3	13
	Vegetation waste	
Corn cobs	1	57
Cereal straw	1.0	50
Wheat straw	0.5	100-150
Corn straw	0.7	51
Oat straw	ID	50
Soy	1.3	33
Alfalfa	2.8	16-17
Beet pulp	0.3-0.4	140-150
	Others	
Grass	4	13
Sawdust	0.1	200-500
Fallen leaves	1.0	50

Source: *developed by the authors based on P.G. Kougias et al. (2014)*

The process of processing organic substances into biogas is called methane fermentation. Based on anaerobic fermentation by splitting biomass with bacteria (methanogens). There are 4 types of bacteria involved in the formation of biogas (Fig. 2).

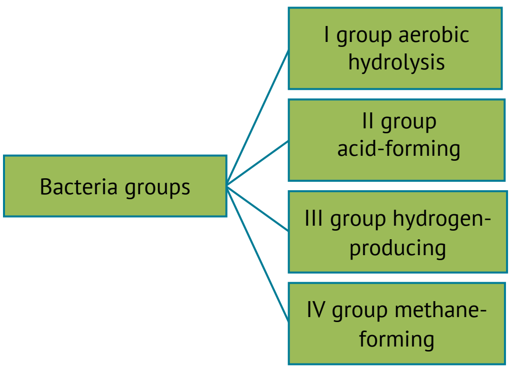

Figure 2. *Bacteria involved in the process of biogas formation*
Source: *developed by the authors*

Metabolites from all groups of bacteria provide nutrients to each subsequent group. In particular, the first group of bacteria uses enzymes to convert organic compounds (proteins, carbohydrates, and fats) into low-molecular compounds (water, fatty acids, and amino acids). Acid-forming bacteria convert these low-molecular compounds into unstable fatty acids (acetic, formic, propionic), ethanol, carbon and gases (carbon dioxide, hydrogen, hydrogen sulfide, ammonia). Hydrogen-producing bacteria are responsible for the conversion of higher fatty acids into acetic and formic acids, carbon dioxide, and hydrogen. The fourth group of bacteria (methane-forming) process acetic and formic acids into methane (Vindis *et al.*, 2009).

The process of anaerobic fermentation is accompanied by a number of biochemical reactions, and the process of biogas formation itself consists of three sequences:

I stage – hydrolysis – is the decomposition of organic substances (9):

$$(C_6H_{10}O_5)n + nH_2O = nC_6H_{12}O_6; \quad (9)$$

II stage – acetonogenesis – is the reproduction of acid-forming bacteria (10):

$$6H_{12}O_6 + 2CH_2O = 2CH_3COOH + 4H_2 + 2CO_2; \quad (10)$$

III stage – methanogenesis – is the reproduction of methane-forming bacteria (11):

$$CH_3COOH = CH_4 + CO_2, 4H_2 + CO_2 = CH_4 + 2H_2O. \quad (11)$$

At the initial stage of anaerobic fermentation, hydrolytic bacteria enzymatically split polymers into low molecular weight formations. Polymers (multimolecular compounds) are converted into monomers (monomolecular). A feature of the described hydrolysis process is time-consuming and dependent on extracellular enzymes, namely protease, amylase and lipase. In the bioreactor, hydrolysis is also influenced by the potential of hydrogen ions.

At the stage of acetogenesis, acid-forming bacteria are engaged in splitting. This stage of methane fermentation is called oxidation, during which the potential of hydrogen ions decreases. Individual molecules penetrate into the bacterial cell and continue to split there. Aerobic bacteria partially participate in this process by consuming residual oxygen to create the anaerobic conditions necessary for methanogenic bacteria, some of which become anaerobic. At this stage, such gases as unstable fatty acids (acetic, formic, butyric, propionic), low-molecular alcohols (ethanol, methanol), carbon, carbon dioxide, hydrogen, hydrogen sulfide, and ammonia are formed. In addition, hydrogen-producing bacteria utilize organic fatty acids to produce acetic, formic acids, carbon dioxide, and hydrogen for methanogenesis. Such bacteria are very sensitive to temperature, as they reduce the amount of carbon (as part of organic acids) (Bacenetti *et al.*, 2013).

