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Morphology, organo- and histometric features of the heart and lungs of a sexually mature domestic dog (*Canis Lupus Familiaris* L., 1758)

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Abstract. The cardiovascular system and respiratory organs in animals are interconnected, they perform extremely important functions for the vital activity of the organism, the main of which is gas exchange. Therefore, the study of the cardiovascular system and respiratory organs is an urgent issue of the present. The aim of the study was to morphologically evaluate the macro- and histological structures of the heart and lungs of the domestic dog. Comprehensive morphological methods of research were used: histological, anatomical, organ, histo-, cytometric, and statistical, which provided new

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data on the peculiarities of macro-, histo-, and cytomorphometric characteristics of the morphological structures of the heart and lungs. The dog heart has a rounded shape, its absolute weight is 167.58 ± 9.46 g (without epicardial fat – 154.22 ± 8.04 g), relative weight – $0.72 \pm 0.005\%$. It was found that cardiomyocytes of the left ventricle had the largest volume, the right ventricle – the smallest, and atrial cardiomyocytes – the smallest. At the same time, the nuclear-cytoplasmic ratio of cardiomyocytes of the left ventricle is 0.0224 ± 0.0076 , the cardiomyocytes of the right ventricle have a greater value – 0.0275 ± 0.0081 and the atrial cardiomyocytes have the highest value – 0.0367 ± 0.0105 . Such ambiguous cytometric parameters of cardiomyocytes are associated with the morphological and functional activity of the myocardial ventricular muscle tissue and its functional features inherent in spontaneous and rhythmic contractions, which result in blood flow through a closed system of vessels. The absolute weight of the domestic dog's lungs is 201.3 ± 18.4 g, the relative weight is $1.21 \pm 0.14\%$, the ratio of the absolute weight of the left to the right lung is 1:1.33. According to the asymmetry coefficient (1.37:1), the lungs of dogs are of the narrowed-elongated type. The connective tissue stroma of the lungs occupies $59.62 \pm 3.4\%$, the respiratory part – $40.38 \pm 2.6\%$. The data on the morphology of the heart and lungs of the domestic dog, including the results of the study of the macro- and microscopic structure of the organs under investigation, which are presented in the publication, are of great importance for histology and comparative anatomy, and also make a significant contribution to clinical veterinary medicine

Keywords: comparative anatomy; histostructure of organs; cytometric parameters; cardiomyocytes; myofibrils; bronchial tree; alveolar tree

INTRODUCTION

The cardiovascular system and respiratory apparatus in mammals perform vital functions, ensuring the vital activity of the animal and human body. They are among the first to respond to various natural and anthropogenic environmental factors and to physical activity. These are phylogenetically interconnected organs whose morphological and functional activities are closely interconnected with the environment, thus forming a single "morphological and functional complex": organism (organ system) ↔ environment (Sarah *et al.*, 2020). The main function of such a complex, multifunctional "complex" is to ensure gas exchange in the human and animal body through the process of inhaling air from the environment and excretion of CO_2 already formed in the body. At the same time, the response of the mammalian body to environmental factors occurs during the normal functioning of all its organs and systems, including the cardiovascular system, respiratory system and nervous system, which transforms them into a single whole. Therefore, an important priority area in veterinary medicine to prevent the emergence and spread of diseases of various geneses is the prevention of contagious and non-contagious pathologies, which, along with organizational and preventive measures, requires in-depth fundamental morphological studies of the animal body, its macro- and microscopic structure, including the cardiovascular system and respiratory organs.

The assessment of the functional state of the respiratory and cardiovascular systems is of great importance in clinical practice. Knowledge of respiratory and cardiac function is important for making a diagnosis, determining the severity of the disease, and choosing an effective treatment. According to B. Bi & G. Zhang (2021), in the process of mammalian phylogenetic development, a morphological and functional pattern of continuous combination and interdependence of all

anatomical structures and their functions has historically been formed, especially between the respiratory system and the cardiovascular system, which exchanges gases between the environment and the blood of the animal body. It is this close relationship, formed in mammals in the course of their evolutionary development, between the structure and functions of the cardiovascular system (its closed system of large and small blood vessels) and the respiratory organs (their unique structure of the aerogeometric barrier of the lung alveoli), which are coordinated by the nervous system, that ensures the joint vital function of gas exchange (respiration) in the animal body with the external environment, as evidenced by the work of O. Voloshyn *et al.* (2020). At the same time, despite the implementation of preventive measures against diseases of the cardiovascular and respiratory systems in animals, according to S. Manickavel (2021), there is a significant increase in the number of diseases of these organ systems of various aetiologies. According to M. Günthel *et al.* (2018), prevention, diagnosis, surgery, and treatment of these pathologies are impossible without knowledge of the morphological and functional parameters of anatomy, histology, and physiology.

According to N. Cesarovic *et al.* (2020), the cardiovascular system, with the heart as its central organ, is extremely important in the physiological regulation of all body systems. Thus, according to studies by G. Liu & R. Summer (2019), it is the dominant system in providing respiratory, trophic and excretory functions, which ensures metabolism. Due to this structure of the cardiovascular system, it forms an important and basic link in the large (somatic) and small (pulmonary) circulation. According to I. Vyshnyvetsky *et al.* (2017), oxygen, hormones, and nutrients are delivered to the tissues of the body throughout the body, and metabolic products are removed from the body. From the point of view of

mechanics, according to the research of O. Shemla *et al.* (2021), the heart can be considered as a mechanism consisting of two discharge pumps formed into a closed system of tubes through which fluid (blood) circulates. In this case, the pumps serve to create a directed flow of blood in the appropriate direction. The heart itself, according to R. Storlund *et al.* (2021), is a muscular hollow organ and is topographically and functionally the central organ of the cardiovascular system, ensuring blood circulation.

Scientists R. Berg *et al.* (2022) noted that the functioning of the respiratory system is assessed through two homeostatic mechanisms: metabolic and conditioning. The first mechanism of regulation depends on the ambient temperature and is provided through the neuroendocrine apparatus of the body. Cutaneous and tracheobronchial receptors activate the adrenal glands and thyroid gland, and contribute to the synthesis of biologically active substances. This leads to changes in haemodynamics involving the large vascular field of the tracheobronchial tree, which results in changes in the haemodynamics of the small circulation.

Thus, according to A.F. Butkiewicz *et al.* (2022), the respiratory organs, which include the lungs, perform the main vital functions in the mammalian body, the most important of which is pulmonary respiration, which is characteristic of almost all terrestrial vertebrates, especially animals of the Mammalia class. Such respiration is the most perfect way of gas exchange between the animal organism and the environment, in contrast to diffuse, gill, and tracheal respiration, which are characteristic of poikilothermic organisms in most cases. In the respiratory department of the lungs, which includes respiratory bronchi, alveolar passages, alveolar sacs – structures containing alveoli, according to L. Cadiz & M. Jonz (2020), gases are exchanged between air and blood through the wall of the alveoli and the wall of capillaries.

Therefore, the purpose of the study was to determine the morphological structure of the heart and lungs at the macro- and microscopic levels, which will serve as markers and criteria for the morphological diagnosis of animal diseases associated with disorders of the cardiovascular and respiratory systems.

MATERIALS AND METHODS

Scientific research was carried out on the basis of the Laboratory of Pathomorphology at the Department of Normal and Pathological Morphology, Hygiene and Forensics, Polissya National University, Zhytomyr, during 2019-2023. The scientific work is a fragment of the department's development: "Development, morphology and histochemistry of animal organs in normal and pathological conditions" under the registration number 0113V000900.

Morphological, morphometric and statistical methods were used in the study. The object of the study was the heart and lungs of mature dogs (n=5), class – Mammalia, species – wolf (*Canis lupus*), subspecies – domestic dog (*Canis familiaris*). The lungs and hearts of

experimental animals were used for anatomical dissection. For the morphological study, their absolute and relative weights were determined. The absolute mass (AM) of the heart and lungs was determined by weighing them on a laboratory balance (RADWAG PS 6000/C/2, Poland). Relative mass (RM) was determined by the formula:

$$BM = \frac{AM}{MA} * 100, \quad (1)$$

where, AM is the absolute mass of organs; MA is the mass of the animal.

Determination of linear parameters of the studied organs (height, width, thickness, and circumference) was carried out by direct measurement. The development index (DI) of organs was determined by the ratio of their total height to width using the following formula:

$$DI = \frac{HO}{WO} * 100, \quad (2)$$

where HO is the height of the organ; WO is the width of the organ.

For microscopic examination of the heart and lungs, the pieces of material made from them were fixed in a 10-12% chilled aqueous formalin solution for 24 hours or more. After fixation, the pieces of material were embedded in paraffin according to the schemes proposed in the methods of Manual L. Horalskyi *et al.* (2015). Sections, 10-12 μ m thick, were made on a microtome, type MS-2.

To study the cyto- and histoarchitectonics of the heart and lungs, histological sections (after deparaffinisation) were stained with haematoxylin (Diapath, Italy, 2021) and eosin (Leica Geosystems, Germany, 2020). In addition, for microscopic examination (visualization of elements) of transverse striated myocardial muscle tissue, detection of cardiomyocyte cytostructure, staining of histological specimens by the Heidenhain method was used. The prepared histopreparations were used to study the main structures that make up the lungs and heart and for histological and cytometric studies.

Histometric characteristics: determination of the respiratory part and connective tissue base of the lungs (per unit area equal to 5.0 mm²); average alveolar volume; length and width (diameter) of cardiomyocytes; volume of cardiomyocyte nuclei, was performed by light microscopy using Micros microscopes (Micros, Austria, 2012) with an imaging system and MBS-10 (Micromed, China, 1998), according to the recommendations provided in the manual (Horalskyi *et al.*, 2015).

The volume of myocardial cells (cardiomyocytes) was determined by the following calculations:

$$V = \pi * \left(\frac{B}{2}\right)^2 * A, \quad (3)$$

where V is the volume of the cardiomyocyte; π – 3.14; A – cardiomyocyte length; B is the width of the cardiomyocyte.

To determine the volume of nuclei cardiomyocytes, the following formula was used:

$$V = \frac{\pi}{6} * A * B^2, \quad (4)$$

where V is the volume of the cardiomyocyte; $\pi - 3.14$; A is the length of the nuclei cardiomyocyte; B is the

width of the nuclei cardiomyocyte. The nuclear-cytoplasmic ratio (NCR) was determined by the formula:

$$NCR = \frac{\text{The volume of the nuclei}}{\text{The volume of cells} - \text{The volume of the nuclei}} \quad (5)$$

Photographs of histological specimens were taken using a CAM V-200 video camera (Inter Med, China, 2017). Anatomical and histological terms of the heart and lung structures are given in accordance with the International Veterinary Histological and Anatomical Nomenclature (Terminology Dictionary) (Khomych, 2019). The statistical data of the results of quantitative studies were performed using the Statistica 7.0 software package (StatSoft, Tulsa, USA). The difference between the digital data of the studied indicators was carried out using ANOVA, where the difference was considered statistically significant at $p < 0.05$.

All experimental studies were conducted in accordance with modern methodological approaches and in compliance with relevant requirements and standards, in particular, they meet the requirements of DSTU ISO/IEC 17025:2005 (2006). The study animals were kept and all manipulations (methods of morphological studies) were carried out in accordance with the provisions of the "Procedure for conducting experiments and experiments on animals by scientific institutions" (Law of Ukraine No. 249, 2012), the "European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes" (1986).

RESULTS AND DISCUSSION

The heart in dogs is located in the thoracic cavity between the lungs and occupies the space from the 3rd to the 7th rib and is slightly displaced to the left. The base of the heart is located in the plane of the middle of the first rib of the thorax, and its apex has a projection at the level of the 6th-7th ribs. The aorta comes out of the left ventricle of the heart, behind the pulmonary trunk. As it travels dorsally to the spine, it makes an arc at the level of the 11th thoracic vertebra.

Externally, the epicardium of the heart is smooth, moist, shiny, white-grey in colour, transparent, without any layers, and a small amount of white-grey fat is noted. The heart myocardium is of elastic consistency, pale red on the surface and in the section, the fibre pattern is well-defined. It should be noted that the heart has different shapes in mammals (Emam & Abugherin, 2020). In predators, the dominant shape is spherical or cone-ellipsoidal. According to the literature, dogs, depending on their breed characteristics, have different heart shapes: spherical (7%), ellipse-elliptic (26%), cone-elliptic (24%), and most often ellipsoidal (43%) (Gómez-Torres *et al.*, 2021). The heart of mammals, including dogs, is divided into four chambers by partitions: the left and right atria, left and right ventricles. According to the results of research, the right ventricle

has a thicker wall than the atrium, but less thin than the left ventricle. The difference in wall thickness between the right and left ventricles is approximately 2.4 times.

The canine heart has a dilated base directed dorso-cranially and a narrowed apex directed ventro-caudally (Figs. 1, 2). The heart cavity is divided into left and right halves by an internal septum. The latter are divided into atria and ventricles. Each right and left atrium with their respective ventricles are connected to each other by the atrial-ventricular opening. The atria are located at the base of the heart. They are separated from the ventricles of the heart by a transverse coronary groove. The atria at the base of the heart are formed by the right and left heart ears (sac-like protrusions), which are cranial in direction and located on the right and left, relative to the trunk of the pulmonary arteries and aorta. The right and left ventricles of the heart occupy the main part of the organ. Externally, they are separated by interventricular grooves – the near-cone groove, which is located more cranially, and the sub-axillary groove, which is located caudally. These furrows are interconnected on the anterior (cranial) part of the heart, not reaching the apex, and separate the left ventricle from the right ventricle, respectively.

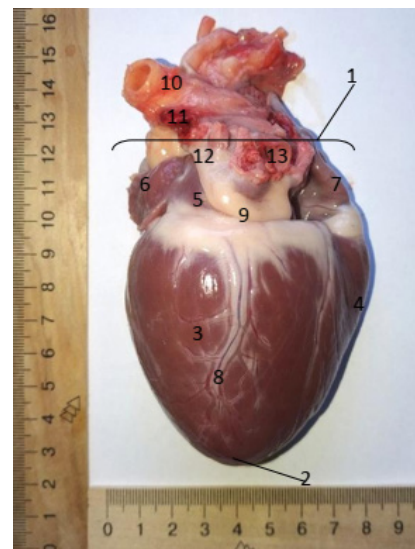


Figure 1. Macroscopic structure of the heart of a sexually mature dog (right side)

Notes: 1 – heart base; 2 – apex of the heart; 3 – right ventricle; 4 – left ventricle; 5 – right atrium; 6 – right auricle; 7 – left atrium; 8 – axillary interventricular groove; 9 – subepicardial fat; 10 – aorta; 11 – trunk of pulmonary arteries; 12 – cranial vena cava; 13 – caudal vena cava. Photo from macropreparation

Source: photo of the authors

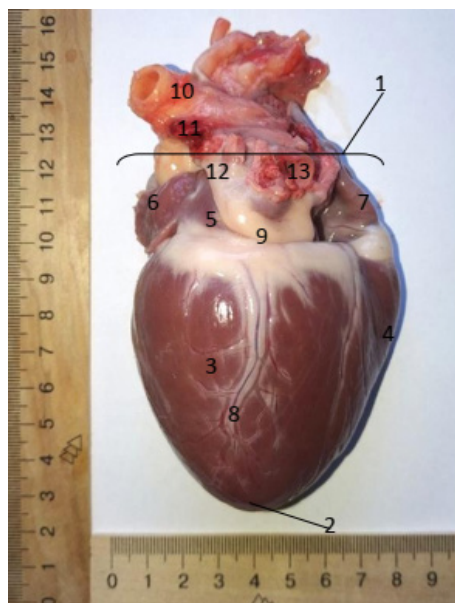


Figure 2. Macroscopic structure of the heart of a sexually mature dog (left side)

Notes: 1 – heart base; 2 – apex of the heart; 3 – right ventricle; 4 – left ventricle; 5 – left atrium; 6 – left auricle; 7 – right auricle; 8 – semi-conical interventricular groove; 9 – subepicardial fat; 10 – blood vessels; 11 – pulmonary veins; 12 – aorta. Photo from macropreparation

Source: photo of the authors

Studies have been published that show that the absolute heart weight depends on the breed and age of dogs, and in relation to body weight ranges from 0.76 to 1.2% (Brambilla *et al.*, 2020). According to the results of the studies, the absolute heart weight is 167.58 ± 9.46 g, and the RM is $0.72 \pm 0.005\%$. According to L. Queiroz *et al.* (2018), the relative heart weight in dogs ranges from 0.6 to 1.1% of the animal's body weight. Perhaps such ambiguous parameters are due to the breed properties of animals. The ratio of muscle thickness of the left and right ventricles was not the same, the left ventricle was 1.6 times thicker than the right, which is almost the same as in our studies.

The net weight of the heart (without epicardial fat) in the dog is 154.22 ± 8.04 g. The height of the heart is 11.09 ± 0.04 cm, the width is 7.6 ± 0.02 cm, and the circumference is 17.7 ± 0.08 cm. Comparing the morphometric data of A. Best *et al.* (2022) and the analysis of morphological measurements, the heart of the studied mature dogs is more often rounded (ellipsoidal) in shape (Figs. 1, 2).

According to the results of morphometric studies, the weight of the dog's LV heart is 76.24 ± 1.02 g, the weight of the right ventricle is 43.59 ± 0.62 g. The average weight of the right and left ventricles is 120.26 ± 1.98 g, and the weight of the atria is 33.77 ± 0.48 g. At the same time, the ratio of the mass of the ventricles (right and left) of the heart to the net mass is 1:0.78, respectively, the ratio of the mass of the atria (right and left) to the net mass of the heart is 1:0.22, and the ratio of the mass

of the atria to the mass of the ventricles is 1:0.28. The wall thickness of the heart ventricles, depending on their morphological and functional activity, is different: the wall thickness of the left ventricle (15.92 ± 0.34 mm) is 1.52 times ($p \leq 0.01$) greater (10.47 ± 0.11 mm) than that of the right ventricle. Atrial wall thickness was 4.01 ± 0.02 mm.

The wall of the dog's heart, as in other domestic mammals, is formed by 3 membranes: endocardium, myocardium and epicardium, of which the muscular membrane is the most developed. The atrial myocardium consists of two layers – outer (common to both atria) and deep. The middle shell of the ventricles (myocardium) is formed by 5 layers: the outer and inner layers, in which the muscle fibres are located in an oblique longitudinal direction, then deeper layers – the outer and inner layers and the deepest layer, whose muscle fibres have a direction similar to the letter "eight". Due to this structure of the myocardial ventricles and their functional activity, their walls are much thicker than the atrial walls.

The histoarchitecture of the myocardium is built by transversely striated muscle fibres, which form unicellular cells – cardiomyocytes. When histological sections are stained using the Heidenhain method, their cytostructure looks like dark transverse, rectangular stripes (Figs. 3, 4). The sarcolemma, myofibrils, and nuclei located in the centre of cardiomyocytes are differentiated.



Figure 3. Histological section of the myocardium of the left ventricle of the heart of a sexually mature dog

Notes: 1 – cardiomyocyte cells; 2 – nuclei of cardiomyocyte cells; 3 – insert disk; 4 – intermuscular connective tissue; Dyeing according to the Heidenhain method. $\times 280$

Source: photo of the authors

The assessment of changes in the quantitative morphometric parameters of each organ in any of its pathologies should start from a certain point of reference. This starting point is the concept of "normal". However, there are various quantitative variants of the parameters of an unchanged heart, depending on genetic, constitutional factors, physical activity, etc. Therefore, the concept of "normal heart" is rather conditional. According

to S.M. Bilash *et al.* (2019), morphologists should use their own quantitative parameters of the heart, taking into account age-related changes. Mathematical analysis of the structures of morphological objects, which has gained recognition as a method that is distinguished by objectivity and reliability, is of great importance in morphology to determine the structure, shape, size of organs and systems, the ratio of their specific structural features (Hryhorieva & Cherniavskiy, 2018).

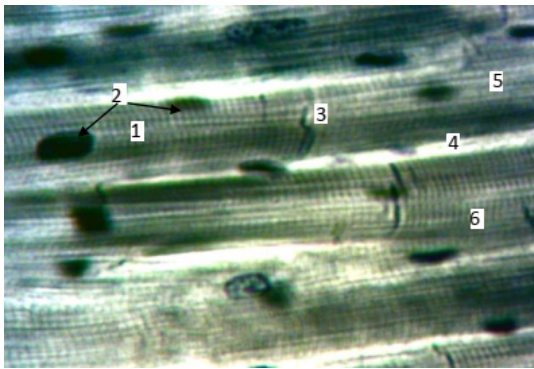


Figure 4. Histological section of the myocardium of the left ventricle of the heart of a sexually mature dog:

Notes: 1 – cardiomyocyte cells; 2 – nuclei of cardiomyocyte cells; 3 – insert disk; 4 – intermuscular connective tissue; 5 – longitudinal striation; 6 – transverse striation; Dyeing according to the Heidenhain method. $\times 600$

Source: photo of the authors

According to the results of morphometric studies, cardiomyocytes of the left (LV) and right ventricles (RV), atrial cardiomyocytes, depending on their morphotopography, and hence on their functional load, have ambiguous cytometric parameters. Morphometric analysis shows that the quantitative parameters of cardiomyocytes of the left ventricle of the dog heart are significantly higher than those of the right ventricle. Thus, the length and width of LV cardiomyocytes are 1.1 times greater than those of the right ventricle and are equal to $46.06 \pm 1.12 \mu\text{m}$ (length) and $9.02 \pm 0.39 \mu\text{m}$ (width), respectively.

Similar changes were found in the morphometric study of cardiomyocyte volumes: the largest volume of cardiomyocytes was determined in the LV ($2941.76 \pm 127.44 \mu\text{m}^3$), in the right ventricle this indicator was significantly ($p < 0.05$) less by 1.31 times and was equal to $2237.24 \pm 103.02 \mu\text{m}^3$. Similar results of

morphometric parameters were found when determining the volume of cardiomyocyte nuclei: the average volume of the nucleus of cardiomyocytes of the left ventricle was $64.58 \pm 5.09 \mu\text{m}^3$, of the right ventricle – $59.97 \pm 5.83 \mu\text{m}^3$. According to such ambiguous quantitative cytometric characteristics of cardiomyocytes for the ventricles of the dog heart, they formed different NCR: the lowest such indicator was characteristic of LV cardiomyocytes (0.0224 ± 0.0076), the highest for RV cardiomyocytes (0.0275 ± 0.0081), which indicated their morphological and functional load. According to S.C. Orozco *et al.* (2019) and the results of our own studies, this is an objective reality, since the LV functions mainly as a pump, and the RV functions as a volume pump.

Therefore, an increase in the morphometric parameters of cardiomyocytes of the left ventricle myocardium, compared to the right ventricle, correlates with the morphological and functional load of myocardial muscle tissue, namely, the consequence of rhythmic contractions of cardiomyocytes of the heart, promoting blood flow through a closed circle of vessels. At the same time, LV cardiomyocytes perform a higher load, contributing to the movement of blood through a large circle of blood circulation; RV cardiomyocytes perform a lower load, contributing to the movement of blood through the vessels of a small circle of blood circulation.

Significantly lower cytometric parameters (length and width), cardiomyocyte volume, and nuclei volume were characteristic of atrial cardiomyocytes, and thus, such cardiomyocytes had the highest nuclear-cytoplasmic ratio (0.0367 ± 0.0105) (Table 1). The results indicate that such an increase in the nuclear-cytoplasmic index of atrial cardiomyocytes, relative to the ventricles, indicated a lower morphological and functional load, since more functionally mature and active cells are those characterized by a low nuclear-cytoplasmic ratio and, conversely, cells with a high nuclear-cytoplasmic ratio are less functionally active (Horalskyi *et al.*, 2022). Such ambiguous morphometric parameters of cardiomyocytes of the left and right ventricles and atria are associated with morphological and functional features of the heart. In this case, the right and left atria receive blood that returns to the heart from the body, performing a lower load, and the ventricles (left and right) pump blood from the heart to the body of animals, performing a much higher load.