The last stage of methane production by methanogenic bacteria involves splitting into carbon dioxide and water from formic and acetic acids, hydrogen and carbon. At this stage, 90 percent of all methane is formed, while only 70% is produced from acetic acid. It should be noted that methane-forming bacteria are exclusively anaerobic. Thus, the process of anaerobic fermentation is influenced by four factors:

- biological (the composition of the fermented mass, the composition of the microflora, the living conditions of organisms);
- physical (fermentation temperature, biogas plant pressure, hydraulics);
- chemical (concentration, acidity of the environment, volume and composition of the formed biogas);
- organizational and technological (volume of loading biomass, residual substances).

Modern biogas plants consist of the following main elements:

- system of preparation and supply of raw materials to the bioreactor;
- bioreactor with raw material mixing and heating systems;
- system of unloading and transportation of fermented waste;
- biogas storage and use system (Meyer *et al.*, 2018).

The main unit of a bioenergy plant for biogas production is a methane tank (bioreactor). The main requirements of methane tanks include: technological, hydraulic, thermal and economic. The main criteria when choosing a bioreactor design are the possibility of its practical application, economic feasibility and convenience of its maintenance and operation. As of 2023, the market offers a variety of bioreactors by design. The classification of methane tanks is shown in Figure 3.

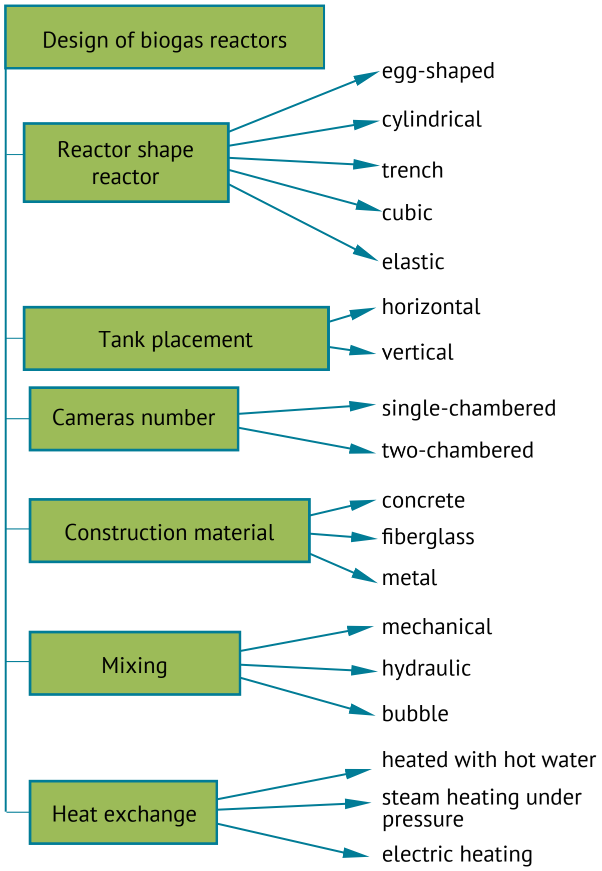

Figure 3. *Classification of biogas reactors by structural features*
Source: *developed by the authors*

A biogas plant is a complex of constructions and technical support combined into an autonomous process of anaerobic fermentation for the production of biogas. It can be installed both indoors and outdoors, fixing it with a foundation or the ground. Essential requirements for its structure are compliance with hermeticity and corrosion resistance, the installation of a hatch in the model is provided for.

Biogas complexes can be divided into one- and two-staged. The first ones are more common and basic, because they are suitable for many substrates. The second ones are more complicated due to an additional hydrolysis reactor. They are used for rapidly decomposing working material that is easily oxidized (Tabatabaei & Ghanavati, 2018). The basic equipment of the biogas plant is shown in Figure 4, and a detailed description of the depicted construction nodes is given below.

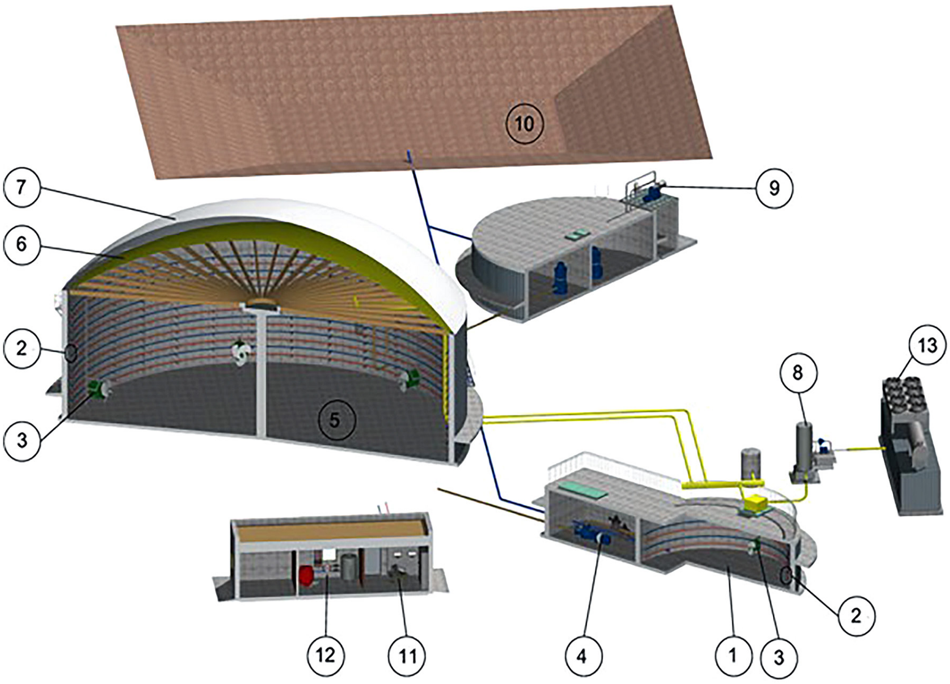

Figure 4. *Structure of the biogas plant*
Notes: *1 – receiving container; 2 – heating system; 3 – mechanical stirrers; 4 – biomass supply system; 5 – fermenter; 6 – gas holder; 7 – dome; 8 – gas removal and gas supply system with condensate removal and sulfur purification system; 9 – separator; 10 – liquid fertilizer storage tank; 11 – automation system, visualization of processes and management; 12 – heating point; 13 – generator*
Source: *developed by the authors*

Maximum automation and minimum manual work is the basic principle of this installation. The material for reducing the volume to be processed enters the receiving container (1). This container is used for pre-settling, heating (2) and thorough mixing (3). The raw material is fed to the fermenter (5) several times a day. The fermenter (5) is a sealed, gas-tight tank. To maintain a stable temperature, the inside of the methane tank is equipped with a heating system (2). In the cold season, the bioreactor is insulated from the outside to prevent heat loss. Continuous mixing of the substrates using a low-speed mechanical stirrer (3) ensures complete and thorough mixing of the raw materials. Physicomechanical methods applied to substrates use different types of mixing systems, such as mechanical, hydraulic or pneumatic.

Fermented substrate is automatically discharged as often as it is fed. The operation process of the biogas plant is generally controlled by an automation system (11). The produced biogas is collected and stored in a gas holder (6). They are used as a gas-tight element for the fermenter, which serves as a gas storage tank. The outer dome roof (7) is UV resistant, fire resistant and easily scalable. The design of the biogas plant ensures high flexibility of this element and reliable fixation of the plant. Biogas is transported through the pipeline (8), which is equipped with an automatic condensate drain and a safety device that protects the gas holder (6) from exceeding the allowable pressure. The gas holder (6) continuously supplies biogas to the cogeneration plant or the biogas preparation plant. Then the processed substrate is fed to the separator (9). The mechanical separator works 4-6 times a day to separate the fermentation residues into solid and liquid fertilizers. All equipment is controlled by the automation system (11). The design of the biogas plant minimizes the need for manpower during operation. The heating point (12) in the biogas plant helps ensure energy-efficient use of biogas, which is a renewable energy source. It allows you to make the most of the potential of biogas by converting it into thermal energy. The generator (13) is designed to convert the mechanical energy obtained from the movement of the engine into electrical energy. In a biogas plant, a generator uses biogas as a fuel to drive an engine that rotates the generator and produces electricity (Misak *et al.*, 2014).