Table 1. Histometry cardiomyocytes of the heart of a sexually mature dog, ($M \pm m, n=5$)

| Indexes | Length cardiomyocytes (μm) | Width of cardiomyocytes (μm) | Volume cardiomyocytes (μm^3) | Volume nuclei cardiomyocytes (μm^3) | Nuclear-cytoplasmic relationship |
|-----------------|---|---|---|--|----------------------------------|
| Left ventricle | 46.06 ± 1.12 | 9.02 ± 0.39 | 2941.7 ± 127.44 | 64.58 ± 5.09 | 0.0224 ± 0.0076 |
| Right ventricle | 41.47 ± 1.24 | 8.29 ± 0.42 | $2237.24 \pm 103.02^*$ | 59.97 ± 5.83 | $0.0275 \pm 0.0081^*$ |
| Auricle | $39.06 \pm 1.35^*$ | $7.19 \pm 0.49^*$ | $1496.92 \pm 98.02^{**}$ | $53.06 \pm 6.02^*$ | $0.0367 \pm 0.0105^{**}$ |

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ in relation to the left

Source: developed by the authors

The lungs of mature dogs have a similar structure and morphotopography to those of domestic mammals (Zamorska & Grushanska, 2022). Thus, the left and right lungs of dogs are divided into lobes (cranial, middle, caudal) by deep notches on the ventral side. The right lung has an additional lobe. At the same time, in comparison with other domestic animals, the lobes of the lungs of the dog have distinct deep interlobar notches that pass through the dorsal margin and reach almost to the main bronchus. The pattern on the lung surface is smoothed (Fig. 5).

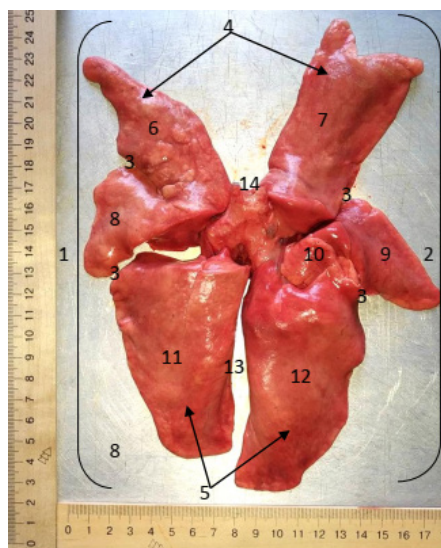


Figure 5. Anatomical structure of the lungs of a sexually mature dog (costal surface)

Notes: 1 – left lung; 2 – right lung; 3 – deep cuts; 4 – top of the lung; 5 – the base of the lung; 6 – left cranial lobe; 7 – right cranial lobe; 8 – left middle (cardiac) lobe; 9 – right middle (cardiac) lobe; 10 – additional share; 11 – left caudal lobe; 12 – right caudal lobe; 13 – interlobular slits; 14 fragment of tracheal bifurcation; Photo from macropreparation

Source: photo of the authors

The middle lobe of the left lung in dogs caudally overlaps the cranial lobe, and at the blunt (dorsal) edge, these parts merge with each other (there is no separation between the lobes). The caudal lobe of the left lung in dogs is compact and has an irregular pyramidal

shape. The cranial lobe of the right lung in dogs is almost completely separated from the other lobes by the cranial interlobar gap. The cranial contour of the cranial lobe is rounded. The middle lobe is located between the cranial and caudal lobes, not reaching the dorsal edge of the lung. The ventral end of this lobe is pointed. The directed cranial margin of the middle lobe forms the cardiac notch together with the directed caudal sharp margin of the cranial lobe. The caudal lobe of the right lung is similar in shape to the caudal lobe of the left lung. On its surface, which borders on the diaphragm, an uneven depression is found medially due to the adjacent accessory lobe. The accessory lobe of the right lung is different in shape from the other lobes: its middle part is relatively thicker and has three processes directed dorsally, ventrally and laterally. The accessory lobe of the right lung of dogs is fused to the medial surface of the caudal lobe.

The peculiarity of the anatomical structure of the canine lung is that the interlobular gaps dividing the lung into lobes are deep and reach the main bronchus. Lung lobes are not connected to each other by parenchyma, except for the cranial and middle lobes of the left lung, where they are connected to each other in the dorsal part (Fig. 5). Morphometric studies of organs and systems in clinically healthy humans and animals are important for their assessment at the cellular, tissue and organ levels, which are criteria for the diagnosis of diseases of contagious and non-contagious pathology (Hosapatna et al., 2022).

According to the results of morphometric studies, the total length of the dog's lungs is 23.0 ± 2.42 cm, width 16.7 ± 1.34 , and thickness 1.9 ± 0.36 cm. The right lung was 22.9 ± 2.18 cm long, 8.1 ± 0.62 cm wide, and 1.8 ± 0.11 cm thick. The left lung was 20.2 ± 2.44 cm long, 7.6 ± 0.54 cm wide, and 1.5 ± 0.09 cm thick. The ratio of the average lung length to lung width in dogs is 1.37:1, so the lungs in dogs are of the narrowed-elongated type. The AM of the lungs of dogs is 201.3 ± 18.4 g, the relative weight is $1.21 \pm 0.14\%$. At the same time, the absolute weight of the left lung in dogs is 86.26 ± 8.01 g, and the right 115.04 ± 10.14 g, their ratio in mature clinically healthy dogs, according to the results of organometry, is 1:1.33 (Table 2).

Table 2. Absolute and relative mass of lung lobes of a sexually mature dog, ($M \pm m$, $n=5$)

| Particles lungs | Left lung | | Right lung | | Both lungs | |
|-----------------|------------------|------------------|----------------------|------------------|------------------|------------------|
| | AM (g) | RM (%) | AM (g) | RM (%) | AM (g) | RM (%) |
| Cranial | 22.09 ± 3.01 | 10.97 ± 0.96 | $27.29 \pm 3.21^*$ | 13.56 ± 0.92 | 49.38 ± 6.34 | 24.52 ± 1.52 |
| average | 19.91 ± 2.84 | 9.89 ± 0.64 | 23.65 ± 2.96 | 11.75 ± 1.14 | 43.56 ± 5.87 | 21.64 ± 2.03 |
| Caudal | 44.26 ± 6.02 | 21.98 ± 1.82 | 47.96 ± 6.38 | 23.83 ± 1.82 | 92.22 ± 8.76 | 45.81 ± 5.38 |
| Additional | – | – | 16.14 ± 2.08 | 8.02 ± 0.48 | 16.14 ± 2.08 | 8.02 ± 0.48 |
| Total: | 86.26 ± 8.01 | 42.84 ± 6.04 | $115.04 \pm 10.14^*$ | 57.16 ± 8.02 | 201.3 ± 18.4 | 100 |

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ in relation to the left lobe

Source: developed by the authors

At the same time, the absolute weight of the cranial lobe of the left lung is on average 22.09 ± 3.01 g, and the cranial lobe of the right lung is 27.29 ± 3.21 g. The absolute weight of the middle lobe of the left lung averaged 19.91 ± 2.84 g, and the right lobe – 23.65 ± 2.96 g. The absolute weight of the left lung caudal lobe is 44.26 ± 6.02 g, and the absolute weight of the right lung caudal lobe is 47.96 ± 6.38 g. The absolute weight of the additional lobe of the right lung was 16.14 ± 2.08 g (Table 2). Thus, the results of organometric studies indicate that in dogs, the most developed are the caudal lobes of the right and left lungs, followed by the cranial and middle lobes (Table 2).

The relative weight of the cranial lobe to the absolute weight of both (right and left) lungs in dogs averages $10.97 \pm 0.96\%$ in the left lung and $13.56 \pm 0.92\%$ in the right lung. The relative weight of the middle lobe in relation to the absolute weight of the lungs in the left lung is $9.89 \pm 0.64\%$, in the right lung, respectively, $11.75 \pm 1.14\%$. The average volume of the caudal lobe in both lungs was $21.98 \pm 1.82\%$ in the left lung and $23.83 \pm 1.82\%$ in the right lung. The relative weight of the additional lobe, respectively, is $8.02 \pm 0.48\%$ (Table 2).

The lungs are formed by branches of the bronchi (bronchial tree), which have different sizes and branches of the respiratory department (alveolar tree). Such branches of the alveolar tree are usually accompanied by blood vessels, nerves and delicate layers of loose connective tissue. Haematoxylin and eosin staining of histological specimens reveals a significant amount of collagen and elastic fibres in the connective tissue, which are red and clearly differentiated in the lung tissue section. The bronchi are divided into extrapulmonary (main and interlaminal) and pulmonary bronchi, which are part of the lungs, where they branch out to form the bronchial tree. The lobular bronchi are branched off by segmental bronchi of different sizes. They are divided into dorsal and ventral segmental bronchi depending on the direction.

To date, it has been proven that the structure of the bronchial tree in animals corresponds to the location of the lobes of the lungs. It is known that the lobular bronchi of the right and left lungs are not developed equally. In the studies of A.F. Butkiewicz *et al.* (2022), it was noted that the pig lungs have dorsal, ventral, medial, and lateral bronchiolar systems on both sides. In addition, the tracheal bronchiole (bronchus) arises from the right side of the trachea. According to the bronchial branching, the right lung consists of cranial, middle, caudal and accessory lobes, and the left lung consists of bilobed middle and caudal lobes. The branching of the lung bronchi in dogs is as follows: the trachea branches into two main bronchi at the bifurcation (Fig. 6). The main bronchi enter the lungs, giving rise to the lobar bronchi. The anatomical structure of the main and lobar bronchi is similar to that of the trachea. However, the right main bronchus has a larger diameter than the left one.

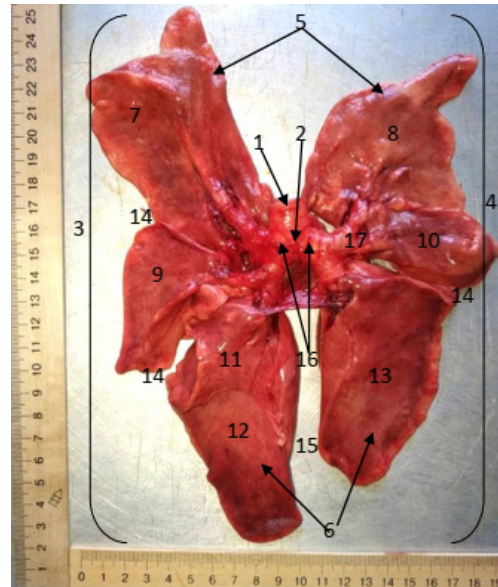


Figure 6. Anatomical structure of the lungs of a sexually mature dog (mediastinal surface)

Notes: 1 – trachea; 2 – bifurcations of the trachea; 3 – right lung; 4 – left lung; 5 – top of the lung; 6 – the base of the lung; 7 – right cranial lobe; 8 – left cranial lobe; 9 – right middle (cardiac) lobe; 10 – left middle (cardiac) lobe; 11 – additional share; 12 – right caudal lobe; 13 – left caudal lobe; 14 – deep cuts; 15 – interlobular gap; 16 – main right and left bronchus; 17 – branching of the bronchi of the left lung; Photo from macropreparation

Source: photo of the authors

In the area where the trachea divides into two main bronchi (bifurcation), the latter form an angle of 65° – 70° . At the same time, the left main bronchus deviates more strongly from the tracheal axis, forming an angle of 45° – 50° with it (Fig. 6). Both main bronchi branch first cardio-laterally, then caudally and are directed to the caudal lobes, forming their bronchi. Branching in each lung of the main bronchus into large, then medium, small bronchi, terminal bronchioles, occurs at the base of their blunt edges, where they go caudally, forming a bronchial tree. At the same time, the largest branches of the main bronchus branch and, one branch at a time, go to the cranial, middle, caudal and additional lobes – only for the right lung. Thus, directly after the bifurcation, the right cranial lobar bronchus branches off from the right main bronchus at almost right angles. Immediately afterwards, the middle lobar bronchus extends ventro-laterally. The next branch is the ventro-medial bronchus of the accessory lobe.

From the left main bronchus, the left cranial bronchus for the cranial lobe branches cranially. After the branching of this bronchus, the left main bronchus continues as a bronchus (caudal bronchus) for the left caudal lobe of the lungs. The large bronchus of the caudal lobe gives eight (four dorsal and four ventral) branches to its parenchyma in each lung. The smallest

intralobular bronchi enter the lung lobes, where they branch into terminal bronchioles, which branch into respiratory bronchioles, then alveolar ducts and alveolar sacs, thus forming the alveolar tree (Fig. 7).

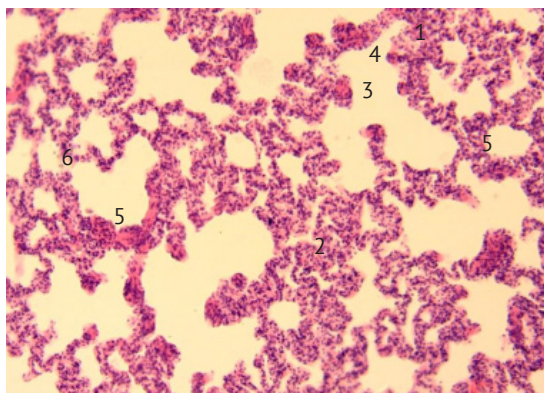


Figure 7. Histological section of the lung tissue of a sexually mature dog

Notes: 1 – respiratory part of lung tissue; 2 – connective tissue; 3 – alveolar course; 4 – alveolar sac; 5 – alveoli; 6 – interalveolar partitions; Haematoxylin and eosin staining. $\times 280$

Source: photo of the authors

The bronchial tree is the airways of the lungs, which are microscopically formed by bronchi of different calibre (main bronchi, large, medium, and small), which vary in diameter and structure along the direction of the bronchial tree. Thus, the histoarchitectonics of the wall of bronchi, especially large ones, is similar to the wall of the trachea, which is formed by the inner – mucous, middle – fibrous -cartilaginous, and outer – adventitia membranes (Fig. 8).

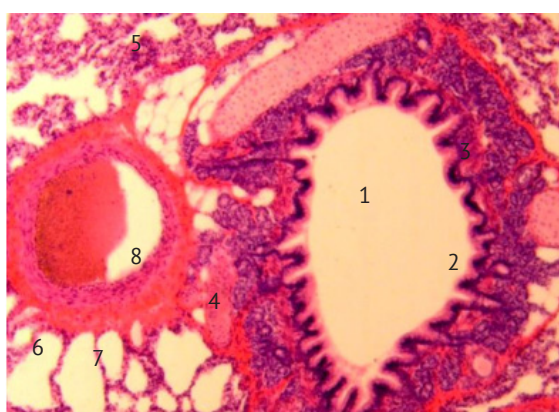


Figure 8. Histological section of the lung tissue of a sexually mature dog

Notes: 1 – lumen of a large bronchus; 2 – epithelial plate; 3 – muscle plate; 4 – cartilage plates; 5 – connective tissue stroma; 6 – alveoli; 7 – interalveolar septa; 8 – vessel; Haematoxylin and eosin staining. $\times 280$

Source: photo of the authors

In the large bronchi, the cartilage rings of the fibrous-cartilaginous membrane are represented by separate, clearly defined cartilage plates (Fig. 8), and the middle shell of the middle bronchi contains cartilage plates that occur in groups in the form of separate cartilage islands (Fig. 9). The wall of the small bronchi is formed only by the mucous membrane and adventitia. There are no cartilage plates in the wall of the small bronchi.

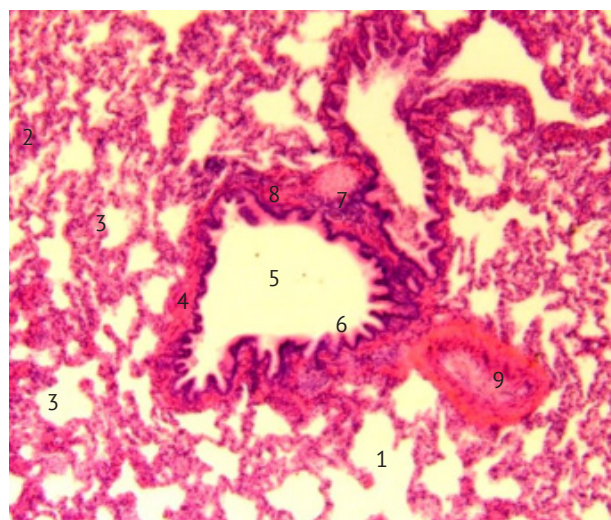


Figure 9. Histological section of the lung tissue of a sexually mature dog

Notes: 1 – respiratory part; 2 – connective tissue stroma; 3 – alveoli; 4 – middle bronchus; 5 – lumen of the middle bronchus; 6 – internal mucous membrane; 7 – cartilage plates in the form of cartilage islands; 8 – muscle plate; 9 – vessel; Haematoxylin and eosin staining. $\times 280$

Source: photo of the authors

The histoarchitectonics of dog lungs is formed by pulmonary lobules. The latter have a pyramidal or conical shape. The lobules include pulmonary acini, which are formed by respiratory bronchioles, alveolar ducts, alveolar sacs, and alveoli. In dogs, unlike other domestic animals, terminal bronchioles are generally poorly developed. Each terminal bronchiole is joined by several respiratory bronchioles, which are well-developed in dogs. Their wall is lined with a single-layer prismatic epithelium. The wall of the alveoli is lined with a single-layer flat epithelium (alveolocytes), which include respiratory and secretory cells and alveolar macrophages. Interalveolar membranes of alveoli are formed by layers of loose connective tissue. According to the results of histometry, the average volume of lung alveoli of sexually mature dogs is 58.9 ± 6.26 thousand μm^3 .

The respiratory part of the lungs in adult animals occupies $40.38 \pm 2.6\%$, the connective tissue base, respectively, $59.62 \pm 3.4\%$ (Fig. 10).

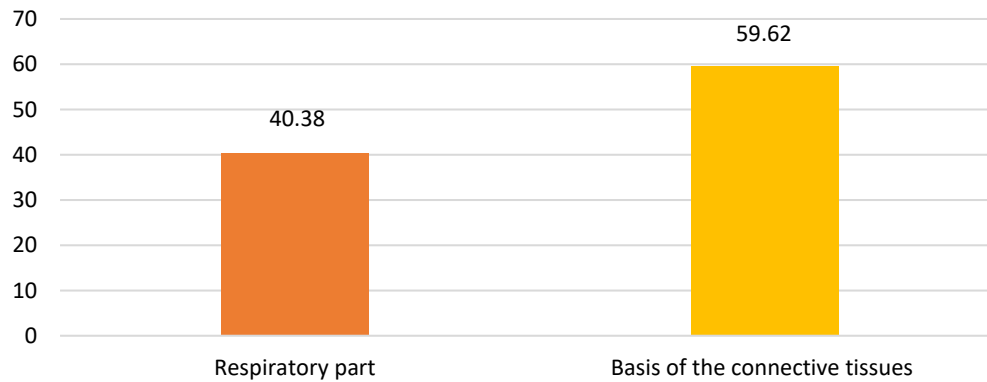


Figure 10. The area of the histostructure of the lungs of a sexually mature dog

Source: developed by the authors

Thus, the cardiovascular system and respiratory organs are interconnected and perform extremely important functions in the body for the vital activity of the organism. Their main function is gas exchange, through inhalation of air from the environment and excretion of carbon dioxide formed in the body of humans and animals. Gas exchange in the body directly occurs in the lungs, between air and blood by diffusion of O_2 and CO_2 through the walls of the pulmonary alveoli into the blood capillaries (Voloshyn *et al.*, 2020). Studies in this area have shown that the morphological structure of the heart and lungs in clinically healthy dogs has a similar morphoarchitectonics to that of other species of mammals, but differs in morphometric parameters.

Thus, depending on the morphofunctional load, the largest morphometric parameters (cardiomyocyte volume, volume of their nuclei) are characteristic of cardiomyocytes of the left and right ventricles, in which the NRC is the smallest (respectively, 0.0224 ± 0.0076 and 0.0275 ± 0.0081), compared to the NRC of atrial cardiomyocytes (0.0367 ± 0.0105), indicating their morphological and functional activity (the most functionally mature cells are those with a low NRC index and, conversely, cells with a high NRC are less active). Depending on the type of respiration characteristic of dogs, their lungs are of the elongated type according to the developmental index ($IDI = 137 \pm 2.84$), and the lung asymmetry ratio is 1:1.33. The respiratory part of the lung parenchyma is $40.38 \pm 2.6\%$, the connective tissue base is $59.62 \pm 3.4\%$, and the average volume of the pulmonary alveoli is 58.9 ± 6.26 thousand μm^3 . Such studies are of great importance for comparative morphology and are the basis for clinical veterinary medicine as criteria for the morphological diagnosis of diseases of various geneses.

CONCLUSIONS

The heart of most mature dogs has a rounded (ellipsoidal) shape. The absolute weight of the heart is 167.58 ± 9.46 g (without epicardial fat – 154.22 ± 8.04 g), the relative weight – $0.72 \pm 0.005\%$. Height was 11.09 ± 0.04 cm, width – 7.6 ± 0.02 cm, circumference –

17.7 ± 0.08 cm. The ratio of the total mass of the right and left atria to the mass of the right and left ventricles is 1:0.28, the ratio of the mass of both ventricles to the net mass of the heart is 1:0.78, respectively, the mass of the atria is 1:0.22. The microscopic structure of the ventricles and atria of the dog heart has a similar histoarchitectonics, but differs in cytometric parameters, according to the functional load: the largest volumes are characteristic of cardiomyocytes of the left ventricle – $2941.76 \pm 127.44 \mu m^3$, smaller – of the right ventricle $2237.24 \pm 103.02 \mu m^3$ and the smallest – of atrial cardiomyocytes $1496.92 \pm 98.02 \mu m^3$. The volume of nuclei of cardiomyocytes of the left ($64.58 \pm 5.09 \mu m^3$) and right ($59.97 \pm 5.83 \mu m^3$) ventricles of the heart is almost the same, in atrial cardiomyocytes this index is much lower ($53.06 \pm 6.02 \mu m^3$).

The nuclear-cytoplasmic ratio of cardiomyocytes of the left ventricle is 0.0224 ± 0.0076 , a slightly higher value is observed in cardiomyocytes of the right ventricle – 0.0275 ± 0.0081 and the highest value is observed in atrial cardiomyocytes (0.0367 ± 0.0105). The dog's lungs have a partial structure. The left lung is characterized by three lobes (cranial, middle, caudal), and the right lung by four lobes (cranial, middle, caudal and accessory). The absolute weight of the lungs of dogs is 201.3 ± 18.4 g, the relative weight is $1.21 \pm 0.14\%$. The weight of the left lung is less (86.26 ± 8.01 g) than the right (115.04 ± 10.14 g), their ratio is 1:1.33.

The length of the lungs of dogs is 23.0 ± 2.42 cm, width 16.7 ± 1.34 , thickness 1.9 ± 0.36 cm. The ratio of their length to width (asymmetry ratio) is 1.37:1, so the lungs in dogs are of the narrowed-elongated type. The histoarchitecture of the lungs is formed by cone-shaped or pyramidal lobules separated by connective tissue septa, which form the connective tissue stroma ($59.62 \pm 3.4\%$), formed by loose connective tissue and containing elastic fibres, blood and lymphatic vessels. The respiratory parenchyma of the lungs ($40.38 \pm 2.6\%$) is formed by respiratory bronchioles, alveolar ducts and alveolar sacs, the walls of which contain alveoli (large, medium, small), which together form the alveolar tree. The average value

of the alveolar volume is 58.9 ± 6.26 thousand μm^3 . Prospects for further research are to conduct a species-specific morphological study of the heart of domestic animals of the class Mammalia – Mammals.