Signals regulating the operation of the entire plant are sent to the central programmed logic controller. The controller regularly polls all elements of the combined technological chain and displays the information on the monitor screen. All constructions and components, as well as drives and parameter sensors are displayed on the monitor screen. All operating parameters of the biogas plant are displayed on the monitor in the central control room. The control room has a central control panel, from which all parts of the biogas plant can be switched between automatic and manual modes of operation, as well as controlled locally or remotely (Geletukha *et al.*, 2013).

The analysis of the results obtained in the above-described experiment led to a number of conclusions regarding the technological aspects of biogas production. In particular, the first and most important is the correct preparation of the substrate. This stage involves the preparation of raw materials used for biogas production. This may involve dissolving, grinding or enzymatically treating the feedstock to facilitate the biogas fermentation process. Next, the substrate that has been prepared is subjected to the fermentation process. In this stage, microorganisms, such as bacteria or anaerobic fungi, decompose organic substances in the substrate and release biogas. Biogas, which is formed during fermentation, is collected and stored in special containers or tanks. It can be a gas holder or compressed gas cylinders. It should also be taken into account that biogas often requires processing and purification before use. This includes removing contaminants such as moisture, hydrogen sulfide, or other impurities that may adversely affect the quality of the gas or equipment. Well, at the very end comes the effective use of the final product. Purified biogas can be used to produce heat, electricity or in processes that require gas as a fuel. This may include the use of biogas in a boiler room for heating, a combustion plant for electricity production or use in manufacturing processes.

A general overview of the sphere of biogas production in Ukraine leads to the following conclusions. The development of biomass processing technologies for biogas production is constantly being improved. The use of highly efficient biogas plants, optimization of fermentation processes and purification of biogas allow to increase production efficiency and reduce environmental impact. The production of biogas from the biomass of fallen leaves can have significant economic benefits. This can create new workplaces, attract investment and promote the development of rural and forest areas. The use of biomass for biogas production in Ukraine can help achieve energy independence, reduce greenhouse gas emissions, and develop a sustainable energy sector.

DISCUSSION

Many scientists were engaged in the study of anaerobic fermentation and establishment of regularities for the calculation of biogas plants. However, given the chemical complexity of realizing the interaction between groups and species of bacteria and the diversity of substrate components, the laws of the methane fermentation process are extremely complex and largely unexplored. In the practice of research, the development of anaerobic fermentation technologies is based on empirical models of the process, which in turn are based on the equations of microbiological kinetics and the theory of the homeostat.

An example for the discussion of this thesis is the study of authors S. Ma *et al.* (2021), in which, using detailed sequencing of digestate samples from 56 full-scale biogas plants (BGPs) processing different feedstocks, they presented a microbial anaerobic fermentation (AF) gene catalog containing more than 22.8 million genes with attached information on their role in cellular processes. The results confirm the presence of a core microbiome in AF and show that the type of raw material (cattle manure, poultry manure, pig manure) has a significant effect on the breakdown of carbohydrates by hydrolysis, oxidation of volatile fatty acids and methane production. In addition, 2,426 genomes assembled from metagenomic data from full-scale BGPs were also provided. Compared to previously published catalogs of microbial genes from various ecosystems, including soil, marine environments, gut, and animal rumen, BGP is an artificial highly anaerobic ecosystem where AF is carried out by a complex community of anaerobic microorganisms. Therefore, their gene list not only serves as a valuable reference base for rapid analysis of microbiome data in AF, but will also provide a rich source of microbial genes for the study and use of anaerobic microbiota.

A study published by K. Pilarski *et al.* (2020), describes the process of yielding methane obtained from corn silage, pig manure, potato waste, and sugar beet pulp. An original methodology for determining the Biochemical Methane Potential Correction Coefficient (BMPCC) based on biomass conversion calculations at industrial and laboratory scales is also presented. BMPCC is a tool that can be used to increase the efficiency of biogas plants and avoid unnecessary losses. The calculated BMPCC values showed that the amount of methane produced in the laboratory was overestimated compared to the amount of methane according to specifications. Differences were observed for each substrate.

In the study of M. Fugol *et al.* (2023), the authors studied the use of enzyme additives in anaerobic fermentation and concluded that in the case of corn silage, the use of additives increased the efficiency of the adsorption process compared to the control in the range of 17 to 62%, depending on the additive used. In the case of silage, igniscum produced more biogas and grass silage showed a decrease in biogas production efficiency compared to the control (no additives) sample, but it increased methane production in corn and grass silage. It is noted that bio-additives lead to improved energy performance, but this depends on the agricultural substrates and additives used.

The work published by scientists S. O'Connor *et al.* (2021) confirms that small-scale anaerobic fermentation is a promising renewable energy technology for agriculture. Bioenergy is profitable due to the possibility of producing biofertilizers and reducing emissions into the atmosphere. Issues related to plant design, energy use, political implications and barriers were discussed. This study examines the current state of small-scale anaerobic fermentation technology in Europe, identifying process flow and performance characteristics, the impact of European Union policies, recent developments and the challenges they face.

At the same time, S. Cinar *et al.* (2022) in the course of their research concluded that process optimization is already a prerequisite for market viability in all sectors. This statement is also relevant to anaerobic fermentation in bio-plants. The benefits of using renewable energy plants can be extended by more technologically advanced and less expensive systems, with the overall goal of minimizing costs and maximizing process efficiency. With the help of data science and predictive analytics, traditional methods of process optimization and operational excellence, statistical process management can be taken to a new level. The more perfect the optimization of the process, the more transparent and more sensitive the system becomes. In the study, laboratory results were compared with several separate machine theory procedures (logistic and linear regression, K-NN, decision trees, random forests, direct vector machines (SVM and XGBoost)) to detect and predict a wide range of possible temperature fluctuations on process stability. According to measured by the accuracy of the models calculated according to the principle of the error matrix, SVM provided the best accuracy – 0.93.

Based on the conclusions made as a result of research, it can be said that the problem of producing biogas from secondary material for energy supply is urgent, that is why the works of international and Ukrainian scientists are dedicated to it. At the same time, the introduction of innovations to reduce the negative impact on the environment has not been implemented sufficiently. The methods of waste processing with electricity generation need to be optimized primarily at the regional levels. This implies a clearly expressed need for conducting additional research in this field and carrying out specific calculations of economic and environmental benefits from waste processing for the production of biogas in Ukraine and its regions.

CONCLUSIONS

The main sources of biogas production are products, plant and animal husbandry waste. As a result of the review, it was established that the problems of the rational use of animal waste were considered in many scientific works, but at the same time, due attention was not paid to the processing of plant waste, in particular, the disposal of fallen leaves and dry grass. This confirms the perspective in the use of biological leaf waste and the hypothesis that the raw material base itself is not used enough.

In autumn, an ecological problem in the cities of Ukraine is the utilization of fallen leaves. The most common methods of utilization of fallen leaves in Ukraine are: in the best case, it is unloading solid household waste at suburban landfills; at worst it is burning, which leads to atmospheric pollution (prohibited by law). Removal of leaves to landfills requires significant costs, and when burned, harmful substances are released (nitrogen oxide, carbon monoxide, benzopyrene, formaldehydes, and others). That is why it is appropriate to consider that the most acceptable solution to the problems with the utilization of fallen leaf residues is biodestruction under anaerobic conditions. Such a means of processing foliage is not only environmentally safe, but also economically justified, because the biogas formed in the process of methane fermentation can be considered an alternative source of energy, and fermentation waste can be considered a valuable biofertilizer.

The analysis of scientific and technical literature made it possible to determine the main factors affecting the process of anaerobic fermentation in the production of biogas from fallen leaves, which requires technological improvement of the equipment in order to ensure the maximum value of the final product and to substantiate the cost-effective utilization of organic waste with the production of biogas and organic fertilizers.