There is none.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Морфологія, органо- та гістометричні особливості серця та легень статевозрілої свійської собаки (*Canis Lupus Familiaris* L., 1758)

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Анотація. Серцево-судинна система та органи дихання в організмі тварин взаємопов'язані між собою, вони виконують надзвичайно важливі функції для життєдіяльності організму, основною з яких газообмін. Тому, дослідження серцево-судинної системи та органів дихання є актуальним питанням сьогодення. Метою роботи була морфологічна оцінка макро- та гістоstruktur серця і легень свійської собаки. Для роботи застосовували комплексні морфологічні методи досліджень: гістологічні, анатомічні, органо-, гісто та цитометричні, статистичні, завдяки яким представлено нові дані щодо особливостей макро-, гісто- та цитоморфометричної характеристики морфологічних структур серця та легень. Серце собаки має округлу форму, його абсолютна маса дорівнює 167,58±9,46 г (без епікардіального жиру – 154,22±8,04 г), відносна маса – 0,72±0,005 %. Встановлено, що найбільший об'єм мають кардіоміоцити лівого шлуночка, менший – правого та найменший – кардіоміоцити передсердь. При тім, ядерно-цитоплазматичне відношення кардіоміоцитів лівого шлуночка дорівнює 0,0224±0,0076, більше значення мають кардіоміоцити правого шлуночка – 0,0275±0,0081 і найбільше кардіоміоцити передсердь – 0,0367±0,0105. Такі неоднозначні цитометричні параметри кардіоміоцитів пов'язані з морфофункціональною діяльністю м'язової тканини шлуночків міокарду та функціональними її особливостями, властивими до спонтанних і ритмічних скорочень, внаслідок чого відбувається рух крові по замкнутій системі судин. Абсолютна маса легень свійської собаки становить 201,3±18,4 г, відносна – 1,21±0,14 %, співвідношення абсолютної маси лівої до правої легені становить 1:1,33. Згідно коефіцієнту асиметрії (1,37:1), легені у собак звужено-втягнутого типу. Сполучнотканинна строма легень займає 59,62±3,4 %, респіраторна частина – 40,38±2,6 %. Відомості з морфології серця та легень свійської собаки, включаючи результати дослідження макро- та мікроскопічної будови досліджуваних органів, які представлені у публікації, мають велике значення для гістології та порівняльної анатомії, а також роблять вагомий внесок у клінічну ветеринарну медицину

Ключові слова: порівняльна анатомія; гістоструктура органів; цитометричні параметри; кардіоміоцити; міофібрили; бронхіальне дерево; альвеолярне дерево



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Study of the embryonic period of female crayfish egg development in different species

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Abstract. Freshwater crayfish farming is a promising area of production in the food market. This aquaculture industry is currently gaining popularity around the world, but given the high consumer demand, it requires modernisation. The efficiency of aquaculture production is based on the introduction of innovative methods into production processes, which are based on knowledge of biological characteristics, including reproductive capacity and the embryonic period of caviar development. The study aims to assess the

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reproductive quality of females and determine the incubation period of caviar, its quantity, weight, and survival rate. The study presents the results of research on the reproductive qualities and embryonic period of crayfish eggs of four species (*Cherax quadricarinatus*, *Procambarus clarkii*, *Procambarus fallax forma virginalis*, *Cherax destructor*) kept in separate closed water supply tanks at an optimal planting density of 4 individuals per 0.45 m². Studies have shown that the colour range of caviar and the duration of the incubation period for its maturation varies among different crayfish species. Thus, the first stage of incubation was the shortest and ranged from 2.80 (Florida crayfish) to 3.55 (destructor crayfish) days, while the second stage lasted the longest – from 13.17 to 15.80 days for Australian and broad-toed crayfish, respectively. Based on the analysis of the physiological characteristics of the female crayfish micropopulation, they were divided into quality categories, considering the following indicators: female weight, egg weight, total number of eggs, and number of eggs per 1 g of female. Females of the Australian red snapper of the excellent category was the best among all species in terms of live weight (63.0±0.67 g), egg weight (5.0±0.05 g) and total number of eggs (376.8±16.34 pcs.), the lowest similar indicators were in the marble species (16.8±0.15 g, 1.6±0.03 g, 124.5±2.66 pcs.), respectively. In terms of the number of eggs per 1 g of female weight, Florida crayfish prevailed (7.8±0.19). Instead, the destructor crayfish had intermediate results in these characteristics. The study results can be used in the economic activities of enterprises producing aquatic organisms

Keywords: *Cherax quadricarinatus*; *Procambarus clarkii*; *Procambarus fallax forma virginalis*; *Cherax destructor*; reproductive female qualities

INTRODUCTION

Crayfish belong to the aquaculture segment, and their production technologies in artificial conditions are still under development, which requires scientifically sound approaches to keeping, feeding and production systems. The incubation period of female crayfish eggs is no exception, as it determines the size of the future micro-population. Therefore, the selected research topic is relevant. Freshwater crayfish are in great demand around the world. According to the International Food and Agriculture Organisation (FAO), crayfish products were sold for USD 7.6 billion, and it is also noted that the demand for this type of aquatic organism constantly exceeds supply (FAO, 2021).

F. Liu *et al.* (2020) note that the level of production of aquaculture products is negatively affected by the use of traditional, labour-intensive production methods, depending on the season and the effects of inbreeding. According to A. Asher (2020); only traditional caviar production to increase the number of crustaceans requires the use of up to 30% of production tanks, which significantly reduces production efficiency, and the use of the above methods has a direct impact on the industry's ability to meet current market requirements and indicates their unsuitability for intensive production systems. J. Bitomsky (2008) describes that modern technologies of crayfish farming in industrial conditions should be based on a high percentage of preservation of individuals by creating optimal conditions for their reproduction and maintenance, as well as obtaining products in the projected volumes. N.E. Hrynevych *et al.* (2022) indicate that to increase the growth rate and reduce cannibalism in crayfish, it is advisable to use dietary supplements (Spirulina+Chlorella, Digestarom, carotenoids) with extruded feed, which contributes to the production of high-quality protein products, and the process of production of aquatic organisms is determined

by their technological level of cultivation and the development of aquaculture as an industry.

J. Patoka *et al.* (2016) believe that out of more than 100 species of Australian freshwater crayfish, only three have the potential for commercial farming, including marron (*C. tenuimanus*), yabby (*C. destructor*), and red-clawed (*C. quadricarinatus*). I. Norshida *et al.* (2021) indicate that the most promising for commercial farming is the Australian red snapper. N.P. José *et al.* (2019) describe that the production of freshwater crayfish products began with the Australian red snapper, as this species has biological characteristics that contribute to its rapid breeding. D. Lodge *et al.* (2012) describe Australian red-claw crayfish as a native species, best suited for aquaculture.

E.I. Fedorovych *et al.* (2022a) note that the average weight gain in the first year of life of red snapper in closed water supply systems is 50-150 g. Up to 70% of the maximum growth can be achieved at temperatures in the range of 23-28°C. For adults, a comfortable level of dissolved oxygen in water is 6-8 mg/l, and the Ph level is 6.0-8.0. M. Amer *et al.* (2015) studied the maturation period of Florida crayfish eggs in the natural conditions of the Nile River basin and proposed to divide them into ten stages of development during maturation. G. Vogt *et al.* (2008) pointed out that the marbled crayfish is the only crustacean in the world that reproduces by apomictic parthenogenesis. In particular, the author notes that there are only females that lay unfertilised eggs, the development of which causes a genetically homogeneous population. C.M. Jones *et al.* (2009), having conducted several studies in laboratory conditions and natural populations, indicate that no males of this species have been found. Females reared at a temperature of 20-25°C began to breed at the age of 141-255 days, their fecundity ranged from 45 to 416 eggs and varied depending on the size of the female. The incubation period was 22-42 days.

Given the above, the issue of studying the growth and development of female crayfish eggs of different species in closed-water supply systems remains relevant. The study was aimed at assessing the embryonic period of development of female crayfish eggs of *Cherax quadricarinatus*, *Procambarus clarkii*, *Procambarus fallax forma virginali*, and *Cherax destructor*.

MATERIALS AND METHODS

The experiment was carried out in the aquaculture laboratory of the Polissia National University (39 B Korolova St., Zhytomyr, Zhytomyr region). The experiment was conducted in the second half of 2021. For the experiment, 70 females of the Australian red snapper, 67 females of the marbled snapper, 64 females of the destructor and Florida crayfish were selected. They were kept in separate breeding tanks measuring 23×35 cm. The water filtration system included three

stages of purification: mechanical – using a filtration sponge, biological – using a special biofilter, and bioremediation – purification with plants. The water was saturated with oxygen using an air aerator. The water temperature was maintained at 28°C. The optimum planting density for the breeding stock was 4 individuals per 0.45 m².

Before forming a group, each female was weighed, and the stage of egg development was determined. Sampling to determine the number of eggs was carried out immediately after the females laid eggs on the pleopods and at the end of the embryonic period of egg development, just before the larvae emerged. Fecundity was determined by counting all eggs on the female pleopods. To determine the stage of egg development, females were examined weekly. Experimental animals were fed with balanced feed, its nutritional value is indicated per 100 g of product (Table 1).

Table 1. Feed nutritional value

| Feed | Water, g | Protein, g | Fat, d | Carbohydrate, g | Fibre, g | Calorie content, kcal |
|---------------------|----------|------------|--------|-----------------|----------|-----------------------|
| Grain crops: | | | | | | |
| sprouted wheat | 48 | 7.5 | 1.3 | 41.4 | 2.0 | 198 |
| non-polished rice | 12 | 7.5 | 2.7 | 72.8 | 3.4 | 362 |
| oats | 14 | 10 | 6.2 | 55.1 | 12 | 316 |
| Fish fillet: | | | | | | |
| hake | 79.7 | 16.7 | 2.0 | 0 | 0 | 86 |
| pike | 79 | 18.4 | 1.1 | 0 | 0 | 84 |
| Oak leaves | 0 | 0.1 | 0 | 0.1 | 0 | 1 |

Source: compiled by the authors

During feeding, females were observed, and the stage of egg development was determined. When formed fry appeared, the female was removed, and the crayfish were counted. To complete the incubation cycle, the fry was reared to a weight of 0.02 g, and such crayfish were considered formed. However, individuals weighing less than 0.02 g were vulnerable and a significant percentage of mortality was observed among them, which is associated with an increase in the frequency of moulting at small sizes. The reproductive quality of females was assessed by the following indicators: female weight, egg weight, total number of eggs, and number of eggs per 1 g of female body weight. Subsequently, based on the results obtained, the females were divided into quality categories: excellent, good, satisfactory, and unsatisfactory.

All experimental studies were carried out by modern methodological approaches and in compliance with relevant requirements and standards, in particular, they meet the requirements of DSTU ISO/IEC 17025:2005 (2006). The animals were kept, and all manipulations were carried out following the provisions of the Procedure for conducting experiments and experiments on animals by scientific institutions (Law of Ukraine No. 249, 2012), the European Convention for the

Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (European Convention on the Recognition of the Legal Personality of International Non-Governmental Organisations, 1986).

RESULTS AND DISCUSSION

In 3-4 weeks after mating, females begin to lay eggs, releasing them through the anus, the eggs attach to the pleopods under the pond and remain there until the developmental period is complete. This is the most difficult stage in a female's life, as she constantly needs to move her tail, flex and extend her abdomen, creating constant dynamics in the water under the pelvis, as the eggs require continuous flushing with oxygen-enriched water. It has been shown that during this process, some eggs are detached from the pleopods, fall to the bottom and die. In addition, females do not always manage to create the necessary water movement when placing them in hiding places, which contributes to the stagnation of water and, accordingly, a decrease in its oxygen content and an increase in the level of metabolic products, which also contributes to an increase in the percentage of eggs killed. It is worth noting that at this time, the body is forming, and the colour of the eggs is changing.

H. Aydin and M.K. Dilek (2004) provide data on the duration of embryonic development of broad-toed crayfish eggs. They kept females with eggs in cages at a temperature of $10\pm 2^{\circ}\text{C}$ and then transferred them to incubation pools with temperatures of 11.8°C , 16.0°C , and 20.0°C . The period of embryonic development of eggs under experimental temperature conditions was 120 ± 4 , 92 ± 4 and 71 ± 2 days, respectively. According to other scientists, in particular, S. Koca *et al.* (2013), the development of longnose crayfish eggs occurred at an average temperature of 12°C and a period of 134 days. The above studies were performed *in vivo*. The experiment was conducted in closed water supply systems at a temperature of 28°C , which is optimal for the development of eggs of most species of aquatic organisms.

According to the observations, the colour range of crayfish eggs and their embryonic development varied in the following time intervals: Australian red-clawed crayfish caviar – from 0 to 4 days (olive or dark green shades), from 4 to 17 days (yellow and orange), from 17 to 22 days (eye spots and barely visible limbs), from 22 to 30 days (abdomen is formed and separated from the head and chest), from 30 to 38 days (fry has a formed body structure, limbs are available and is weaned from the female); marble crayfish caviar – from 0 to 3 days (dark grey or pale green shades), from 3 to 15 days (light yellow), from 15 to 19 days (pink colour, eye formation), from 19 to 28 days (abdomen is formed, its separation from the head and neck is observed), from 28 to 35 days (fry is fully formed and weaned from the female); Florida crayfish caviar – from 0 to 3 days (black), from 3 to 13 days (the head is formed, has a black dorsal protrusion containing yolk residues, eye spots are formed), from 13 to 18 days (the abdomen is formed, its clear separation from the head is observed), from 18 to 28 days (the body becomes similar to adults), yambi crayfish caviar – from 0 to 4 days (black in colour), from 4 to 19 days (yellow or light yellow), from 19 to 27 days (orange in colour, eye spots are formed, and the abdominal part of the body is barely visible); from 27 to 39 days (eyes are fully formed, the abdomen is separated from the thorax, there is a dorsal projection containing the remains of the yolk),

from 39 to 45 days (anatomically, the body is similar to adults, the presence of limbs is observed). Thus, based on our research, the following division of the embryonic period of development of female crayfish eggs of different species is proposed, in particular:

Australian red snapper. In the first stage – the eggs had a dark green and, in some individuals, olive colour. Olive-coloured eggs gradually changed to yellow, and dark green eggs to orange (second stage). Regardless of colour, as the eggs developed, eye spots appeared (stage 3), and the abdomen formed and was separated from the head and neck (stage 4). At the last stage of development, the tadpoles hatched with a fully formed body (stage 5). Marble crayfish. In the first stage, the caviar had dark grey or pale green shades, by the next stage it changed to light yellow, in the third stage – to pink and eyes formed, in the final stage of incubation the body and limbs began to form (stage 4) and in the fifth stage the crayfish were weaned from the females.

Florida crayfish had one less stage of maturation compared to other crayfish species due to the shorter time of egg maturation. Thus, they were weaned from the female at the fourth stage between the 26th and 28th day. In contrast, the incubation period for yabby crayfish was longer than for the other species studied, with the fifth stage coming to an end on day 45. It is worth noting that unfertilised eggs for all species of females were transparent or light grey in colour. It was located on the outer part of the pleopods in the culled females, was unevenly distributed, and aborted after a while. In other individuals, however, the eggs were tightly adjacent to each other and resembled bunches of grapes.

According to observations, the hatching of crayfish from eggs coincides with the process described by Ya. Tsukerzis (1989). The crustacean, making movements with its abdomen and limbs, breaks the eggshell and hatches out of it, then it hangs on the so-called hyaline threads. The tadpoles stay in this position for 1 to 4 days, feeding on the yolk from the dorsal projection above the thorax. The average incubation time for each stage of caviar is shown in Figure 1.

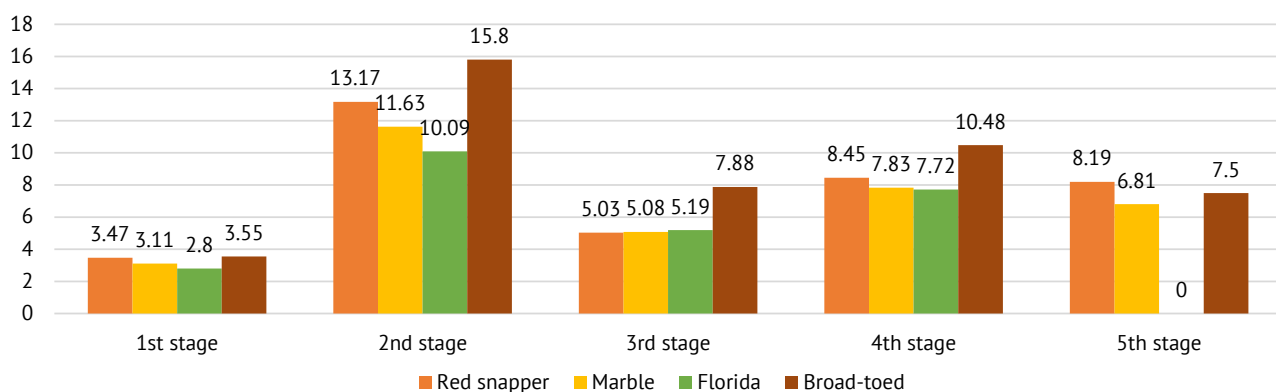


Figure 1. The average incubation time of eggs of the studied female crayfish

Source: compiled by the authors

The average duration of the 1st stage of caviar incubation for each experimental group was: Australian crayfish females – 3.47 days, marbled crayfish – 3.11 days, Florida crayfish – 2.80 days and yabby – 3.55 days. The longest stage was the 2nd stage, which was 9.70 days longer than the previous one for the Australian, 8.52 for the marbled, 7.29 for the Florida and 12.25 for the destructor crayfish. The third stage is shorter than the second and lasted 8.14 days less in red snapper, 6.55 days in marble, 4.90 days in Florida and 7.92 days in yabby. The last two stages of development were almost the

same for the Australian, which was 8.46 and 8.18 days, respectively. In the marbled, the period of these stages was 7.83 and 6.81 days. In the female Florida crayfish, the last-fourth stage lasted 7.72 days. The final - fourth and fifth stages of incubation of caviar in the destructor were within 10.48 and 7.50 days, respectively. As mentioned earlier, the reproductive capacity of female crayfish was assessed throughout the incubation period and during the weaning of fry. Thus, at the final stage of the research, five female groups were formed: culled, unsatisfactory, satisfactory, good and excellent (Table 2).

Table 2. Categories of reproductive quality of female crayfish of different species

| Female crayfish species | Quality category | | | | |
|-------------------------------|--------------------------|---------------------|-----------------------------|-------------------------------|--------------------------|
| | Excellent, individuals/% | Good, individuals/% | Satisfactory, individuals/% | Unsatisfactory, individuals/% | Defective, individuals/% |
| Australian red-bellied shiner | 36/51.43 | 8/11.43 | 11/15.71 | 9/12.86 | 6/8.57 |
| Marbled | 22/32.83 | 16/23.88 | 18/26.86 | 5/7.46 | 6/8.95 |
| Destructor | 25/39.06 | 14/21.88 | 12/18.75 | 4/6.25 | 9/14.06 |
| Florida | 27/42.19 | 13/20.31 | 14/21.88 | 3/4.69 | 7/10.9 |

Source: compiled by the authors

Australian red snapper females were distributed by quality categories as follows: rejected – 8.57%, unsatisfactory – 12.86%, satisfactory – 15.71%, good – 11.43% and excellent – 51.43%. For marble crayfish, 32.83% were in the excellent category, 23.88% were good, 26.86% were satisfactory, and 7.46% were unsatisfactory, with the proportion of culls being 8.95%. The largest percentage of females in the destructor crayfish was in the excellent category (39.06%), 21.88% were in the good category, 18.75% in the satisfactory category, 6.25% in the unsatisfactory category, and 14.06%

in the cull category. The lowest number of Florida crayfish was in the unsatisfactory group and amounted to 4.69%, while the highest rate was in the excellent quality category – 42.19% of individuals, in the good and satisfactory groups the rates were 20.31% and 21.88%, respectively, with 10.9% of females rejected. The following indicators were considered when forming the above groups: weight of females, weight of eggs, total number of eggs, and number of eggs per 1 g of female. The weight of female crayfish of different species according to the quality category is presented in Table 3.

Table 3. Weight of female crayfish of different species according to the quality category

| Female species | Quality category and female weight | | | | | | | | | |
|-----------------------|------------------------------------|--------------------|-------------------|--------------------|---------------------------|--------------------|-----------------------------|--------------------|-----------------------|--------------------|
| | Excellent, individuals | | Good, individuals | | Satisfactory, individuals | | Unsatisfactory, individuals | | Rejected, individuals | |
| | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % |
| Australian red-clawed | (n=36) | | (n=8) | | (n=11) | | (n=9) | | (n=6) | |
| | 63.0±0.67 | 6.4 | 57.6±1.01*** | 4.9 | 58.3±1.10*** | 6.3 | 56.6±1.88** | 10.0 | 56.1±2.34** | 12.0 |
| Marbled | (n=22) | | (n=16) | | (n=18) | | (n=5) | | (n=6) | |
| | 16.8±0.15 | 4.2 | 15.7±0.08*** | 2.1 | 14.9±0.09** | 2.7 | 13.7±0.19*** | 3.2 | 16.0±0.23* | 2.5 |
| Destructor | (n=25) | | (n=14) | | (n=12) | | (n=4) | | (n=9) | |
| | 46.9±0.23 | 7.5 | 44.4±0.84** | 7.2 | 46.4±1.18 | 8.8 | 45.3±2.08 | 8.0 | 46.2±0.87 | 5.7 |
| Florida | (n=27) | | (n=13) | | (n=14) | | (n=3) | | (n=7) | |
| | 21.8±0.17 | 4.1 | 20.5±0.19*** | 3.5 | 20.3±0.17*** | 3.2 | 20.9±0.39 | 3.3 | 20.8±0.91 | 7.6 |

Note: difference relevance is shown in comparison with the "excellent" group of females in the quality category: *P<0.05; **P<0.01; ***P<0.001

Source: compiled by the authors

In particular, among the analysed micro-populations, females of the Australian red snapper had the highest weight. At the same time, 44 (62.8%) out

of 70 individuals were of excellent and good quality. The proportion of such individuals among Florida crayfish was also significant – 62.5%. However, weight

does not always determine female quality. This is evident among Australian red snappers, where females of satisfactory quality outnumbered those of good quality by weight, although the qualitative difference with the best group was highly significant ($p < 0.001$).

This indicates the need for an integrated approach to assessing the quality of females since weight cannot be the only criterion for their quality. The weight of female caviar of different species is presented in Table 4.

Table 4. Female crayfish egg weight of different species as per quality category

| Female species | Quality category and egg weight | | | | | | | | | |
|-----------------------|---------------------------------|--------------------|-------------------|--------------------|---------------------------|--------------------|-----------------------------|--------------------|-----------------------|--------------------|
| | Excellent, individuals | | Good, individuals | | Satisfactory, individuals | | Unsatisfactory, individuals | | Rejected, individuals | |
| | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % | M±m, r | C _v , % |
| Australian red-clawed | (n=36) | | (n=8) | | (n=11) | | (n=9) | | (n=6) | |
| | 5.0±0.05 | 6.4 | 3.9±0.05*** | 4.3 | 3.5±0.04*** | 3.9 | 1.7±0.15*** | 28.5 | - | - |
| Marbled | (n=22) | | (n=16) | | (n=18) | | (n=5) | | (n=6) | |
| | 1.6±0.03 | 10.7 | 1.5±0.04*** | 10.9 | 1.4±0.02*** | 8.1 | 0.7±0.04*** | 15.3 | - | - |
| Destructor | (n=25) | | (n=14) | | (n=12) | | (n=4) | | (n=9) | |
| | 3.7±0.02 | 11.7 | 3.5±0.12*** | 13.8 | 3.0±0.21*** | 24.7 | 2.1±0.34*** | 28.9 | - | - |
| Florida | (n=27) | | (n=13) | | (n=14) | | (n=3) | | (n=7) | |
| | 2.1±0.04 | 12.0 | 1.8±0.06*** | 13.5 | 1.5±0.03*** | 7.4 | 1.4±0.10*** | 13.6 | - | - |

Note: difference relevance is shown in comparison with the "excellent" group of females in the quality category: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Source: compiled by the authors

The analysis of Table 4 highlights a clear trend – an increase in the quality category of females to "good" and "excellent", causes an increase in the weight of their caviar. At the same time, there was a highly significant difference in the quality category ($p < 0.001$). The total amount of caviar varied depending on both the type of crayfish and the quality category (Table 5). Thus, the total loss of caviar during sampling during the incubation period was 65%. Such losses were caused, among

other things, by the counting process, as the slightest manipulation provoked the development of stress in females, due to which they shed part of their caviar. However, the quality category of females is a crucial factor in caviar production. In particular, in all groups, without exception, a significant amount of caviar production by females of good and excellent quality was recorded, with a highly significant difference within groups ($p < 0.001$).

Table 5. Total number of eggs of female crayfish of different species as per quality category

| Female species | Quality category and total quantity of female caviar | | | | | | | | | |
|------------------------|--|--------------------|-------------------|--------------------|---------------------------|--------------------|-----------------------------|--------------------|-----------------------|--------------------|
| | Excellent, individuals | | Good, individuals | | Satisfactory, individuals | | Unsatisfactory, individuals | | Rejected, individuals | |
| | M±m, pcs. | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % |
| Australian red snapper | (n=36) | | (n=8) | | (n=11) | | (n=9) | | (n=6) | |
| | 376.8±16.34 | 26.0 | 214.3±6.95*** | 9.2 | 172.7±4.41*** | 8.5 | 80.1±6.92*** | 25.9 | - | - |
| Marbled | (n=22) | | (n=16) | | (n=18) | | (n=5) | | (n=6) | |
| | 124.5±2.66 | 10.1 | 101.2±1.51 | 6.0 | 87.3±1.81*** | 8.8 | 29.2±2.19*** | 16.8 | - | - |
| Destructor | (n=25) | | (n=14) | | (n=12) | | (n=4) | | (n=9) | |
| | 261.8±13.17 | 14.1 | 207.9±9.62 | 17.3 | 179.9±9.50** | 18.3 | 73.8±8.99*** | 21.1 | - | - |
| Florida | (n=27) | | (n=13) | | (n=14) | | (n=3) | | (n=7) | |
| | 164.9±4.46 | 14.1 | 143.5±1.81*** | 4.6 | 115.1±1.64*** | 5.4 | 71.7±7.51*** | 18.2 | - | - |

Note: difference relevance is shown in comparison with the "excellent" group of females in the quality category: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Source: compiled by the authors

The number of eggs per 1 g of female body weight is presented in Table 6.

Females of all groups of "excellent" and "good" quality produced significantly more eggs per 1 g of

body weight compared to the worst quality individuals. Moreover, this difference, compared to the category of females rated as "excellent", was highly significant ($p < 0.001$).

Table 6. Number of eggs per 1 g of female weight as per the category of quality

| Female species | Quality category and female weight | | | | | | | | | |
|------------------------|------------------------------------|--------------------|-------------------|--------------------|---------------------------|--------------------|-----------------------------|--------------------|-----------------------|--------------------|
| | Excellent, individuals | | Good, individuals | | Satisfactory, individuals | | Unsatisfactory, individuals | | Rejected, individuals | |
| | M±m, pcs. | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % | M±m, pcs | C _v , % |
| Australian red snapper | (n=36) | | (n=8) | | (n=11) | | (n=9) | | (n=6) | |
| | 6.1±0.22 | 22.0 | 3.8±0.12*** | 9.1 | 3.0±0.06*** | 7.2 | 1.4±0.13*** | 28.1 | - | - |
| Marbled | (n=22) | | (n=16) | | (n=18) | | (n=5) | | (n=6) | |
| | 7.7±0.11 | 7.2 | 6.8±0.09*** | 5.6 | 6.3±0.12*** | 8.7 | 2.2±0.16*** | 16.2 | - | - |
| Destructor | (n=25) | | (n=14) | | (n=12) | | (n=4) | | (n=9) | |
| | 5.8±0.05 | 13.2 | 4.8±0.20*** | 16.4 | 4.1±0.22*** | 18.8 | 1.7±0.14*** | 14.9 | - | - |
| Florida | (n=27) | | (n=13) | | (n=14) | | (n=3) | | (n=7) | |
| | 7.8±0.19 | 12.9 | 7.2±0.09* | 5.5 | 5.8±0.09*** | 5.9 | 3.6±0.41*** | 19.6 | - | - |

Note: difference relevance is shown in comparison with the "excellent" group of females in the quality category: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Source: compiled by the authors

Thus, observation of females, the state of caviar (depending on the periods of its development) during the incubation period, and the division of females into quality categories of all studied groups contribute to their selection for the best economically useful traits. In the course of research by C. R. King (1993), conducted at the Queensland University of Technology, a division by stages of incubation of *C. quadricarinatus* eggs, based on changes in their colour and development: 0 to 3 days (olive or khaki), 3 to 16 days (reddish-brown or orange), 16 to 20 days (formation of the abdomen and its separation from the cephalothoracic region), 20 to 23 days (eyes and barely visible limbs appear on the eggs), 23 to 31 days (limbs and eyes are more distinct), 31 to 41 days (fry are fully formed and released from the female).

In 1997, several studies were conducted at the Southern Regional Aquaculture Centre in Australia to characterise the morphological, functional, and reproductive qualities of red snapper crayfish (Masser & Rouse, 1997). According to these studies, crayfish reach sexual maturity at the age of 6 months; spawning occurs several times a year; the female lays from 100 to 1000 eggs (depending on the size of the latter). The average period from the beginning of spawning to weaning is 6-8 weeks. At the age of 4-5 years, the weight of adults reaches over 400 g.

C. quadricarinatus was first commercially farmed in Australia in 1985. In 1988, this species was introduced to the United States, where it was named the Freshwater Lobster. In 1989, Auburn University began research on the biology of the species, which led to the design of closed-water supply systems. In the same year, several private companies and research institutions, including the Louisiana Agricultural Experiment Station, assessed the potential for farming red snapper and proposed a farming technology. The main disadvantages of this technology were cannibalism, loss of

eggs during spawning, diseases (bacterial and parasitic), mortality during moulting, and high energy consumption (Jones, 1998).

P.B. Medley *et al.* (1993) noted that the growth rate and productivity of red snapper are influenced by stocking density and diet. C.M. Jones (1992) studied the fecundity of red snapper crayfish and the factors that affect spawning, namely stocking density, weight of males and females, diet, mortality and its causes, and cannibalism. Y.I. Fedorovych *et al.* (2022b) and A. Radzikhovskiy (2017) describe that since the introduction of this species into commercial aquaculture, its cultivation has spread throughout the globe, and the main producers that grow it on a commercial scale are the USA, China, Spain, Israel, and Indonesia. That is why, as noted by R. Hutchings *et al.* (1990), the introduction of innovative methods into production will give an impetus to the intensive development of the aquaculture industry in general and crayfish farming in particular and will allow it to meet significant market needs.

Thus, the most promising for breeding and use is the Australian red snapper, as females of this species significantly outweigh other crayfish species in terms of weight and a set of reproductive traits.

CONCLUSIONS

The embryonic period of egg development in different species of crayfish was studied during the entire period of incubation and weaning, considering the following indicators: change in colour shades of eggs, duration of incubation stages, weight of females, weight of eggs, total number of eggs, number of eggs per 1 g of female weight. According to the results obtained, it was proposed to divide the females of the studied species into five quality categories.

The incubation period of egg development was shortest in Florida crayfish (the fry was separated from the female from day 26 to 28), and the longest in yabby

crayfish – the completion of the fifth stage took place on day 45. The colour shades of the eggs were different in all species studied and varied depending on their maturity, while unfertilised eggs were transparent or light grey in females of all species. The quality category of females is a crucial factor in the production of eggs by females, their weight, and the number of eggs per 1 g of female weight, as there is a highly significant difference in all studied crayfish micro-populations between all categories of female quality. Given the research, the most promising for commercial breeding is Australian red snapper and Florida crayfish, as their females are characterised by high reproductive capacity and, accordingly, belong to the “excellent” category.

The results of the research can be used in the educational process, as a theoretical basis for teaching relevant aquaculture disciplines and in the activities of aquaculture farms to improve the artificial breeding of crayfish. Further research will be aimed at determining the dependence of the postembryonic development of individuals on the quality of caviar and the reproductive capacity of female crayfish.

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CONFLICT OF INTEREST

None.

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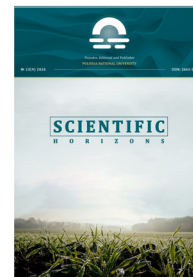
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Анотація. Вирощування прісноводних раків є перспективним напрямом виробництва на ринку продуктів харчування. Наразі ця галузь аквакультури набуває популярності у всьому світі, однак, з урахуванням великого споживацького попиту, потребує модернізації виробництва. Ефективність виробництва гідробіонтів ґрунтується на впровадженні у виробничі процеси інноваційних методів, в основу яких покладено знання про біологічні особливості, в тому числі про відтворювальну здатність та ембріональний період розвитку ікри. Саме тому метою роботи було дослідження самок за відтворною якістю, визначення інкубаційного періоду ікри, її кількості, ваги, виживаності. У статті подано результати досліджень щодо відтворних якостей та ембріонального періоду розвитку ікри самок раків чотирьох видів (*Cherax quadricarinatus*, *Procambarus clarkii*, *Procambarus fallax forma virginalis*, *Cherax destructor*), які утримувались в окремих резервуарах замкнутого водопостачання за оптимальної щільності посадки 4 особини на 0,45 м². Дослідження показали, що кольорова гамма ікри та тривалість інкубаційного періоду її дозрівання є неоднаковою у різних видів раків. Так, перша стадія інкубації була найкоротшою і перебувала в межах 2,80 (флоридський рак) та 3,55 (рак деструктор) доби, друга тривала найдовше – від 13,17 до 15,80 діб у австралійського і широкопалого рака відповідно. Згідно аналізу фізіологічних особливостей мікропопуляції самок раків нами проведено їх поділ за категоріями якості з врахуванням таких показників – маса самок, маса ікри, сумарна кількість ікринок, кількість ікринок на 1 г самки. Самки австралійського червоноклешневого рака відмінної категорії були найкращими серед усіх видів за показниками живої маси (63,0±0,67 г), маси ікри (5,0±0,05 г) та сумарної кількості ікринок (376,8±16,34 шт.), найнижчими аналогічні показники були у мрамурового виду (16,8±0,15 г, 1,6±0,03 г, 124,5±2,66 шт.) відповідно. За показником кількості ікринок на 1 г маси самки переважали раки флоридського виду (7,8±0,19). Натомість рак деструктор мав проміжні результати за цими характеристиками. Результати дослідження можуть бути використані у господарській діяльності підприємств з виробництва гідробіонтів

Ключові слова: *Cherax quadricarinatus*; *Procambarus clarkii*; *Procambarus fallax forma virginalis*; *Cherax destructor*; відтворні якості самок



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The effect of live chlorella suspension on the growth and development of grafted seedlings of Cabernet Sauvignon grapes

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Abstract. One of the ways to grow high-quality grafted grape seedlings is to use modern, environmentally friendly biologically active preparations. Today, such preparations include live chlorella suspension. Its use in grape nursery is a new and relevant technological method of growing planting material. The aim of the study was to show the effect of live chlorella suspension on the realization of the biological potential of grapevines, with the subsequent production of high-quality grafted grape seedlings. Field (recording of plant growth and development), laboratory (determination of quantitative and qualitative parameters of plants) and statistical (confirmation of the reliability of the results) research methods were used. The obtained results showed

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that for soaking rootstock and scion components it is advisable to use the strain *Chlorella vulgaris* Beijer, dilution 1:5, soaking should be carried out for 72 hours – rootstock components, 18 hours – scion components; for irrigation of grape garden plot it is advisable to use the strain *Chlorella vulgaris* Beijer. + Ge, dilution 1:5, it was carried out immediately after planting scions and three times during the growing season – in June, July, and August. The use of these strains of live chlorella suspension allowed obtaining a higher yield of standard seedlings from the garden plot, the plants had a well-developed root system and annual growth. Compared to the control, which was water, the total number of roots increased. Plants in these variants were also characterized by increased growth of the aboveground part. Indicators of total and mature growth, which characterize the overall development of grafted grape seedlings, were in the range of 687.1-773.2 cm³ (total growth volume), 337.9-386.6 cm³ (mature growth volume), while 730.1 and 362.6 cm³, respectively, in the control. The records of the output of standard seedlings from the garden plot also showed the advantage of using a suspension of live chlorella (an increase of 19.0-21.0%) compared to water. The above technological methods allow obtaining high-quality grape seedling products and can be a promising alternative for more sustainable and environmentally friendly agricultural methods

Keywords: cuttings; vegetative organs; annual growth; root system; microalgae *Chlorella vulgaris* Beijer.; germanium

INTRODUCTION

Viticulture is an important economic sector of Ukraine's agro-industrial complex. This is due to the valuable consumer, energy, health, and wellness properties of fresh grapes and their products. In agricultural production, grapes are considered an "insurance fund" as they are undemanding to soils (vineyards are often planted and cultivated on land unsuitable for growing grain or other crops) and always yield a crop even under extreme conditions of drought, frost, and other negative influences. Therefore, long-term highly productive grape plantations will ensure the stable and full development of the viticulture and winemaking industry.

The analysis of scientific research on the use of live chlorella suspension in crop production showed that the work that is currently being carried out mainly concerns annual crops. In the work of T. Hajnal-Jafari *et al.* (2020), the authors studied the effect of *Chlorella vulgaris* Beijer. strain S45 suspension on the growth of *Beta vulgaris* L. subsp. *cicla*. plants and the pigment content in leaves. The best results in the development of the leaf apparatus and root system were obtained after soil treatment with 10% suspension solution.

A. Kusvuran & A. Can (2020) and A. Kusvuran & C. Kusvuran (2019) investigated the effect of a liquid fertilizer containing the microalgae *Chlorella vulgaris* Beijer. on the nutrient content of the aboveground mass of *Cyamopsis tetragonoloba* (L.) *Taub.* plants and their resistance to salinity and drought conditions. The authors came to the conclusion that foliar fertilization with a fertilizer based on *Chlorella vulgaris* Beijer. contributed to an increase in shoot length, wet and dry leaf weight, and their number, while an increase in the content of photosynthetic pigments, total phenolics, flavonoids, potassium, and calcium was noted in the leaves. And plants of *Cyamopsis Tetragonoloba* (L.) *Taub.* tolerated the negative effects of salinity better.

In the study by Y.J. Park *et al.* (2022), the positive effect of *Chlorella vulgaris* Beijer. (suspension, biomass, filtered supernatant) on the growth of *Brassica napus* var.

Pabularia plants and the content of secondary metabolites in the leaves were shown. The authors showed that the filtered supernatant had a positive effect on the accumulation of phenols and flavonoids in the leaves, while the supernatant treatment had a positive effect on the accumulation of anthocyanins. G.E. Özer Uyar & N. Mismil (2022) grew *Mentha spp.* seedlings, while they introduced the microalgae *Chlorella vulgaris* Beijer into the hydroponic culture. The results of the research showed that the increase in wet weight of plants was the highest after the application of microalgae under aeration conditions. However, the height of the plants did not change significantly.

In the study by Sh.L. Tian *et al.* (2022), the effect of *Chlorella vulgaris* Beijer extract on the growth of *Capsicum annuum* plants of the "Chao Tian Jiao" variety was investigated. Two weeks after transplanting into pots, the seedlings of the experimental groups were sprayed with *Chlorella* extracts. The results showed that the use of the extract significantly increased the height of the seedlings, stem diameter and leaf area, increased the pigment content and enzyme activity in the leaf tissues, and the root system was more powerful and branched. Similar results in terms of biometric indicators of growth and development of vegetative organs were obtained when growing *Eruca vesicaria ssp. sativa* Mill plants in greenhouse conditions with a closed root system (Turhan *et al.*, 2022).

Few studies have been devoted to the use of live chlorella suspension in viticulture, which are mainly aimed at increasing berry yields. For example, S. Tangolar *et al.* (2019) studied the effect of root and foliar treatments with *Chlorella vulgaris* Beijer algae extract on the yield and quality of grape varieties "Trakya ilkeren", "Yalova incisi" and "Prima". The results of the experiments showed that the highest grape yield, weight of one bunch, 100 berries were obtained after the complex application of a suspension of live chlorella: root + foliar treatment. After such application, a high

content of K, Ca, Mg and Fe, P, and Zn was also noted in the leaves of plants.

To date, there are no studies related to the use of a suspension of live chlorella – *Chlorella vulgaris* Beijer. in a grape nursery. Separate works on the use of dry extract of *Chlorella vulgaris* Beijer. in the cultivation of vegetative rootstocks of grape variety “Palieri” affected by root ectoparasite *Xiphinema index* were conducted at the Agricultural University of Plovdiv, Bulgaria (2010-2013). *Chlorella vulgaris* Beijer. suspension was not generally used in the technology of growing grafted grape seedlings. Thus, at present, there is no data on its influence on the development of vegetative organs of grape planting material and the production of standard seedlings.

Given the above, the study aimed to determine the effect of live chlorella suspension on the development of vegetative organs of grafted grape seedlings. To achieve this goal, the following research objectives were set: to determine the effect of live chlorella suspension on the development of annual growth and root system of grafted grape seedlings; to determine the effect of live chlorella suspension on the yield of grafted grape seedlings from the garden plot and their compliance with DSTU 4390:2005 (2006); to assess the influence of certain technological factors on the formation of quality indicators of grafted grape seedlings.

MATERIALS AND METHODS

The work was carried out during 2018-2022 at the Department of Nursery, Propagation, and Biotechnology of Grapes of the National Research Centre “Tairov Institute of Viticulture and Winemaking” of the National Academy of Agrarian Sciences of Ukraine. The material for the research was graft components and grafted seedlings of the Cabernet Sauvignon technical grape variety. Cabernet Sauvignon is a late-ripening dark berry grape variety. The growth of the bushes is strong, the ripening of the shoots is satisfactory, and it is relatively winter-hardy. It is characterized by high resistance to mildew and grey rot. Productivity is 6.0-9.0 t/ha, average bunch is weight 73 g. Tasting score: 7.9-8.0 points.

The suspension of live chlorella was used at the following stages of the technology for the production of grafted grape planting material – soaking of scion components and during the cultivation of seedlings in the open ground plot. The strain of *Chlorella vulgaris* Beijer. pure and enriched with germanium (aqueous working solutions) were used in the study. *Chlorella vulgaris* Beijer is a unicellular microalgae belonging to the domain *Eukaryota* → kingdom *Protista* → division *Chlorophyta* → order *Chlorellales* → family *Chlorellaceae* → genus *Chlorella* → species *Chlorella vulgaris* Beijer.

Cultivation of microalgae *Chlorella vulgaris* Beijer. IFR No. C-111 (grade A, TU U 03.0-37613791-001:2017) and *Chlorella vulgaris* Beijer BIN are grown at the farm “At Samvel’s” (Odesa region). The product is used as a plant growth stimulant to increase crop yields (grade B). In terms of organoleptic, physicochemical parameters and toxicity, the chlorella suspension must meet the technical specifications of TU U 03.0-37613791-001:2017.

Scientists of the I.I. Mechnikov Odesa National University together with the International Research and Production Company “Living Chlorella” have developed a method for growing a suspension culture of live cells of the microalgae *Chlorella vulgaris* Beijer with the addition of germanium. The preparation contains vitamins (B₁, B₂, B₅, B₆, B₉, B₁₂, A, C, D, E, PP, K), macro- and microelements (N, P, K, Ca, Cu, Mg, Fe, S, Zn, Mn, Zr, Rb, I, Co), amino acids (alanine, valine, glycine, leucine, threonine), vegetable protein, growth regulators (gibberellins, cytokinins, auxins, natural steroids and phenols), and a natural antibiotic – chlorelin.

In the experimental variants, the scion components were soaked in *Chlorella vulgaris* Beijer working solutions for 72 (rootstock scions) and 18 (grafting scions) hours, in the control variants they were soaked in water for similar time intervals. Watering of grape planting material in the open field (plot) with aqueous solutions of live chlorella suspension was carried out immediately after planting and three times during the growing season – in June, July, and August. Control grafts and seedlings were watered at the indicated times.

Scheme of the experiment:

| Soaking components of grafts: | |
|------------------------------------|--|
| Option 1 | Water (control 1). |
| Option 2 | <i>Chlorella vulgaris</i> Beijer. (dilution of the suspension solution: water 1:5). |
| Option 3 | <i>Chlorella vulgaris</i> Beijer. + Ge (dilution of the suspension solution: water 1:5). |
| Watering the scion in the nursery: | |
| Option 4 | Water (control 2). |
| Option 5 | <i>Chlorella vulgaris</i> Beijer. (dilution of the suspension solution: water 1:5). |
| Option 6 | <i>Chlorella vulgaris</i> Beijer. + Ge (dilution of the suspension solution: water 1:5). |
| Option 7 | <i>Chlorella vulgaris</i> Beijer. (dilution of the suspension solution: water 1:1). |
| Option 8 | <i>Chlorella vulgaris</i> Beijer. + Ge (dilution of the suspension solution: water 1:1). |

Source: developed by the authors

The produced grape scions were stratified in a closed way on coconut substrate for 20 days, hardening – for 7 days openly on water in the greenhouse complex of the Institute. After the end of the growing season and digging of the grafted grape seedlings, the following indicators were determined: total number of roots (including those with a diameter of more than 2 mm) (pcs.); root length (including gradations) (cm); shoot height and part of the matured vine (cm); shoot maturation (%); shoot diameter (mm); volume of total, matured growth (cm³); yield of standard seedlings (%). Determinations and calculations were made according to the methods described in the textbook “Features of the grape plant and methods for assessing organ and tissue indices” (Scherer & Zelenyanskaya, 2011). The quality of the grafted grape seedlings was determined by determining whether the development of vegetative organs – annual shoots and roots – corresponded to the parameters and characteristics specified in DSTU 4390:2005 (2006).

To determine the effect of live chlorella suspension on the biometric parameters of growth and development of grafted grape planting material, the value of stimulating efficiency (R, %) was calculated: $R = (\sum K_1/N_1) - (\sum K_2/N_2)$, where R is the value of stimulating efficiency (%); $\sum K_1$ is the number of plants characterized by the studied trait after exposure to the suspension (%); N_1, N_2 is the number of replications during the study period; $\sum K_2$ is the number of plants characterized by the studied trait without the influence of the suspension (%). Depending on the value of R, the results were evaluated as follows: $R > 0$ – the suspension showed stimulating properties, $R = 0$ – the suspension did not show stimulating properties; $R < 0$ – the suspension had an inhibitory effect. The study was conducted

in accordance with the requirements of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

The development of the root system of plants in general and grapes in particular determines the degree of development of aboveground organs, fruiting, and yield of bushes. The development of the root system of a grape plant and the placement of roots in soil horizons depends on many agronomic practices, including plant nutrition. Therefore, the issue of determining the effect of live chlorella suspension on the development of the root system of grafted grape seedlings is relevant and timely.