Having considered the modern designs of gas bioreactors, we can conclude that the main criteria for choosing a methane tank for the disposal of fallen leaves are the possibility of using it in practice, its economic feasibility and the convenience of its maintenance during operation. To obtain biogas from fallen leaves, the most optimal design is an egg-shaped bioreactor. Its shape reduces hydraulic resistance when mixing raw materials and allows you to avoid stagnant areas thanks to aerodynamic design. Optimizing the technical parameters of bioreactors will lead to the maximization of the amount of biogas from a unit volume of biomass (foliage) and will increase productivity indicators. Their formation is influenced by the system of mixing and heating the substrate. When choosing a mixing system, it is necessary to take into account its effect on the rate of methane formation and the fermentation time of biomass in the methane tank. To reduce the influence of environmental temperature fluctuations and achieve thermal stability in methane tanks, you can resort to thermal insulation of the walls of the bioreactor at the same time as heating the biomass.

The development of biogas plants in Ukraine is an important step on the way to sustainable development and the use of renewable energy sources. Work is needed to improve fermentation and gasification processes to produce more biogas from different types of organic matter. Further experiments can be aimed at optimizing the fermentation conditions, increasing the efficiency of the reactors and reducing the processing time. Another important aspect of research is the use of new types of raw materials. In experiments, it is possible to develop methods of utilization of various types of raw materials, such as agricultural waste, municipal waste and other organic materials. For each raw material, it is necessary to determine the optimal conditions for its transformation into biogas and to investigate the effectiveness of this process. It is also possible to focus on the development of effective systems for waste management and monitoring of gas emissions from biogas plants, including methods of removing hazardous substances. It is important to conduct an evaluation analysis of costs for biogas production and develop business models and financing strategies. In addition, such research can contribute to political support and regulation of the development of biogas plants. Focusing on the development of effective mechanisms will stimulate development in the biogas industry, in particular, it will have an impact on tax incentives, support for government programs and development strategies. It is expected that these areas of research will contribute to the further development of biogas plants in Ukraine, providing a sustainable source of energy, reducing greenhouse gas emissions, and promoting the country's economic development.

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CONFLICT OF INTEREST

None.

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Аналіз виробництва біогазу та перспективи розвитку біогазових технологій в Україні

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Анотація. Актуальність цього дослідження зумовлена тим, що з роками тенденція пошуку нових видів сировини і технологій для їх переробки в біогаз стрімко зростає. До переваг у його виробництві схиляються не лише в європейських країнах, а й у всесвітніх масштабах. Для України розвиток інфраструктури та детальне дослідження цієї галузі згодом стане необхідним стимулом для відбудови економіки в післявоєнний час. Метою роботи є проведення аналізу потенціалу біомаси опалого листя для виробництва біогазу, враховуючи можливості технологічного розвитку даної сфери в Україні. Для досягнення поставленої мети застосовано кілька методів та підходів. Зокрема, було вивчено фізико-хімічні основи процесу анаеробного бродіння органіки для отримання біогазу. Також здійснювалася розробка математичної моделі процесу отримання біогазу в реакторі з опалого листя. І на сам кінець, проведено розрахунок економічної ефективності застосування біогазової установки для утилізації опалого листя в біореакторі. Підсумовуючи основні результати, можна виділити розробку патентно захищеної конструкції біореактора, інженерної методики та математичної моделі розрахунку метантанку для виробництва біогазу з опалого листя. Передусім було проаналізовано потенціал біомаси рослинного походження для виробництва біогазу і це привело до висновку, що застосування опалого листя є перспективним напрямком, проте значні переваги використання сировинної бази ігноруються. Однією з основних екологічних проблем української держави залишається утилізація опалого листя та іншої органіки рослинного походження. В той же час, проведене дослідження продукує не лише ряд вирішень цього питання, а й перетворює проблему на економічно вигідне рішення і нівелює всі екологічно не виправдані методи переробки

Ключові слова: газгольдер; анаеробне бродіння; органічні відходи; сировина; біореактор

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