In the process of growing grafted grape seedlings, it is very important to obtain plants with well-developed roots with a diameter of more than 2.0 mm. Since these roots are characterized by a perfect conductive system and thick parenchyma, the latter performs protective, reserve and mechanical functions. Therefore, during the autumn and winter storage of seedlings, these roots counteract the negative effects of environmental factors to the maximum extent possible, are better preserved, and in the spring, when laying out a vineyard or planting individual bushes, they ensure high plant survival. Roots with a smaller diameter are more often exposed to abiotic and biotic factors during storage, are damaged and die.

The development of the root system of the grafted grape seedlings was recorded after excavation from the garden plot. The results showed the following. In the control variants, the grafted grape seedlings, on average, had 10-11 roots, of which 31.0% were roots with a diameter of more than 2.0 mm and 69.0% were roots with a diameter of less than 2.0 mm (Table 1).

Table 1. The effect of live chlorella suspension on the formation of the root system of grafted grape seedlings (average for 2018-2022)

| Research options | Total number of roots, pcs. | Number of roots, $d \geq 2$ mm, pcs. | Number of roots, $d \leq 2$ mm, pcs. | The length of one root $d \geq 2$ mm, cm | The total length of the roots, $d \geq 2$ mm, cm | The length of one root $d \leq 2$ mm, cm | Total length of roots $d \leq 2$ mm, cm |
|------------------|-----------------------------|--------------------------------------|--------------------------------------|--|--|--|---|
| 1 | 11.3±0.5 | 3.0±0.2 | 7.8±0.4 | 27.0±1.5 | 94.8±5.5 | 9.3±0.7 | 73.1±3.8 |
| 2 | 16.0±0.3 | 5.8±0.3 | 10.1±0.5 | 43.3±2.7 | 253.3±7.2 | 16.3±0.9 | 166.2±5.6 |
| 3 | 13.6±0.6 | 4.6±0.3 | 9.0±0.5 | 34.6±2.1 | 162.0±5.8 | 9.3±0.8 | 84.3±4.0 |
| 4 | 10.6±0.5 | 3.0±0.2 | 6.9±0.3 | 29.0±1.4 | 108.0±5.0 | 9.6±0.7 | 67.1±4.2 |
| 5 | 14.4±0.5 | 3.8±0.2 | 10.6±0.6 | 30.4±1.6 | 116.5±4.6 | 10.0±0.6 | 106.3±5.0 |
| 6 | 19.2±0.8 | 5.7±0.4 | 13.4±0.7 | 43.8±1.8 | 251.5±6.6 | 19.0±0.8 | 255.8±5.9 |
| 7 | 14.9±0.4 | 4.4±0.3 | 10.5±0.5 | 37.5±2.3 | 165.7±6.0 | 11.3±0.6 | 119.5±3.5 |
| 8 | 16.4±0.3 | 4.8±0.3 | 11.6±0.4 | 35.3±2.2 | 170.8±6.5 | 14.6±0.6 | 170.7±3.3 |

Source: developed by the authors

After applying the method of soaking the grafted components in aqueous solutions of live chlorella suspension with subsequent grafting and growing seedlings in a garden plot, the number of roots increased to 14.0 (*Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5)) – 16.0 (*Chlorella vulgaris* Beijer. (dilution 1:5)), of which 33.8-36.2% were roots with a diameter of more than 2.0 mm

and 63.1-66.1% were roots with a diameter of less than 2.0 mm. In general, after soaking the scion components in the live chlorella suspension, a significant difference was observed in the total length of roots of different gradations. Compared to control 1 (water application), the total length of roots $d \geq 2$ mm increased by 1.7-2.6 times, and the total length of roots $d \leq 2$ mm – by 1.5-2.2

times, respectively. At the same time, the length of one root differed significantly from the control only after soaking the scion components in a solution of *Chlorella vulgaris* Beijer (dilution 1:5).

After applying the suspension of live chlorella for watering grape scions and seedlings during the growing season in the garden plot, the total number of roots increased by 33.3 and 54.7% compared to the control after using aqueous solutions of *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5, 1:1) and by 35.8 and 40.5% after using aqueous solutions of *Chlorella vulgaris* Beijer. of the corresponding dilutions. The number of roots with a diameter of more than 2.0 mm, on average, increased by 29.0% in variants and in relation to control 2. After the application of *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5, 1:1), a significant increase in the length of roots of both gradations was observed. Compared to the control, such an increase for roots of the first order ($d \geq 2$ mm) was 1.5 (*Chlorella vulgaris* Beijer. + *Ge*, *Chlorella vulgaris* Beijer. (dilution 1:1)) – 2.3 (*Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5)) times, for roots of the second order ($d \leq 2$ mm), respectively, 2.5–3.8 times after application of *Chlorella*

vulgaris Beijer. + *Ge* and 1.5–1.7 times after application of *Chlorella vulgaris* Beijer.

In grapes, a certain relationship has been established between the root system and the aerial part of the bushes: the leaf apparatus provides organic matter to both the aerial parts and the root system, the latter provides water and minerals to the aerial part. Therefore, by regulating the growth of the grape root system through the use of appropriate agricultural products, it is possible to stimulate the growth of shoots and leaf surface. Enhanced growth of the aerial part, on the contrary, promotes the development of the root system. In the process of growing grafted grape seedlings, it is very important to stimulate the growth of shoots, as the development of the assimilation (leaf) apparatus will depend on their development. According to the results of the work, it was found that the longest annual shoots were formed in seedlings after the use of *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5, 1:1) (sixth, eighth variants, watering of scions) and *Chlorella vulgaris* Beijer. (second variant, soaking of components) (dilution 1:5) (Table 2).

Table 2. The influence of live chlorella suspension on the development of the vegetative mass of grafted grape seedlings (average for 2018–2022)

| Research options | The total length of the shoot, cm | Shoot diameter, mm | The length of the mature part of the shoot, cm | Ripening of shoots, % | Total growth volume, cm ³ | Volume of mature growth, cm ³ |
|------------------|-----------------------------------|--------------------|--|-----------------------|--------------------------------------|--|
| 1 | 49.5±3.1 | 4.2±0.10 | 24.3±1.6 | 49.1 | 687.1±22.5 | 337.9±12.5 |
| 2 | 60.3±3.8 | 5.0±0.31 | 34.6±1.8 | 57.5 | 1216.6±23.3 | 698.4±14.5 |
| 3 | 55.0±3.4 | 4.6±0.24 | 25.6±1.5 | 46.6 | 929.8±23.4 | 434.5±13.0 |
| 4 | 50.1±3.0 | 4.4±0.22 | 25.0±1.5 | 49.9 | 773.2±21.0 | 386.6±12.4 |
| 5 | 53.7±3.5 | 4.5±0.32 | 27.6±1.7 | 51.5 | 885.2±20.5 | 450.3±12.5 |
| 6 | 71.2±4.5 | 6.0±0.51 | 45.6±2.0 | 63.9 | 2017.7±23.1 | 1295.1±14.1 |
| 7 | 60.2±3.7 | 5.0±0.20 | 31.6±2.1 | 52.5 | 1200.4±22.2 | 625.0±13.8 |
| 8 | 65.9±4.1 | 5.4±0.50 | 39.0±2.4 | 58.9 | 1526.0±23.0 | 899.6±13.2 |

Source: developed by the authors

In comparison with the controls, the shoot height in plants of the second variant was 10.8 cm or 21.8% higher, in plants of the sixth and eighth variants, respectively, by 21.1, 15.8 cm or 42.1 and 31.5%. The plants of these variants also had a larger shoot diameter. And this is an important feature, since this indicator affects the formation of the volume of total and mature growth. The latter determines the degree of development of grape plants in general, the content of reserve and plastic substances in lignified and perennial parts of the bushes, which indicate the quality of the planting material and its stability during storage.

The use of a suspension of live *Chlorella vulgaris* Beijer. (dilution 1:5) for soaking the components of grape scions contributed to an increase in the volume of total and mature growth, compared to the control, by 1.8 (total growth), 2.0 (mature growth) times. The use of the strain *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5) also contributed to different results from the control,

but these indicators were lower and increased by 1.3 times compared to the control. After applying a suspension of live chlorella for watering grape scions and seedlings in the garden plot, the best results were obtained after using the strain *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5 (sixth variant) and 1:1 (eighth variant)). In plants of these variants, the volume of total growth was 2.6 times (sixth variant) and 1.9 times (eighth variant) higher than the control value, the volume of mature growth was 3.3 times (sixth variant) and 2.3 times (eighth variant). After the use of the strain *Chlorella vulgaris* Beijer. dilution 1:5, these indicators were at the level of control values, and after the use of the solution dilution 1:1 increased by 1.5 times.

A similar dependence was found for the maturation of annual shoots. In the technological process of growing grafted grape seedlings, it is very important to achieve maximum ripening of shoots (vines). It is of great practical importance – it is associated with the

winter hardiness of shoots, buds, and the quality of rootstock and scion in the production of planting material. Therefore, the issue of shoot ripening is of great interest, especially after the phylloxera invasion. The best shoots ripened in the variants where the plants were watered in the garden plot with a suspension of live *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5) – 63.9%, which is 14.0% more than in the control. After the use of *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:1) for watering plants and *Chlorella vulgaris* Beijer. (dilution 1:5) for soaking the components of scions – shoots maturation was in the range of 57.5-58.9%, which was 8.4-9.0% higher than in the control. In all other variants, this increase was not significant. Obtaining grafted grape seedlings with the specified parameters of vegetative organs development allows increasing the survival rate of plants in a permanent place. Comparison of plant development indicators obtained after the use of a suspension of live chlorella and water in the technology of growing grafted grape seedlings showed that the root system development of seedlings of the experimental variants, where the strain *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5 and 1:1) for irrigation and *Chlorella vulgaris* Beijer. (dilution 1:5) for soaking the scion components fully met the parameters of DSTU 4390:2005 (2006).

Plants of control variants and after application of the strain *Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5, soaking), *Chlorella vulgaris* Beijer. (dilution 1:1, 1:5, watering) the number of roots corresponded to the minimum value, but the roots were placed asymmetrically (on the one hand) on the “heels” of plants, which does not correspond to DSTU 4390:2005 (2006). According to the development of one-year growth, namely the thickness of the shoot, only plants in the second group (*Chlorella vulgaris* Beijer. (dilution 1:5, soaking)), sixth (*Chlorella vulgaris* Beijer. + *Ge* (dilution 1:5, watering)), seventh (*Chlorella vulgaris* Beijer. (dilution 1:1, watering)) and eighth (*Chlorella vulgaris* Beijer. + *Ge* (dilution 1:1, watering)) variants.

Thus, summarizing the above, it should be noted that the suspension of live chlorella promotes the powerful development of both the root system and the aboveground vegetative mass of grafted grape seedlings. Its use at the stage of soaking the scion components

involves the use of the strain *Chlorella vulgaris* Beijer. dilution 1:5, at the stage of watering plants in the garden plot during the growing season – the use of the strain *Chlorella vulgaris* Beijer. + *Ge* dilution 1:5 or 1:1.

The reliability of the data obtained on the development of vegetative organs of grafted grape seedlings was proved by the results of analysis of variance. The main factors of influence are: technological method (factor 1), strain of live chlorella suspension (factor 2) and dilution of live chlorella suspension solution (factor 3). The identified differences between the experimental and control variants are reliable, since the actual values of Fisher's criterion (for most of the main factors of influence) at the level of significance $P = 0.05$ were higher than their tabulated values. $F_{\text{fact.}} = 4.35$, $F_{\text{theor.}} = 6.58-55.7$ (limits for different indicators). However, the results of the interaction of factors 2 and 3 were not always reliable in the development of annual growth and root system of plants.

Determination of the share of influence of the main factors on the development of annual growth and root system showed that the factor “technological method” (i.e. how the live chlorella suspension was used: soaking or for irrigation) was of the greatest importance – 27.0-52.0%. The influence of other factors was as follows: factor “dilution of the live chlorella suspension solution” – 11.2-33.0% (vegetative mass), 14.0-29.6% (root system), factor “strain of live chlorella suspension” – 12.1-25.0% (vegetative mass), 10.0-17.3% (root system), interaction of factors “technological method” and “strain of live chlorella suspension” – 11.1-37.2% (vegetative mass), 13.1-22.2% (root system).

In nursery farming, the effectiveness of new or improved technological methods is assessed by the yield of planting material, in this work it is the number of grafted grape seedlings that must meet the parameters of DSTU 4390:2005 (2006). The largest number of such plants was obtained in the variants after the use of live chlorella suspension for irrigation of grape garden plot – 48.0-55.5% and these are variants with the strain *Chlorella vulgaris* Beijer. + *Ge* and after the use of live chlorella suspension for soaking the grafted components – these are variants with the strain *Chlorella vulgaris* Beijer.

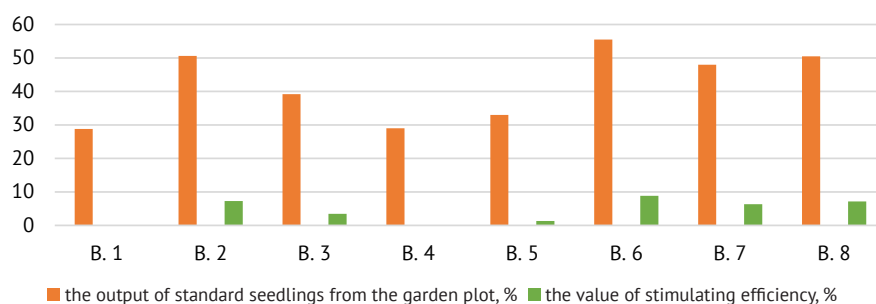


Figure 1. The yield of grafted grape seedlings from the nursery and the assessment of the effect of live chlorella suspension on this indicator (average for 2018-2022)

Source: developed by the authors

The effectiveness of the influence of live chlorella suspension on the yield of standard grape seedlings from the garden plot is confirmed by the value of stimulating efficiency. It had the highest values in the variants identified as the best (sixth, eighth, second, and seventh). Thus, the results obtained indicate the positive effect and expediency of using a suspension of live chlorella *Chlorella vulgaris* Beijer. in the technology of production of grafted grape planting material, in particular at the stages of soaking the scion components and watering the seedlings in the garden plot. Its use allowed increasing the yield and improving the quality of planting material.

Microalgae produce a wide range of metabolites, which, due to their biological activity, can be used in agriculture as biofertilizers, biostimulants or biopesticides. They play an important role in: soil decontamination and fertilization, protection of plants from biotic and abiotic factors, and promoting better plant development (Gonçalves, 2021). In the current study, the authors concluded that the live chlorella suspension has a stimulating effect and promotes the growth and development of the vegetative organs of grafted grape seedlings, in particular the development of shoots and root systems. According to the authors, these results are associated with the influence of biologically active substances contained in the live chlorella suspension. These are: vitamins (B₁, B₂, B₅, B₆, B₉, B₁₂, A, C, D, E, PP, K), macro- and microelements (N, P, K, Ca, Cu, Mg, Fe, S, Zn, Mn, Zr, Rb, I, Co), amino acids (alanine, valine, glycine, leucine, threonine), plant protein, plant growth and development regulators (auxins, gibberellins, cytokinins, natural steroids, phenolic compounds). The conclusions about the stimulating effect of algal fertilizers were also reached by C. Schreiber *et al.* (2018), who grew *Triticum aestivum* L. on two poor substrates: "null Erde" and sand, and liquid algal fertilizer was used for irrigation. As a result, it was shown that plants grown in sand were smaller in terms of biometric parameters, but fertilization with algal fertilizer led to increased growth processes, which, according to the authors, was similar to the use of chemical fertilizers. These results showed that algal biomass and its nutrients can be a natural alternative to support agriculture.

The positive effect of minerals and vitamins in their works is pointed out by R. Rahman *et al.* (2022). The authors note that, in addition to vitamins and minerals, the intensification of the growth processes of grape seedlings is also explained by the presence of a number of active amino acids in the live chlorella suspension, which are central to metabolic processes and building blocks of cell walls. H. Baqer *et al.* (2019) also associate active growth processes with the presence of active amino acids. The authors believe that a group of natural regulators of plant growth and development contained in the suspension – auxins, cytokinins, gibberellins – also contributes to the activation of the metabolism of the plant

organism in general, and grape seedlings in particular. They ensure the architecture and development of vegetative organs and the vascular system. Y. Durán-Medina *et al.* (2017) also reported a similar effect on the development of *Arabidopsis thaliana* (L.) Heynh. under the influence of these plant growth regulators.

After applying a suspension of live chlorella *Chlorella vulgaris* Beijer. + *Ge.*, dilution 1:5, grafted grape seedlings with a well-developed root system were obtained. During the growing season, it was noted that immediately after planting the grafts in the open ground plot, they took root faster, rooted and moved to the vegetation stage. The positive effect of microalgae on plant rooting is emphasized in the works of N. Pereira *et al.* (2018). They showed that the use of chlorella stimulated the rooting of the orchid *Schomburgkia crista in vitro*. Other authors explain this effect through the influence of microalgae directly on soil microbial populations (changes in biomass, activity, species composition and diversity), improvement of soil physical properties (structure, water holding capacity), enrichment of soil with phytohormones and other biologically active substances (Marks *et al.*, 2019; Nisha *et al.*, 2018; Chanda *et al.*, 2019).

The use of live chlorella suspension *Chlorella vulgaris* Beijer., dilution 1:1, 1:5 at the stage of soaking the scion components was also aimed at intensifying callusogenesis in the current study. And, according to the results obtained, it intensified the formation of callus tissue on rootstock and scion sections, the formation of the vascular-conductive system (xylem and phloem), and the formation of "fusion rods". This was facilitated by auxins, cytokinins, amino acids and vitamins that activate callus growth and vascular tissue formation. These data are consistent with the results of A.K. Nanda and C.W. Melnyk (2018), who showed the overall effect of biologically active substances on the formation of a whole organism after vaccination and A. Aydin *et al.* (2022), who proved that the treatment of cucumber (*Cucumis sativus* L.) cuttings during the grafting process with auxin substances contributed to better plant formation (increased moisture, dry weight of roots and stems). The use of a suspension of live chlorella with germanium at this technological stage did not give the desired results. In previous laboratory studies by N.M. Zelenianska and O.M. Mandych (2022), the authors showed that after soaking the inoculated components in aqueous solutions of *Chlorella vulgaris* Beijer. suspension with germanium, the mass of callus was lower, and callus tissue was formed unevenly around the circumference of the copulation cut. Most likely, germanium, in this case, had an inhibitory effect, and the strain *Chlorella vulgaris* Beijer. gave positive results.

When comparing the parameters of the development of vegetative organs of grafted grape seedlings after application of live chlorella suspension, it should be noted that they were higher than the standard ones after application of *Chlorella vulgaris* Beijer. + *Ge* for

watering plants in the garden plot. According to the authors, this is due to the introduction of germanium into the suspension. In plant tissues, it promotes the decomposition of water into oxygen and hydrogen, which is then used in physiological processes, thus stimulating plant growth. K.V. Chernega *et al.* (2019), in their work on *Cucumis sativum* L., *Cucurbita pepo* subsp., *Solanum lycopersicum* L. and *Lepidium sativum* L. plants, also showed the stimulating effect of germanium obtained from the culture fluid of the microalgae *Chlorella vulgaris* Beijer. on seed germination and further morphometric development of plants.

Thus, taking into account the theoretically substantiated effect of physiological and biochemical substances that are components of the suspension of live chlorella, it becomes clear that the formation of better parameters of the development of the aboveground mass and root system of grafted grape seedlings after its application is possible. Therefore, based on the theoretical and practical results obtained, it is advisable to use the suspension of live chlorella – *Chlorella vulgaris* Beijer. at the technological stages of growing grafted grape seedlings – pre-stratification soaking of grafted components and for irrigation of grape garden plot.

CONCLUSIONS

The suspension of live chlorella *Chlorella vulgaris* Beijer. has a stimulating effect on the development of vegetative mass, root system of grafted grape seedlings and their exit from the garden plot. It should be recommended for use at the following stages: soaking of grape scion components with subsequent production of scions and when growing grafted seedlings in an open ground plot for irrigation through a drip irrigation system. For soaking grape scion components, the strain *Chlorella vulgaris* Beijer. should be used at a dilution of 1:5. In this case, the scion components should be soaked for 18 hours, and the rootstock components – for 72 hours. For irrigation of grape scions and seedlings in the garden plot – use the strain *Chlorella vulgaris* Beijer. + Ge dilution of the working solution 1:5 or 1:1. Watering should be carried out with aqueous solutions in time – immediately after planting the scions in the garden plot and three times during the growing season – in June, July, and August.

The use of such strains at different technological stages contributed to the formation of more roots, including roots with a diameter of more than 2 mm, an increase in their length and better branching of the root system. Compared to the controls, the total number of roots increased by an average of 41.5-81.1%, the number of roots with a diameter of more than 2 mm – by 29.3-36.2%, and the length of roots – by 1.5-2.6 times. After the application of live chlorella suspension of these strains, the plants were also characterized by better development of annual growth: the volume of total growth was in the range of 1216.6-2017.7 cm³, mature growth – 698.4-1295.1 cm³, while 730.1 cm³ and 362.2 cm³ in the control. The use of such strains and dilutions allows producing grafted grape seedlings that fully meet the parameters of DSTU 4390:2005. The yield of standard seedlings from the garden plot exceeded the control values by an average of 21.5-26.5%.

The reliability of the obtained results was confirmed by the results of the analysis of variance. The identified differences between the experimental and control variants are reliable, since the actual values of Fisher's criterion (at the significance level $P \leq 0.05$) were higher than their tabulated values. Determination of the share of influence of the main factors (technological method, strain of live chlorella suspension, dilution of live chlorella suspension solution) on the development of annual growth and root system of grafted grape seedlings showed that the factor "technological method" was the most important – 27.0-52.0%. The influence of other factors was in the range of 10.0-33.0%. Prospects for further work in this area are to determine the effect of live chlorella suspension on the course of physiological and biochemical processes in the tissues of grape leaves and shoots.

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CONFLICT OF INTEREST

There is none.

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Вплив суспензії живої хлорели на ріст і розвиток щеплених саджанців винограду сорту «Каберне Совіньйон»

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Анотація. Одним із шляхів вирощування високоякісних щеплених саджанців винограду є використання сучасних, екологічно безпечних біологічно активних препаратів. До таких препаратів сьогодні відносять суспензію живої хлорели. Її застосування у виноградному розсадництві є новим та актуальним технологічним прийомом вирощування садивного матеріалу. Метою роботи було показати вплив суспензії живої хлорели на реалізацію біологічного потенціалу виноградної лози з подальшим одержанням високоякісних щеплених саджанців винограду. У роботі використовували польові (обліки росту та розвитку рослин), лабораторні (визначення кількісних та якісних параметрів рослин) і статистичні (підтвердження достовірності результатів) методи досліджень. Отримані результати показали, що для вимочування підщепних і прищепних компонентів доцільно використовувати штам *Chlorella vulgaris* Beijer., розведення 1:5, вимочування проводити протягом 72 годин – підщепні компоненти, 18 годин – прищепні компоненти; для поливу виноградної шкільки доцільно використовувати штам *Chlorella vulgaris* Beijer + Ge, розведення 1:5, його здійснювали одразу після висаджування щеп та трічі протягом вегетації – у червні, липні та серпні. Застосування вказаних штамів суспензії живої хлорели дозволило отримати більший вихід стандартних саджанців зі шкільки, рослини мали добре розвинену кореневу систему та однорічний приріст. Порівняно з контролем, яким слугувала вода, у рослин збільшувалась загальна кількість коренів. Рослини у цих варіантах характеризувалися і посиленням ростом надземної частини. Показники загального та визрілого приросту, які характеризують загальний розвиток щеплених саджанців винограду, знаходилися у межах 687,1-773,2 см³ (об'єм загального приросту), 337,9-386,6 см³ (об'єм визрілого приросту), при 730,1 та 362,6 см³ відповідно у контролі. Обліки виходу стандартних саджанців із шкільки також показали перевагу застосування суспензії живої хлорели (збільшення на 19,0-21,0 %) у порівнянні з водою. Наведені технологічні прийоми дозволяють отримувати високоякісну продукцію виноградного розсадництва та можуть бути перспективною альтернативою для більш стійких і екологічно чистих методів ведення сільського господарства

Ключові слова: щепи; вегетативні органи; однорічний приріст; коренева система; мікрородорість *Chlorella vulgaris* Beijer.; германій

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Influence of varietal characteristics of winter wheat and weather conditions on lodging resistance and productivity

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Abstract. Growing technologies and variety selection are crucial for increasing yields and improving the quality of winter wheat grain. The area under winter wheat is the largest in Ukraine, which is associated with the production of high-quality grain. The aim of the study was to determine the influence of weather conditions and variety characteristics on winter wheat plant height, internode length, lodging resistance, productivity factor and yield during the years under study. In the course of the study, the following generally accepted methods were used: systematic approach, system analysis approach, analytical synthesis approach, field approach and statistical approach. The article presents data on the results of research with 20 varieties of soft winter wheat in the conditions of the Training and Practical Centre of Mykolaiv National Agrarian University from 2017 to 2023. Agricultural technology for growing winter wheat varieties is widespread in the steppes of southern Ukraine. The influence of weather conditions and varietal characteristics on lodging resistance and productivity of winter wheat was investigated.

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The results showed that the optimum plant height of winter wheat varieties ranged from 82.1 to 84.5 cm, and the highest yield was 6.32 t/ha in Staleva and 6.68 t/ha in Duma Odeska. A significant effect of varietal traits on stem length, second and last internode, number of stems formed per 1 m², grain weight in the ear and lodging resistance of winter bread wheat was established. Plants of the tested winter soft wheat varieties Staleva, Dyvo, Katarina, Felix, Ozerna, PONTICUS, Faust, Glaucus have a very high (9.0 points) resistance to lodging regardless of the weather conditions of the year. Ukrainian varieties Duma Odeska (6.68 t/ha) and Staleva (6.32 t/ha) achieved higher productivity. The obtained scientific results of the research contribute to the widespread use of the studied winter wheat varieties of this reasonably climatic zone and contribute to further improvement of grain production

Keywords: plant height; internode length; spike length; number of productive stems; weight of 1000 grains; soft winter wheat; amount of precipitation

INTRODUCTION

Under current conditions, an important factor in stabilizing and increasing high grain yields is the introduction of high-yielding, competitive new varieties with significant agro-ecological plasticity and increased adaptability to adverse and extreme environmental conditions, the most important of which is lodging resistance. In the south of Ukraine, where wheat crops often suffer from drought, plant height is almost always lower than in the north, so lodging is not common. However, in years with favourable moisture conditions and under irrigation, plants often lodge, resulting in significant yield losses.

Wheat is the main crop in many countries of the world, and in the steppe zone it is the main food crop, so the system of agronomic practices should focus on creating optimal conditions for high yields of this crop (Domaratskiy *et al.*, 2019). As the world's population grows, military operations lead to a decrease in the area of cultivated land and overall crop production, the problem of finding innovative ways to increase crop yields, thereby increasing global food supplies, arises. Wheat yields vary from year to year, depending on factors such as water availability during the growing season, the variety and agricultural practices used to grow the crop, and especially the nutrients applied (Panfilova, 2021).

The authors K. Mottaleb *et al.* (2022) and R. Ihle *et al.* (2022) pointed out that in poor countries, where people often suffer from hunger, wheat provides 14% of daily dietary energy and protein intake per person. Due to the hostilities in Ukraine, which is one of the world's major wheat producers and exporters, food prices have risen significantly, with serious implications for food security. According to the UN online database, in 2020, 864 million people – 8.9% of the world's population – suffered from hunger, while at least 63 countries imported wheat from Ukraine (The state of food security and nutrition..., 2020).

According to T. Rife *et al.* (2019), one of the ways to overcome the crisis in the global grain sector is to increase gross grain harvests by increasing yields. Studies conducted by O. Berdnikova and E. Kucherak (2021) found that variety selection is a key factor in obtaining technical indicators of high yield and grain quality. The development of new winter wheat varieties is one of

the ways to increase the profitability of winter wheat cultivation, but the average yield of winter wheat in Ukraine is 2.5 times lower than in Western Europe. There are several reasons for this, one of which is the use of outdated varieties that do not meet the requirements of modern high-intensity farming.

The research of M. Korkhova *et al.* (2022) found that the determining criteria for selecting modern winter wheat varieties are the degree of durability and response to growing conditions. Each variety has certain morph-agrobiological traits and characteristics so that it can develop its genetic potential if a favourable environment is created for it. A. Muszynska *et al.* (2021) found that lower internode bending (stem bending) is common in wheat, barley, and oats due to a marked difference in weight and strength between the upper and lower internodes. Plant height; stem length, diameter, and weight; ear weight; and stem wall thickness of soft winter wheat are known to be most strongly related to lodging resistance.

The study conducted by T. Shah *et al.* (2019) found that lodging resistance is completely dependent on internode length, plant height and stem bending strength. Reducing plant height develops tolerance to lodging due to a relatively low centre of gravity and a decrease in the aboveground load of the plant on the lower part of the stem in rice. A negative relationship was found between basal internode length and lodging index, indicating that longer internodes at the base may lead to a higher lodging index in winter wheat plants.

Studies conducted by F.J. Piñera-Chavez *et al.* (2020) found that in plant breeding, checking lodging resistance is very difficult, as this quantitative trait is controlled by different genes, and its expression is significantly affected by environmental factors. M. Bondarenko & M. Nazarenko (2022) argue that high-yielding genotypes increase yields by producing more ears, are more resistant to lodging due to lower plant height and grain weight per ear, respectively, and use fewer nutrients for stem formation.

As of 11.04.2023, the State Register of Plant Varieties (2022) includes more than 600 varieties of soft winter wheat, but their economic and biological

characteristics, including lodging resistance, have not been sufficiently studied. During state variety testing, plants cannot always get into favourable weather conditions for stem growth, which can lead to lodging. Yields of winter wheat varieties are influenced by climatic conditions of crop cultivation and agricultural practices.

The analysis of scientific sources showed that the chosen topic has been studied insufficiently. That is why the aim of the work was to determine the influence of weather conditions and varietal characteristics during the study period on lodging resistance and productivity elements of winter wheat plants.

MATERIALS AND METHODS

The field trials were conducted over six years (2017-2023) at the Educational and Research Centre of Mykolaiv National Agrarian University, located in the South of Ukraine. The experimental scheme included 20 varieties of soft winter wheat of Ukrainian and foreign selection: Ozerna, Staleva, Kvitka poliv, Legend of Bila Tserkva, Mudrist Odeska, Maria, Duma Odeska, Dyvo, Koshova, Zdobna, Myronivsky Institute of Wheat (MIW) Assol, and MIW Valencia, Pamyati Hirka, Kraevid, Katarina, Centurion, Felix, PONTICUS, Faustus, Glaucus, which are short-stemmed (50%), semi-dwarf (35%) and medium-sized (15%) (Table 1).

Table 1. Varieties of soft winter wheat by height (stem and ear)

| No | Medium-sized | Short-stemmed | Half dwarfs |
|----|----------------------------|----------------|--------------|
| 1 | Kvitka Poliv | Ozerna | MIW Valencia |
| 2 | The legend of Bila Tserkva | Steel | Katarina |
| 3 | MIW Assol | Mudrist Odeska | Centurion |
| 4 | | Duma Odeska | Felix |
| 5 | | Koshova | PONTICUS |
| 6 | | Maria | Faustus |
| 7 | | Zdobna | Glaucus |
| 8 | | Dyvo | |
| 9 | | Pamyati Hirka | |
| 10 | | Kraevid | |

Source: developed by the authors

Plants of all varieties tested had weakly filled straw. The area of the sowing plot was 70 m² and the accounting plot was 35 m². The experiment was designed by the method of randomization. Agricultural practices included sowing winter wheat in the first decade of October, using a seeding rate of 4.5 million seeds/ha. The soil of the experimental plot is a typical southern black soil, heavy humus with a slightly saline residue in the loess, humus content (0-30 cm) – 3.1-3.3%, average soil solution in the calculation (pH -6.8-7.2). On average, the topsoil contains 15-25 mobile nitrates, 41-46 mobile phosphorus and 389-425 mg/kg of exchangeable potassium.

The height of winter wheat plants was measured in the period before harvesting on 100 permanently allocated plants using a measuring ruler, which was evenly placed on the calculated area of each plot. The stem is measured from the soil surface to the top of the plant. The final indicator is the average height of the plants in the plot. The resistance to lodging of winter wheat plants was determined on a five-point scale: 5 points – no lodging, 4 points – weak lodging, 3 points – moderate lodging, 2 points – significant lodging, which

complicates harvesting, 1 point – significant lodging occurs long before harvesting and the crop is not suitable for combining. Observations were made every 5-10 days from the onset of this phenomenon until harvest.

The weight of 1000 grains was determined according to DSTU ISO 520:2015 (2016). The average number of grains per ear was determined by the ratio of the total number of grains after threshing 25 ears to the sum of the average sample, and the weight of grain per 1 ear was determined by the weight of grain per sheaf to the number of productive stems in the sheaf sample. Harvesting was carried out continuously from the entire accounting area. Soft winter wheat was harvested with a SAMPO-500 combine harvester (Finland). After threshing in each plot, the combine was stopped, and the grain was weighed and brought to the standard moisture content (14%) and purity (100%). The weather conditions during the years of research differed significantly. Thus, the 2017/2018, 2021/2022 and 2022/2023 agricultural years were medium-wet, with 338.5, 331.6 and 343.4 mm of precipitation during the growing season, respectively, while in 2019/2020 – 161.2 mm; 2018/2019 – 547.6 mm and 2020/2021 – 603.7 mm (Fig. 1).

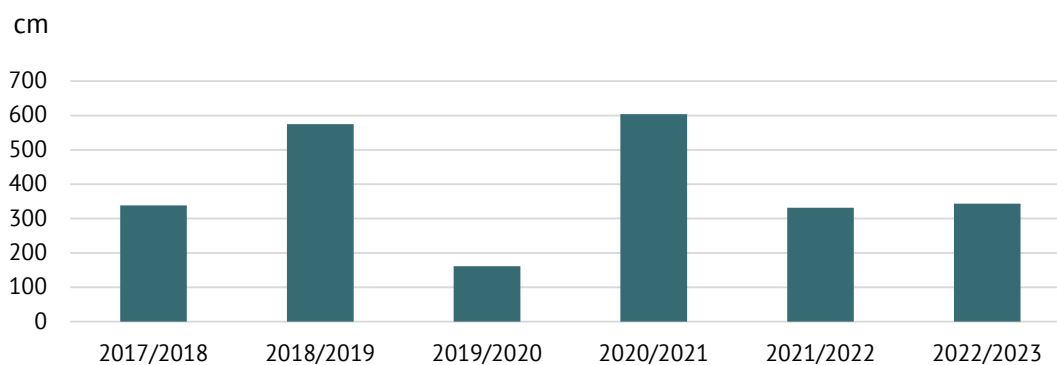


Figure 1. Amount of precipitation (mm) during the growing season of soft winter wheat plants, 2017/2018-2022/2023
Source: developed by the authors

Thus, the most favourable weather conditions were in 2018/2019 and 2020/2021, and the least favourable – in 2019/2020. Such contrasting conditions allowed the authors to study the influence of weather conditions on the formation of plant height, internode length, lodging resistance and grain productivity of the studied winter bread wheat varieties. Mathematical processing of the research results was performed using one-factor analysis of variance. The scale of R.E. Chaddock (Emmet & Chaddock, 1928) was used to assess the closeness of the relationship between the studied indicators. The value of the correlation coefficient can be used to estimate the strength of the relationship on the following scale: 0.1-0.3 – weak, 0.3-0.5 – moderate, 0.5-0.7 – significant, 0.7-0.9 – high, 0.9-0.99 – very high.

The experimental studies of plants (both cultivated and wild), including the collection of plant material,

were in accordance with institutional, national or international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

On average, over the six years of research (2017-2023), medium-sized soft winter wheat varieties of Kvitka poliv (108.6 cm), Legend of Bila Tserkva (106.9 cm) and MIW Assol (103.1 cm) formed 7.5-14.0% higher plant height than short-stemmed varieties (Kraevit, Mudrist Odeska, Ozerna, Duma Odeska, Staleva, Koshova, Zdobna, Dyvo, Maria, Pamyati Hirka) and by 18.6-23.8% more than semi-dwarfs (MIW Valencia, Katarina, Centurion, Felix, PONTICUS, Faustus, Glaucus) (Fig. 2).

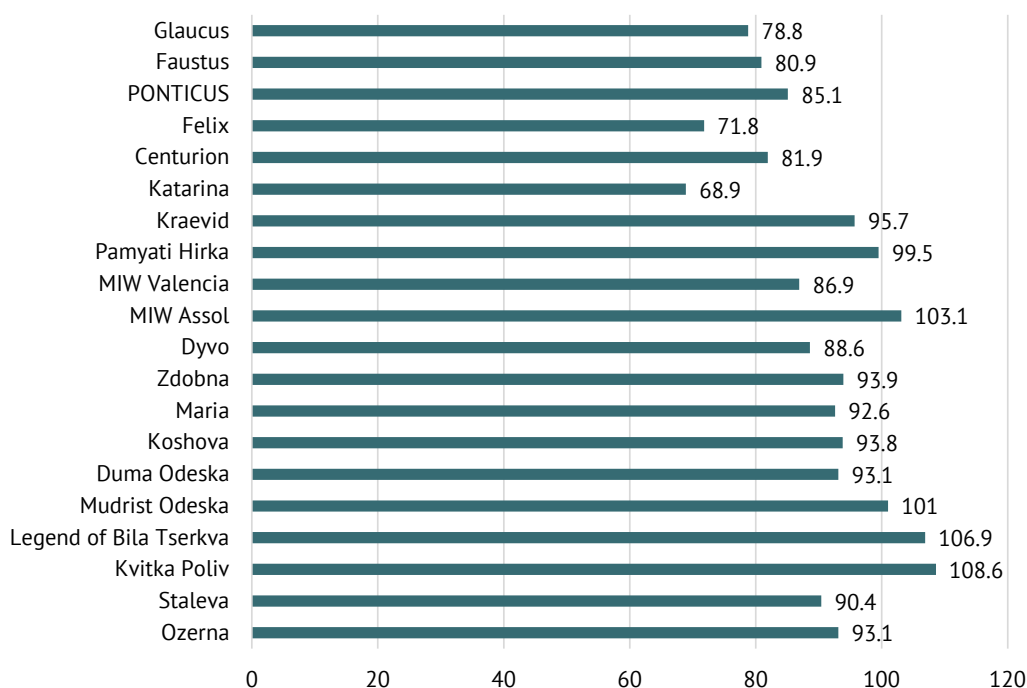


Figure 2. Influence of varietal features on the height of soft winter wheat plants (cm), average for 2017-2023
Source: developed by the authors

The lowest plant height on average for 2018-2023 was formed by semi-dwarf varieties: MIW Valencia (86.9 cm), PONTICUS (85.1 cm), Faustus (80.9 cm), Centurion (81.9 cm), Glaucus (78.8 cm), Katarina (68.9 cm) and Felix (71.2 cm). Medium-sized soft winter wheat varieties Kvitka Poliv, Legend of Bila Tserkva and MIW Assol had above average and high lodging resistance at the level of 7.0-8.2 points over the years of research, while short-stemmed varieties Maria, Mudrist Odeska,

Ozerna, Pamyati Hirka, Duma Odeska, Staleva, Koshova, Zdobna, Dyvo, Kraevid had lodging resistance ranging from 6.5 to 9.0 points. Resistance to lodging of semi-dwarf varieties MIW Valencia, Katarina, Centurion, Felix, PONTICUS, Faustus, Glaucus was high and very high (8.7-9.0 points).

The height of the stem of winter wheat of the studied varieties ranged from 59.2 cm (Felix) to 98.8 cm (Legend of Bila Tserkva) (Table 2).

Table 2. Indicators of lodging resistance and the main elements of productivity of soft winter wheat plants depending on the variety (average for 2017-2023)

| No. | Varieties | Stem height, see | The length of internodes, cm | | The number of productive stems per 1 m ² | Mass of grain from 1 ear, g | Resistance to lying down |
|-----|------------------------|------------------|------------------------------|----------|---|-----------------------------|--------------------------|
| | | | the second lower | the last | | | |
| 1 | Ozerna | 85.1 | 12.3 | 31.4 | 662 | 0.98 | 9.0 |
| 2 | Staleva | 82.1 | 12.1 | 30.4 | 651 | 1.02 | 9.0 |
| 3 | Kvitka Poliv | 98.7 | 15.5 | 32.1 | 663 | 1.00 | 7.7 |
| 4 | Legend of Bila Tserkva | 98.8 | 16.5 | 30.5 | 649 | 0.99 | 7.0 |
| 5 | Mudrist Odeska | 90.9 | 12.8 | 32.2 | 642 | 1.09 | 7.8 |
| 6 | Duma Odeska | 84.5 | 12.1 | 33.1 | 634 | 1.13 | 6.8 |
| 7 | Koshova | 85.6 | 12.2 | 29.5 | 618 | 1.07 | 6.8 |
| 8 | Maria | 84.7 | 12.4 | 30.1 | 615 | 1.05 | 8.0 |
| 9 | Zdobna | 85.7 | 12.0 | 32.2 | 640 | 1.05 | 6.5 |
| 10 | Dyvo | 80.6 | 12.2 | 33.3 | 621 | 1.05 | 9.0 |
| 11 | MIW Assol | 95.0 | 13.0 | 32.8 | 594 | 1.09 | 8.2 |
| 12 | MIW Valencia | 77.9 | 11.5 | 28.0 | 588 | 1.07 | 8.7 |
| 13 | Pamyati Hirka | 90.9 | 12.0 | 31.5 | 615 | 1.07 | 8.5 |
| 14 | Kraevid | 87.5 | 12.1 | 32.7 | 623 | 1.15 | 8.7 |
| 15 | Katarina | 62.1 | 7.9 | 21.2 | 554 | 0.96 | 9.0 |
| 16 | Centurion | 74.8 | 12.2 | 26.0 | 585 | 1.07 | 8.7 |
| 17 | Felix | 59.2 | 8.8 | 22.7 | 548 | 1.01 | 9.0 |
| 18 | PONTICUS | 75.2 | 10.2 | 27.0 | 588 | 1.00 | 9.0 |
| 19 | Faustus | 71.4 | 9.6 | 25.5 | 595 | 0.99 | 9.0 |
| 20 | Glaucus | 68.8 | 9.4 | 25.1 | 610 | 1.01 | 9.0 |
| | Average by grade | 82.0 | 11.8 | 29.2 | 610 | 1.05 | 8.3 |

Source: developed by the authors

The results of the research showed that the length of the second lower internode does not significantly affect the resistance to lodging of the studied winter wheat varieties. Thus, the plants of Kvitka Poliv (15.5 cm) and Legend of Bila Tserkva (16.5 cm) varieties formed a longer length of the second lower internode on average in 2017-2023, but their resistance to lodging was 7.7 and 7.0 points, respectively. The lowest (7.9 cm) was recorded in plants of the Katarina variety, whose resistance to lodging was very high – 9 points.

Shortening and thickening of the stem wall in the last (upper) internode allows avoiding yield losses due to breaking off of ears due to their excessive weight (fullness), adverse weather factors (strong winds, thunderstorms, rain, etc.) and late harvesting. Our re-

search partially confirms this. The smallest length of the last internode of winter wheat plants was formed in foreign-bred varieties – Katarina (21.2 cm); Felix (22.7 cm), Glaucus (25.1 cm); Faustus (25.5 cm); Centurion (26.0 cm) and PONTICUS (27.0 cm), while the resistance to lodging of these varieties was 8.7-9.0 points. The length of the last internode of the straw of plants of Ozerna, Staleva and Dyvo varieties was 30.4-33.3 cm, which is 4.1-14.0% more than the average for six years, but their resistance to lodging was very high (9 points).

No less important is the sowing density, which determines the resistance to lodging. More resistant to lodging (9 points) were winter wheat varieties (Felix, Katarina, PONTICUS, Faustus, Glaucus, Dyvo, Staleva,

Ozerna) with a density of productive stem of 548-662 plants/m². It was found that a smaller number of productive stems (618-663 pcs. per 1 m²) were formed by plants of the varieties Zdobna, Duma odeska, Koshova, Legend of Bila Tserkva, Kvitka poliv and Mudrist odeska, whose resistance to lodging was 6.5-7.8 points. Thus, the smallest productive stem stand (554 units/m²) was formed in plants of the Katarina variety, and the largest – 663 units/m² in plants of the Kvitka Poliv variety.

An important indicator of the yield structure is the grain weight of one ear, which also affects the lodging of the crop. The optimal size of the average grain weight in an ear varies and increases significantly with the emergence of new varieties. On average, over the years of research, a larger grain weight per ear was formed by winter wheat plants of the varieties Kraevid (1.15 g), Duma Odeska (1.13 g), MIW Assol (1.09 g), MIW Valencia (1.07 g), Pamyati Hirka (1.07 g) and Centurion (1.07 g). The lower weight of grain per ear was formed

by Ozerna (0.98 g/ear), Faustus (0.99 g/ear), and Legend of Bila Tserkva (0.99 g/ear).

Previous studies have shown that awned varieties have less resistance to lodging than awnless varieties (Korkhova *et al.*, 2022). Current research partially confirms this. The awned varieties Mudrist Odeska, Ozerna, Duma Odeska, Staleva, Koshova, Zdobna, Maria, Dyvo, Pamyati Hirka, Centurion, MIW Valencia, Kraevid formed 0.3 points more resistance to lodging than the awnless varieties MIW Assol, Kvitka Ooliv, Katarina, Legend of Bila Tserkva, Felix, Faustus, PONTICUS, Glaucus.

The length of the ear depends more on the varietal characteristics. The most important environmental factors are temperature, illumination and daylight hours. Lower temperatures will slow down the growth process. The ears become longer, so the yield potential increases. The largest average spike length over six years was observed in winter wheat plants of Glaucus (10.0 cm), Mudrist Odeska (10.1 cm) and Felix (12.6 cm), and the smallest in Centurion (7.1 cm) and Katarina (6.8 cm) (Table 3).

Table 3. The influence of varietal characteristics on elements of wheat ear productivity mild winter (average for 2017-2023)

| No | Varieties | Spike length, cm | The number of ears in an ear, pcs./ear | The number of grains in an ear, pcs./ear | Weight of 1000 grains, g |
|------------------|------------------------|------------------|--|--|--------------------------|
| 1 | Ozerna | 8.0 | 13.4 | 27.5 | 40.2 |
| 2 | Staleva | 8.3 | 16.2 | 33.1 | 40.3 |
| 3 | Kvitka poliv | 9.9 | 15.0 | 31.1 | 38.0 |
| 4 | Legend of Bila Tserkva | 8.1 | 15.6 | 30.1 | 38.3 |
| 5 | Mudrist odeska | 10.1 | 16.4 | 32.0 | 38.1 |
| 6 | Duma odeska | 8.6 | 16.9 | 35.6 | 37.4 |
| 7 | Koshova | 8.2 | 18.5 | 31.5 | 36.6 |
| 8 | Maria | 7.9 | 17.9 | 30.6 | 37.1 |
| 9 | Zdobna | 8.2 | 16.1 | 29.6 | 38.4 |
| 10 | Dyvo | 8.0 | 15.7 | 34.3 | 39.1 |
| 11 | MIW Assol | 8.1 | 16.4 | 33.8 | 41.3 |
| 12 | MIW Valencia | 9.0 | 17.2 | 36.8 | 40.4 |
| 13 | Pamyati Hirka | 8.6 | 16.9 | 35.6 | 38.6 |
| 14 | Kraevid | 8.2 | 16.2 | 28.9 | 39.1 |
| 15 | Katarina | 6.8 | 14.2 | 25.3 | 40.7 |
| 16 | Centurion | 7.1 | 14.4 | 30.8 | 41.8 |
| 17 | Felix | 12.6 | 16.0 | 28.6 | 39.2 |
| 18 | PONTICUS | 9.9 | 15.4 | 29.1 | 39.3 |
| 19 | Faustus | 9.5 | 14.4 | 28.8 | 38.7 |
| 20 | Glaucus | 10.0 | 14.1 | 29.1 | 39.0 |
| Average by grade | | 8.7 | 15.8 | 31.1 | 39.1 |

Source: developed by the authors

The main stage of plant growth is the period during which the number of ears is established. The process of spikelet differentiation in wheat occurs at the fourth stage of organogenesis, from the end of tillering to the beginning of heading. Each variety is characterized by a certain number of ears. Some varieties have a

low number of ears, while others have a high number of ears. On average, in 2017-2023, the highest number of spikelets per ear was formed by Duma Odeska (16.9 spikelets/ear), MIW Valencia (17.2 spikelets/ear), Maria (17.9 spikelets/ear) and Koshova (18.5 spikelets/ear), and the lowest number of spikelets per ear was 13.4

spikelets/ear in Ozerna, which is 15.2% less than the average number of spikelets per ear for all studied varieties. It was determined that the average number of grains per ear of the studied varieties ranged from 25.3 pcs/ear (Katarina) to 36.8 pcs/ear (MIW Valencia). Thus, the varieties MIW Valencia (36.8 seeds/spike), Pamyati Hirka (35.6 seeds/spike), Duma Odeska (35.6 seeds/spike) formed 14.5-18.3% more grains per spike than the average number of varieties.

Higher yields are achieved due to the formation of better grain filling, i.e. larger, more developed grains, at the later stages of plant growth and development. Grain filling is best characterized by the weight of 1000 grains. On average, over the years of research, the weight of 1000 grains was 39.1 g. This indicator was higher in the varieties Centurion (41.8 g), MIW Assol (41.3 g), Staleva (40.3 g) and Ozerna (40.2 g). The

lowest weight of 1000 grains was formed by the variety Koshova (36.6 g).

According to the results of the research, it was determined that the highest grain yield (6.88 t/ha) on average for 2017-2023 was formed by winter wheat plants of the Duma Odeska variety (6.68 t/ha), which is 5.4% more than in the Staleva variety; 6.0% more than in the Kraevid and Pamyati Hirka and Mudrist odeska varieties; 6.6% more than in the Zdobna variety; 7.0% more than in the Koshova variety; 7.3% more than in the Dyvo variety; 7.6% more than in the Ozerna variety; 9.0% more than Kvitka Poliv and Maria; 10.2% more than MIW Valencia; 10.8% more than Glaucus; 11.7% more than MIW Assol; by 12.1% than in the variety Legend of Bila Tserkva; by 13.8% than in the variety PONTICUS; by 14.7% than in the variety Faustus; by 20.5% than in the variety Felix; by 22.6% than in the variety Katarina (Table 4).

Table 4. Winter wheat grain yield losses from lodging and shedding depending on the variety, average for 2017-2023

| No. | Varieties | Biological yield, t/ha | Actual yield, t/ha | Crop losses, % |
|------------------------|------------------------|------------------------|--------------------|----------------|
| 1 | Ozerna | 6.49 | 6.17 | -4.9 |
| 2 | Staleva | 6.64 | 6.32 | -4.8 |
| 3 | Kvitka Poliv | 6.63 | 6.08 | -8.3 |
| 4 | Legend of Bila Tserkva | 6.43 | 5.87 | -8.7 |
| 5 | Mudrist Odeska | 7.00 | 6.28 | -10.1 |
| 6 | Duma Odeska | 7.16 | 6.68 | -6.7 |
| 7 | Koshova | 6.61 | 6.21 | -6.1 |
| 8 | Maria | 6.46 | 6.08 | -5.9 |
| 9 | Zdobna | 6.72 | 6.24 | -7.1 |
| 10 | Dyvo | 6.52 | 6.19 | -5.1 |
| 11 | MIW Assol | 6.47 | 5.90 | -8.8 |
| 12 | MIW Valencia | 6.29 | 6.00 | -4.6 |
| 13 | Pamyati Hirka | 6.58 | 6.28 | -12.3 |
| 14 | Kraevid | 7.16 | 6.28 | -12.3 |
| 15 | Katarina | 5.32 | 5.17 | -2.8 |
| 16 | Centurion | 6.26 | 6.00 | -4.2 |
| 17 | Felix | 5.53 | 5.31 | -4.0 |
| 18 | PONTICUS | 5.88 | 5.76 | -2.0 |
| 19 | Faustus | 5.89 | 5.70 | -3.2 |
| 20 | Glaucus | 6.16 | 5.96 | -3.2 |
| Average by grade | | 6.41 | 6.03 | -5.9 |
| NIR ₀₅ 2018 | | | 0.22 | |
| NIR ₀₅ 2019 | | | 0.25 | |
| NIR ₀₅ 2020 | | | 0.20 | |
| NIR ₀₅ 2021 | | | 0.24 | |
| NIR ₀₅ 2022 | | | 0.26 | |
| NIR ₀₅ 2023 | | | 0.15 | |

Source: developed by the authors

Thus, the resistance to lodging of wheat crops did not always affect the formation of grain yield. Thus, the varieties with high (7.7-8.7 points) and very high (9 points) resistance to lodging formed grain yields of 5.90-6.28 t/ha and 5.17-6.32 t/ha, respectively, while the varieties with medium resistance to lodging

(6.5-7.0 points) formed 5.87-6.68 t/ha. Grain yield losses due to lodging and grain shattering ranged from 2.0 to 12.3% on average in 2017-2023. Correlation analysis of the relationship between lodging resistance and the number of productive plant stems, ear weight and grain yield of the studied winter wheat varieties over

six years of research showed that there was no relationship for a number of varieties Ozerna, Staleva, Dyvo, Katarina, Felix, PONTICUS, Faustus and Glaucus.

For the varieties Legend of Bila Tserkva ($r=-0.89$), Koshova ($r=-0.78$), Zdobna ($r=-0.72$), MIW Valencia ($r=-0.90$), Pamyati Hirka ($r=-0.94$) and Kraevid ($r=-0.90$) and Centurion ($r=-0.92$), a high and very high inverse relationship between lodging resistance and the number

of productive stems per unit area was found, for MIW Assol varieties ($r=-0.67$), Mudrist Odeska ($r=-0.61$), Maria ($r=-0.60$), Duma Odeska ($r=-0.55$), a significant inverse relationship was found, and for Kvitka Poliv ($r=-0.49$) – a moderate inverse relationship (Table 5). That is, with an increase in the number of productive stems per 1 m², there is a decrease in lodging resistance of most winter wheat varieties.

Table 5. Correlation analysis between dormancy and indicators of the main elements of the productivity of winter wheat plants of different varieties

| No. | Varieties | Performance elements | | |
|-----|------------------------|---|-----------------------------|-------------|
| | | number of productive stems, pcs./m ² | mass of grain from 1 ear, g | yield, t/ha |
| 1 | Kvitka poliv | $r=-0.49$ | $r=-0.79$ | $r=-0.73$ |
| 2 | Legend of Bila Tserkva | $r=-0.89$ | $r=0.11$ | $r=-0.31$ |
| 3 | Mudrist odeska | $r=-0.61$ | $r=-0.57$ | $r=-0.41$ |
| 4 | Duma odeska | $r=-0.55$ | $r=-0.24$ | $r=-0.33$ |
| 5 | Koshova | $r=-0.78$ | $r=-0.32$ | $r=-0.61$ |
| 6 | Maria | $r=-0.60$ | $r=-0.26$ | $r=-0.50$ |
| 7 | Zdobna | $r=-0.72$ | $r=0.12$ | $r=-0.41$ |
| 8 | MIW Assol | $r=-0.67$ | $r=0.11$ | $r=-0.16$ |
| 9 | MIW Valencia | $r=-0.90$ | $r=0.42$ | $r=-0.18$ |
| 10 | Pamyati Hirka | $r=-0.94$ | $r=0.21$ | $r=-0.56$ |
| 11 | Kraevid | $r=-0.90$ | $r=0.55$ | $r=-0.15$ |
| 12 | Centurion | $r=-0.92$ | $r=0.46$ | $r=-0.22$ |

Source: developed by the authors

A weak direct correlation between resistance to lodging and grain weight per 1 ear was established for plants of varieties Legend of Bila Tserkva ($r=0, 11$), Zdobna ($r=0.12$), MIW Assol ($r=0.11$) and Pamyati Hirka ($r=0.21$), moderate for MIW Valencia ($r=0.42$), Centurion ($r=-0.46$) and significant for Kraevid ($r=0.55$). A high and significant inverse correlation between these indices was found for Kvitka Poliv ($r=-0.79$) and Mudrist Odeska ($r=-0.57$); moderate – for Koshova ($r=-0.32$) and weak – for Duma Odeska ($r=-0.24$) and Maria ($r=-0.26$). For all the studied winter bread varieties, there is an inverse correlation between resistance to lodging and yield, which ranges from weak – $r=-0.15-0.22$ (MIW Assol, MIW Valencia, Kraevid, Centurion) to high – $r=-0.73$ (Kvitka Poliv). Thus, the studies have established the influence of varietal characteristics of winter wheat on the formation of plant height, resistance to lodging, productivity elements and grain yield. The highest grain yield was formed by the variety Duma odeska, which is 6.68 t/ha with high resistance (7.8 points) to lodging and high yield losses from lodging and shattering (10.2%).

The research conducted by V.A. Vlasenko *et al.* (2018) with 50 varieties of winter wheat showed that the shorter the growing season of genotypes, the shorter the plants, which is also confirmed by our own research. It was determined that among the 20 varieties studied, the mid-season varieties Kvitka Poliv, Legend of Bila Tserkva and MIW Assol formed the highest plant height

(103.1-108.6 cm), and the lowest was formed by semi-dwarf varieties (68.9-86.9 cm) – MIW Valencia, PONTICUS, Faustus, Centurion, Glaucus, Katarina, and Felix.

Plant height plays a very important role in the formation of grain yields, and is at the same time an important component of the resistance of cereal plants to lodging. According to the research of W-G. Li *et al.* (2022) found that lodging resistance varies greatly depending on the plant height of each variety. Therefore, it is necessary to take this into account when selecting varieties for different soil and climatic growing conditions, agrophones and predecessors. Current research confirms this statement. Thus, the medium-sized varieties Kvitka Poliv, Legend of Bila Tserkva and MIW Assol had above average and high resistance to lodging (7.0-8.2 points) during all years of research, while in short-stemmed varieties the resistance to lodging ranged from 6.5 to 9.0 points.

L. Wang *et al.* (2022) state that with decreasing plant height of winter wheat, productivity increases. Ye. Zaika (2021), F. Spolidorio (2019) argue that short winter wheat varieties are a source of redistribution mechanisms that affect plastic matter, so that tall varieties with high stem strength can outperform short varieties of yield. Current research confirms this. Thus, on average, over the years of research (2017-2023), the winter wheat variety Duma Odeska has a maximum yield of 6.88 t/ha, which is 0.88-1.71 t/ha higher than the

semi-dwarf wheat varieties Centurion, MIW Valencia, Felix, Katarina, Faustus, PONTICUS and Glaucus.

The high grain yield of winter wheat is influenced by the interaction of many factors, namely the number of productive stems, thousand grain weight and grain quality (Tsvey *et al.*, 2021). M. Lozinskiy *et al.* (2021) determined that grain quality or productivity largely depends on the components caused by the action and interaction of genetic factors, so the main ear plays a key role in shaping grain productivity and wheat grain yield.

According to the research of M. Korkhova *et al.* (2022) conducted during 2020-2022 with winter wheat varieties, the largest weight of 1000 grains was formed when growing the variety Duma odeska, which averaged 37.2 g, which is 0.2 g less than in the current research. Research by Bazalii *et al.* (2019) showed that in the South of Ukraine, it is necessary to grow plastic wheat varieties with increased yield stability (Odesa, Kherson Bezosta, Clarissa, Kherson 99, Nakhidka Askaniyska) if there are strict stress limits. Plant height plays a major role in the resistance of cereals to lodging (Rachon *et al.*, 2020). Plant height is closely related to lodging resistance at all stages of cereal development. Varieties with high lodging resistance are better than those with low lodging resistance because they are able to withstand lodging pressure.

T. Makoveychuk *et al.* (2018) determined that lodging of cereals, especially high-yielding wheat crops, is one of the main factors limiting the high yield. Losses of winter wheat grain yield due to lodging can be in the range of 10-80 % due to deterioration of harvesting conditions. A. Zhupina *et al.* (2021) found that in many populations of winter wheat, there is a high interdependence between ear grain weight and grain yield ($r=0.624...0.803$), which suggests the prospects of selecting for yield by the "ear grain weight" indicator.

Thus, since the studies were conducted in years with different climatic conditions, there is no consensus among scientists on the influence of different morphological traits on lodging resistance and grain yield formation of soft winter wheat varieties. With the emergence of new varieties of production, this issue requires further research.

CONCLUSIONS

According to the results of field and laboratory studies conducted during 2018-2023 in the Southern Steppe of Ukraine, a significant influence of varietal characteristics on the formation of plant height, stem length, second and last internodes of winter bread wheat, number of productive stems per 1 m², grain weight per ear and lodging resistance was found. Resistance to lodging of wheat crops did not always affect the formation of grain

yield. The varieties with high (7.7-8.7 points) and very high (9 points) resistance to lodging produced grain yields of 5.90-6.28 t/ha and 5.17-6.32 t/ha, respectively, while the varieties with medium resistance to lodging (6.5-7.0 points) produced 5.87-6.68 t/ha. Grain yield losses due to lodging and grain shattering ranged from 2.0 to 12.3% on average over the years of research.

The highest productivity was recorded in the varieties of Ukrainian breeding Mudrist Odeska (6.28 t/ha) and Duma Odeska (6.68 t/ha), created at the Selection and Genetic Institute – the National Centre for Seed Science and Variety Studies of the National Academy of Agrarian Sciences; Pamyati Hirka (6.28 t/ha) and Kraevid (6.28 t/ha) – National Research Centre "Institute of Agriculture of the National Academy of Sciences of Ukraine" and Staleva (6.32 t/ha) and Ozerna (6.17 t/ha) – Bor Farm. With the increase in the number of productive stems per 1 m², the lodging resistance of most winter wheat varieties decreased. The most resistant to lodging were (Felix, Katarina, PONTICUS, Faustus, Glaucus, Dyvo, Staleva, Ozerna) with a density of productive stems of 548-662 pcs./m², and less resistant to lodging were (Zdobna, Duma Odeska, Koshova, Legend of Bila Tserkva, Kvitka Poliv and Mudrist Odeska) with the number of productive stems 618-663 pcs./m².

Correlation analysis of the relationship between the lodging resistance index and the number of productive plant stems, ear weight and grain yield of the studied winter wheat varieties during six years of research showed that there is no relationship for a number of varieties Ozerna, Staleva, Dyvo, Katarina, Felix, PONTICUS, Faustus and Glaucus. A high and very high inverse relationship between lodging resistance and the number of productive stems per unit area was found for the varieties Legend of Bila Tserkva, Koshova, Zdobna, MIW Valencia, Pamyati Hirka, Kraevid and Centurion. A high and significant inverse correlation between lodging resistance and grain weight per ear was found for Kvitka Poliv and Mudrist Odeska. For all tested winter bread wheat varieties, there is an inverse correlation between lodging resistance and yield, which ranges from weak to high. In the future, it is planned to characterize the effect of weather conditions and characteristics of winter wheat varieties on grain quality, which will provide a more complete description of the winter wheat varieties under study.

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CONFLICT OF INTEREST

There is none.

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Вплив сортових особливостей пшениці озимої та погодних умов на стійкість до вилягання та продуктивність

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Анотація. Технології вирощування, вибір сорту є вирішальним чинником підвищення врожайності та покращення якості зерна пшениці озимої. Посівні площі пшениці озимої посідають перше місце в Україні, з чим пов'язане виробництво якісного зерна. Метою роботи було визначити вплив погодних умов та особливостей сорту на висоту рослин пшениці озимої, довжину міжвузлів, стійкість до вилягання, коефіцієнт продуктивності та врожайність протягом досліджуваних років. У процесі дослідження застосовувалися загальноприйняті методи: системний підхід, підхід системного аналізу, підхід аналітичного синтезу, польовий підхід та статистичний підхід. У статті наведено дані про результати проведених досліджень із 20 сортами пшениці м'якої озимої в умовах Навчально-практичного центру Миколаївського національного аграрного університету з 2017 по 2023 роки. Агротехніка вирощування сортів пшениці озимої широко поширена в степах півдня України. Досліджено вплив погодних умов та сортових особливостей на стійкість до вилягання та продуктивність пшениці озимої. Результати показали, що оптимальна висота рослин сортів

пшениці озимої становила від 82,1 до 84,5 см, а найвища урожайність – 6,32 т/га у сорту Сталева та 6,68 т/га у сорту Дума Одеська. Встановлено достовірний вплив сортових ознак на довжину стебла, друге та останнє міжвузля, кількість стебел, що утворюються на 1 м², масу зерна в колосі та стійкість до вилягання пшениці м'якої озимої. Рослини досліджуваних сортів пшениці м'якої озимої Сталева, Диво, Катаріна, Фелікс, Озерна, ПОНТІКУС, Фауст, Глаукус мають дуже високу (9,0 балів) стійкість до вилягання незалежно від погодних умов року. Вищу продуктивність досягли українські сорти Дума Одеська (6,68 т/га) та Сталева (6,32 т/га). Одержані наукові результати досліджень сприяють широкому використанню досліджуваних сортів пшениці озимої в цій обґрунтовано-кліматичній зоні та сприяють подальшому вдосконаленню виробництва зерна

Ключові слова: висота рослин; довжина міжвузлів; довжина колоса; кількість продуктивних стебел; маса 1000 зерен; пшениця м'яка озима; сума опадів

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Assessment of barley varieties by the level of genotypic variability of quantitative traits

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Abstract. The investigation of the genetic variability of barley varieties is particularly important in the context of a changing climate and the need to ensure agricultural productivity in the face of environmental challenges. The purpose of the study was to assess the tolerance of barley varieties to soil salinity in order to identify the most productive and adapted varieties. To achieve this goal, the salt tolerance of barley varieties was diagnosed and varieties that showed high resistance to salinity were identified. As a result of a study of 45 varieties of barley, it was found that 37 of them showed salt tolerance, but as they grew, some of them could not cope with salinization

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and stopped their development. Of these 37 varieties, 13 genotypes were selected, which had real salt tolerance and continued to grow and develop under stressful conditions, having the ability to give a satisfactory yield in comparison with the standard variety. These varieties are successfully used as testers in hybrid crosses and have a combination of useful characteristics, which makes them valuable for agricultural practice. The study also showed that different characteristics have different degrees of genetic variability. Thus, according to the data obtained, the number of grains in the ear and the weight of 1000 grains have high genetic variability, indicating the importance of genetic factors in their formation. These characteristics play a key role in the selection of plants to increase the yield and quality of grain. The results obtained are of practical importance for agricultural producers, as they can more accurately choose barley varieties that are most suitable for local conditions. This contributes to an increase in yield and product quality, which is important for ensuring food security and economic efficiency of agriculture

Keywords: yield; salt tolerance; selection; breeding; aridity

INTRODUCTION

The selection of agricultural crops, including barley, is an important stage in increasing agricultural productivity and ensuring food security. Genotypic variability, that is, the diversity of genetic characteristics of barley varieties, plays a key role in the development and introduction of new varieties that can meet the needs of agriculture. In addition, their adaptation to various environmental conditions depends on the modification and genetic variability of cultivated plants (Hudzenko *et al.*, 2021).

The study of adaptive changes and genetic variability of cultivated plants is an object of research within the framework of ecological breeding carried out in various natural conditions. Currently, statistical methods are available that combine ecological and geographical data with information about plant characteristics to create strategies aimed at identifying the features of the genetic structure of plant populations based on the characteristics of their germplasm (FIGS). This approach allows identifying links between plant traits and environmental parameters, which can help in identifying regions where germplasm with certain useful traits can be found. Then, based on the information received, it is possible to select suitable samples for further research from large collections of germplasm. An alternative approach is to identify places where new collections of germplasm should be collected in order to look for rare features. This can significantly speed up the selection process.

Conducting research in the field of assessing the genotypic variability of barley varieties, Y. Turuspekov *et al.* (2016) argue that in Kazakhstan, as in many other countries, special attention is paid to the selection and assessment of barley varieties with high yields, adapted to local agro-climatic conditions and other important qualities. Assessment of the genotypic variability of quantitative traits of varieties plays a key role in this process, allowing the identification of the most promising varieties for further development and introduction into agriculture.

Barley is considered a crop that is relatively well adapted to the soil salinity, and different genotypes of barley have the potential for high yields even in saline

conditions. Many researchers who studied resistance at a non-genetic level, including A. Zatybekov *et al.* (2020) and A. Dreiseitl (2020), demonstrated a wide range of genetic variability in barley, especially in relation to its salt tolerance. Therefore, the study of the germplasm of barley and its genetic reactions to different levels of salinity can be an important and useful continuation in the existing area of research.

Research on biological and agronomic tolerance of barley varieties to salinity remains extremely important for several reasons. According to A. Amalova *et al.* (2021) changing climatic conditions in the world, including an increase in the frequency of extreme weather events, may be accompanied by an increase in soil salinization in some regions. Conducting such studies plays a key role in the development of barley varieties that are able to survive and grow on saline soils, which, in turn, helps agricultural enterprises adapt to new climatic realities.

Y. Genievskaya *et al.* (2023) argue that the increase in the level of soil salinity in some regions of the world is caused not only by climate change, but also by improper use of water resources and other human factors. This creates an urgent need for plant varieties that can successfully grow and develop on saline soils, ensuring food security and increasing agricultural productivity. Such studies contribute to the conservation of soil resources, reduce the cost of fertilisers and agrochemicals, and the introduction of modern biotechnological methods to create resistant varieties of barley.

Researchers dealing with the topic of assessing barley varieties by the level of genotypic variability of quantitative traits face several difficulties, namely: a limited amount of research; difficulties in methodology; insufficient attention to certain aspects, such as the influence of the environment and genetic factors on quantitative traits; heterogeneity of research data. To solve these problems and promote further research, it is necessary to develop general methodologies for assessing genotypic variability, and to assess which varieties of barley adapt better to extreme climatic conditions, which will help farmers choose the most suitable varieties.

Thus, the study of the biological and agronomic resistance of barley varieties to salinization remains relevant and important for ensuring the sustainability of agriculture, increasing productivity and mitigating the negative effects of climate change and ecology. The purpose of the study is to assess the level of resistance of barley varieties to soil salinization to develop and recommend the most productive and adapted varieties to improve agriculture and sustainability in a changing climate. To achieve this goal, the following tasks were set: to diagnose the salt resistance of barley varieties, and to identify crop varieties that have shown high resistance to salinity.

MATERIALS AND METHODS

A field experiment was conducted in 2021 to evaluate barley varieties by the level of genotypic variability of quantitative traits. The research was conducted on the territory of Kazakh Scientific Research Institute of Rice

Growing named after I. Zhakhayev, Kyzylorda city. The climate in the Kyzylorda region is characterised as sharply continental with pronounced seasons. Summers are hot and dry, and winters are cool and unstable, with little snow. The annual precipitation is about 130 mm, and in some very dry years, it can drop to 40 mm. The aridity of the climate is the main limiting factor for agriculture and vegetation in this area. The soils on the experimental site belong to the type of meadow-swamp soils. The humus content in the soil is 1.03%, which indicates very low fertility. A dense residue above 1% indicates the presence of organic material in the soil. The mechanical composition of the soil is characterised as a medium loam. The object of the study was 42 collectable samples of barley, the world collection (Table 1). This set of samples represents a variety of genetic and ecological groups of barley from different regions of the world and provides a basis for research in the field of breeding, genetics, and agronomy of this crop. The seeding rate is 65 grains per 1 m.

Table 1. Barley varieties under study

| No. | Ecological and geographical group | Quantity | Variety samples | Country/scientific organisation |
|-------|-----------------------------------|----------|---|---|
| 1 | Samples from Kazakhstan | 10 | Jailau, Saule, Asem | LLP "Kazakh Research Institute of Agriculture and Plant Growing" |
| | | | Syr Aruy, Inkar, Shahristan, Kaysar | Kazakh Scientific Research Institute of Rice Growing named after I. Zhakhayev |
| | | | Granal, Karabalyksky 150 | Karabalyk Agricultural Experimental Station |
| 2 | Samples from CIS-countries | 5 | Odesky 100, Dnipropetrovsky 435, Dnipropetrovsky 85, Donetsk 8, Kharkivsky 74 | Ukraine |
| 3 | European group | 10 | Spring, Marni, Steploe, Scarlett, Millita | Germany |
| | | | Ruby, Accent, Diamond, Forum, Amulet | Czech Republic |
| 4 | Anatolian Group | 7 | k-6891, k-6853, k-520645, k-6848 | Turkey |
| | | | Rihane, Harmal, Legnee | Syria |
| 5 | North American group | 10 | Atlas 46, MT960225, Keystone, Baronesse, Conrad, Stark | USA |
| | | | Stm 48076, Palliser, Harrington, k-920 | Canada |
| Total | | 42 | | |

Source: compiled by the authors

Soil analyses were carried out in the laboratory of the Joint Stock Company (JSC) National Centre of Expertise and Certification in the city of Kyzylorda, which has the appropriate accreditation status. In the course of the study, the methodology of the state variety testing of agricultural crops was used, which provided for strict monitoring of the parameters of the growth and development of wheat plants. The following parameters were measured: length of the upper internode, number of plants that yielded, plant height, number of ears per square metre of plot, weight of 1000 grains, number of grains in each ear, and total weight of grains harvested from each plant.

The number of productive barley stems was calculated by counting the number of stems on an area

of 1 m². The number of ears was calculated using the sampling method on each square metre of the field to determine the sowing density. The weight of 1000 grains was determined by taking two samples of 500 grains and weighing with an accuracy of 0.01 g. The weight of grain from the ear – by collecting samples of ears and subsequent weighing of grains. To diagnose salt tolerance, the method of assessing salt tolerance through seed germination in salt solutions was used. This method can determine the salt tolerance of plants and assess their ability to survive and grow in saline soils. The method of genetic analysis was used to assess the genotypic variability, which makes it possible to assess the diversity of genetic characteristics of barley varieties in the study. Thus, the conducted experiments

considered the features of climate, soil cover, and observation methods, which allowed the study to obtain reliable results and draw conclusions regarding the assessment of barley varieties by the level of genotypic variability of quantitative traits. The obtained results were processed for reliability using two-factor analysis of variance using Microsoft Excel and the Statistica 10 software suites. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

Cultural specifics of barley cultivation in Kazakhstan in 2021 were influenced by various climatic and soil factors, which affected the effectiveness of this agricultural process. Usually, the cultivation of barley in Kazakhstan includes early sowing, following rice. According to the agrochemical analysis of the soil, the average content of dense residue ranges from 0.6% to 0.9%. On such a medium-saline background, varieties differ little in salt tolerance. For a more accurate assessment of the differences in salt tolerance, a highly saline background with a dense residue content of 1.65% was used, for which barley was the predecessor, and barley sowing was carried out at a late date.

In 2021, Kazakhstan experienced an extremely dry climate, with only 21 mm of precipitation recorded during the growing season. The drought in May had a particularly negative impact on the growth and development of barley, when the air temperature reached 43.3°C, with a complete absence of precipitation. The combination of atmospheric and soil drought negatively affected the formation of plants and yields. In June and July there was unstable temperature and lack of precipitation. On some days, the air temperature rose

to an abnormal +52°C, which accelerated the ripening and filling of grain. The growing season of barley was 66-70 days, which is respectively almost 3 weeks earlier than in previous years. Such stressful climatic conditions only aggravated the negative impact of repeated sowing of barley by barley. This led to the development of fusarium root rot, atmospheric and soil drought, and an increase in the content of dense residue in the soil to 1.62%. Also in 2021, characterised by unfavourable climatic conditions, barley plants faced a number of adverse factors that seriously affected their development and yield. Late spring frosts and lack of moisture in the soil posed serious challenges for the crop. Plants began to show signs of stress, such as a decrease in leaf turgor, yellowing and drying of leaves, and sometimes even complete death of plants.

The study was carried out considering the biological salt tolerance and agronomic salt tolerance of varieties. This important study identified differences in the breeding material depending on its geographical origin. Out of the total number of 45 varieties studied, it was found that 37 genotypes had biological salt tolerance, which can be useful when grown in saline or saline soils. However, despite their ability to transfer salt, they were unable to maintain their viability when re-sowing barley. It is important to note that among the studied varieties, 13 genotypes were identified that had true salt resistance. These varieties have demonstrated the ability to maintain productivity even under stress conditions, such as unfavourable climatic conditions and soil salinity. The obtained results emphasise the importance of long-term breeding programmes and research in order to create resistant plant varieties capable of coping with adverse environmental conditions and providing sustainable products even in conditions of climatic fluctuations and soil salinity (Fig. 1).

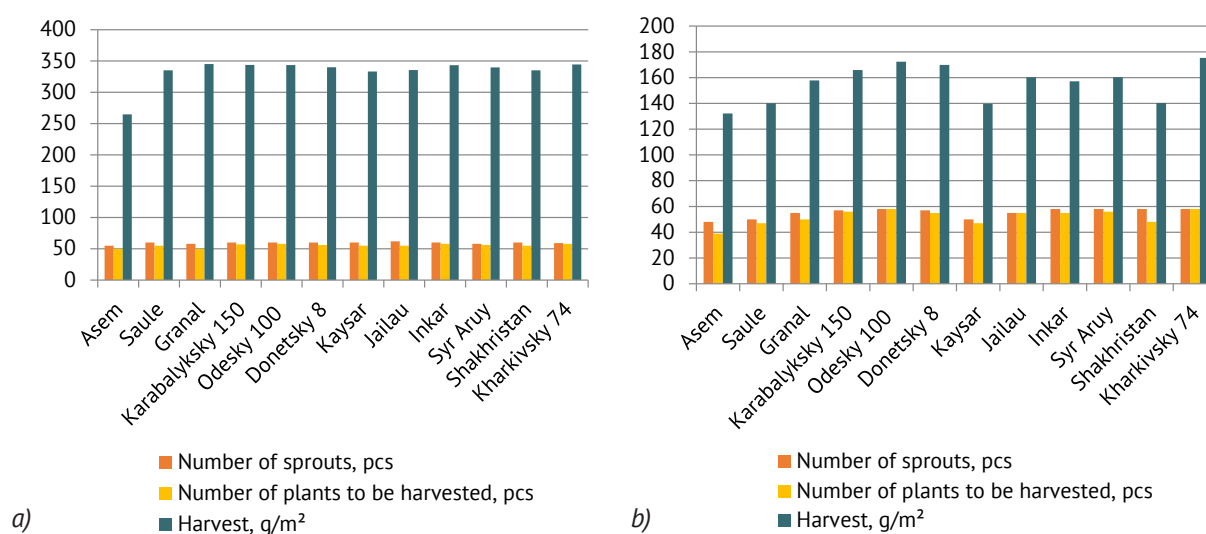


Figure 1. The impact of predecessors on the level of barley yield in rice crop rotation: a) predecessor – rice; b) predecessor – barley

Source: compiled by the authors

Notably, the selected 13 varieties that have real salt resistance are actively used as reference samples in cross-hybridisation and represent important suppliers of genetic characteristics that can be useful in the selection process and the development of breeding programmes for improving barley varieties. The analysis of the data obtained allows drawing several important conclusions. Thus, different varieties of barley have different yields depending on their predecessors. For example, the Asem variety has a yield of 264.8 g/m² after rice and 132.1 g/m² after barley. This indicates that the predecessor affects yield, and the need for careful selection of the predecessor when planning crop rotations and determining which crops

are best combined with barley to maximise yield. Some barley varieties, such as Odesky 100 and Kharkivsky 74, show stable yields regardless of the predecessor. This may be important for farmers who are looking for sustainable varieties that can produce a good harvest in various conditions.

The results of the study indicate that the arid climate and repeated sowing of barley have a significant impact on the development of quantitative characteristics of this crop. It is especially important to note that these factors not only affect the yield, but also modify other quantitative characteristics of barley, such as the number of ears, grain weight, and even the structure of plants (Fig. 2).

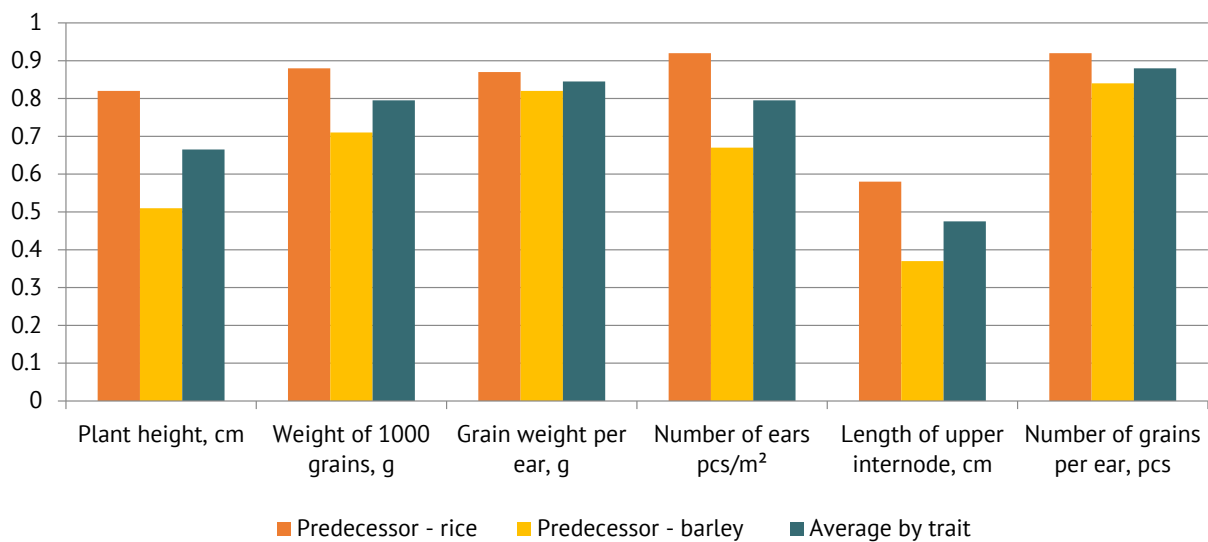


Figure 2. Modification of genotypic variability under the influence of predecessors

Source: compiled by the authors

Thus, the data obtained reflect the influence of predecessors (rice and barley) on the genotypic variability of some quantitative traits of barley culture. For example, the height of plants and the number of ears per 1 m² were higher with the predecessor "rice" compared to "barley". The average value for plant height was 0.82 for the predecessor "rice" and 0.51 for "barley". Similarly, the number of ears per 1 m² was higher with the "rice" predecessor (0.92) compared to "barley" (0.67).

The characteristics of the length of the upper internode, the number of grains in the ear, the weight of 1000 grains and the total weight of the grain also show variations depending on the predecessor. Therefore, in general, it can be concluded that the choice of a predecessor can affect the genotypic variability of barley and its quantitative characteristics. Thus, the study showed that dry climate and repeated sowing lead to changes in the growth and development of barley plants, which, in turn, affects the quantity and quality of the crop. This modifying effect emphasises the importance of adapting agricultural practices and varieties to specific

climatic conditions and agrotechnical factors in order to achieve optimal results in agriculture.

A subsequent study of the genetic variability of quantitative traits of barley allows us to identify several key observations. Different characteristics have different degrees of genetic variability. Signs such as the number of grains in an ear and the weight of 1000 grains have a high genetic variability – more than 49%, which means that genetic factors play an important role in their development. In addition, these two parameters play an important role in the selection of plants at the early stages of hybridisation in order to assess their productivity. This is information that can be valuable in the selection of barley varieties in order to increase the yield and quality of grain.

Genetic variability in traits, such as yield and duration of the growing season, is also high. This underlines the importance of genetic diversity in the selection of barley varieties and the selection of suitable varieties for specific climatic and soil conditions. On the other hand, plant height varies significantly depending on

growth factors and the interaction between plant genetic information and climatic conditions. This is due to the low value of the genotypic variability of this trait,

which was only 12.3%. Thus, the height of plants is more affected by external factors and growing conditions than by genetic characteristics (Table 2).

Table 2. Percentage contribution of the studied factors to the variability of economically important characteristics of the barley crop

| Features | Genotype | Random factors |
|--------------------------------|----------|----------------|
| Yield | 25.8** | 2.1 |
| Duration of the growing season | 27.8** | 10.5 |
| Weight of grain from the ear | 10.2** | 5.2 |
| Number of grains in one ear | 50.6** | 3.1 |
| Weight of 1000 grains | 49.2** | 3.7 |
| Number of productive stems | 13.2** | 4.1 |
| Productive tilling capacity | 15.7** | 3 |
| Plant height | 12.3** | 4.3 |

Note: reliable: at $P < 0.01$ **

Source: compiled by the authors

In general, the data obtained emphasise the importance of the genetic diversity of barley varieties and the need to take this diversity into account when breeding and selecting varieties to optimise grain yield and quality in various climatic conditions. Analysis of genetic variability among varieties showed that the conditions

of subsequent sowing of barley had the greatest impact on quantitative characteristics. As a result of the study, genotypes with a high level of characteristics in this set were identified, especially with respect to drought resistance, which was determined based on the length of the upper internode as a phenotypic indicator (Fig. 3).

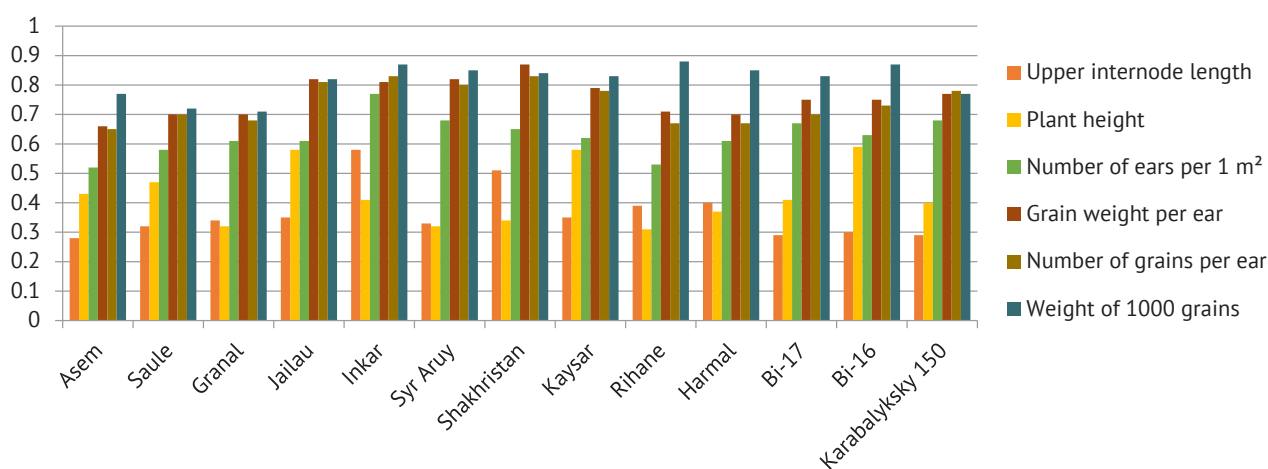


Figure 3. The level of genetic variability of quantitative characteristics in the context of crop rotation with rice (barley as predecessor)

Source: compiled by the authors

According to the results, significant variability was found in key characteristics, such as the number of ears per m^2 , plant height, the length of the upper internode, the weight of 1000 grains, the weight of grains in the ear, and the number of grains in the ear between different varieties. This highlights the potential for improving yields and product quality through breeding and selection work. This allows breeders and agronomists to more accurately select barley varieties that are best adapted to specific growing conditions, considering the

desired product characteristics. In addition, observing the differences between barley varieties from different regions (Kazakhstan, Syria) emphasises the importance of local adaptations and specific characteristics for each region. This means that the selection of varieties for specific climatic and soil conditions can be more effective if the genetic characteristics of varieties adapted to these conditions are considered.

In general, the results obtained emphasise the importance of the genetic diversity of barley varieties and

the need for intensive breeding and agrotechnical solutions to optimise yields in various agro-climatic zones and improve the quality of agricultural products.

DISCUSSION

The study of genotypic variability in barley varieties and the maintenance of varietal biodiversity have profound ecological and agricultural implications. An important environmental benefit is the resilience of agriculture to adverse conditions, such as climate change or disease epidemics, due to the variety of varieties that are ready to adapt to changes. It also helps to reduce the use of chemical pesticides and fertilisers, which has a positive impact on the environment and human health (Beleggia *et al.*, 2021).

Moreover, the assessment of genetic variability contributes to the conservation and increase of the genetic resources of cultivated plants, which is strategically important for agricultural sustainability and food safety. Knowledge of genotypic variability allows creating varieties that are better adapted to changing climatic conditions and can increase yields and product quality. Thus, the assessment of the genetic variability of barley varieties has a direct impact on the conservation of natural resources, the level of productivity and economic efficiency of agriculture, and contributes to food security (Dracatos *et al.*, 2019; Hickey *et al.*, 2021). The selection of agricultural crops, including barley, is the most important component of the agricultural sector of Kazakhstan, since the country has a variety of agro-climatic zones, from steppes to mountainous areas, and, consequently, there is a need for adapted and productive varieties capable of providing stable and high yields in various regions (Iannucci *et al.*, 2021).

Scientific research devoted to the assessment of varieties of barley and other crops by the level of genotypic variability of quantitative traits is carried out regularly in agricultural research institutions, universities, and agricultural enterprises. These studies help to select and develop varieties that are best adapted to specific growing conditions and have the best agricultural characteristics. They provide important information for agricultural research and allow optimising agricultural practices in a climate with low precipitation and aridity (Czembor *et al.*, 2021). There are also studies that confirm the presence of intraspecific variability among barley varieties. This means that even within the same species, there may be different genotypes with different characteristics (Alipour *et al.*, 2019; Bukhari *et al.*, 2021).

Along with this, M.Zh. Nurpeissov *et al.* (2015) note that there is a need to increase agricultural productivity in Kazakhstan, where agricultural products, including cereals, play an important role. The assessment of genotypic variability allows creating new varieties capable of providing high yields and product quality, which, in turn, contributes to an increase in the overall productivity of agriculture. In addition, the creation of

varieties with high resistance to pests and diseases is also important to reduce crop losses and increase stability. The findings of many authors, in particular A.T. Pham *et al.* (2020) and R. Sharma *et al.* (2018), also show that genetic variability depends on specific climatic, soil, and other regional factors. This may emphasise the importance of choosing varieties, considering the specific conditions of regional cultivation, which is also demonstrated in the study.

A. Zatybekov *et al.* (2020) emphasise that changing climatic conditions can seriously affect agro-climatic situation in various regions of Kazakhstan. Assessment of genotypic variability plays an important role in the creation of varieties that can successfully adapt to new climatic conditions and extreme events, such as droughts and high temperatures. Thus, it contributes to ensuring the sustainability of agriculture to environmental changes and the preservation of high crop productivity in a changing climate, which is also reflected in the study. It is important to note that some barley varieties can detect high genetic diversity, which manifests itself in significant fluctuations in quantitative characteristics in different growing conditions and in different regions. This may indicate the possibility of selecting varieties that are most suitable for specific regional conditions (Kaur *et al.*, 2022).

Some varieties may have low genetic variability, which means that quantitative traits remain stable under different conditions. This can be useful for farmers who are looking for stable and predictable results when growing barley (Wiegmann *et al.*, 2019). Along with this, F. Novakazi *et al.* (2020) note that an important result of research may be an assessment of the quality of products obtained from different varieties of barley. Some varieties may have a high protein content, which is important for beer production, while others may stand out with good yields.

A study by M. Mehnaz *et al.* (2021) shows that the results of assessing the genetic variability of barley varieties play an important role in agriculture and plant breeding. They help agricultural producers and researchers to choose and develop the best varieties, considering different growing conditions and consumer preferences. This is important for increasing the productivity and efficiency of agricultural production. The results obtained coincide with the findings of A. Jamshidi & H.R. Javanmard (2018), who found a high degree of heritability in the grain yield from the plant, and in the yield index, the weight of 1000 grains, and the number of grains per ear. The highest level of variability, both genetic and phenotypic, was found in the grain yield from the plant. The researchers also found that some signs, such as the height of the barley plant, the length of the ear, the length of the awn, had moderate heritability.

J. Wang and Z. Zhang (2021) point that the study of genotypic relationships between traits that affect grain

yield allows to more accurately determine the real links between them, since it excludes the influence of the environment. According to the results of the researchers, the yield of barley grain demonstrated a significant positive genotypic correlation with the length and number of awns on the ear, the number and weight of grains on the ear. These results indicate that the genes that control these traits may be related. They can be located close to each other on the same chromosome or be controlled by a single pleiotropic gene. Therefore, the selection to improve these characteristics can be used for indirect selection to increase grain yield, which is also demonstrated in the study.

Considering these factors, the assessment of genotypic variability of barley varieties in Kazakhstan remains the most important and urgent task for the agricultural sector of the country. Kazakhstan, with its diverse climatic and soil conditions, has a huge potential for the production of different barley varieties, and the assessment of genetic variability helps agricultural specialists to choose and develop the most suitable varieties for specific regions and conditions. Understanding genotypic variability also allows breeders to develop barley varieties that can better adapt to changing climates and ensure stable yields even under extreme weather events. This contributes to the sustainable development of agriculture and contributes to the achievement of food security, which is a critical aspect for ensuring the food sovereignty and well-being of the nation. Thus, the assessment of genotypic variability of barley varieties in Kazakhstan remains an integral part of the country's agricultural development strategy and contributes to its sustainable future in agriculture.

The mentioned research papers and the results of the study of the genetic variability of barley varieties in Kazakhstan provide valuable information for agricultural practice and scientific research in the country. These data not only help to optimise the selection of varieties for cultivation in various regions of Kazakhstan, but also contribute to the development of more effective methods of breeding and adaptation to changes in the environment. Considering the challenges associated with climate change and increased requirements for food security, the assessment of genotypic variability remains a key tool for ensuring sustainable agricultural development in Kazakhstan. It contributes to the creation of barley varieties that can successfully adapt to new conditions and ensure stable and high yields, which is critically important for the food security and economic development of the country.

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CONCLUSIONS

In 2021, Kazakhstan experienced an extreme drought, which had a serious impact on agriculture, including barley cultivation. These natural factors greatly affected plant growth, yield, and the general condition of crops, and also led to the emergence of various diseases and deterioration of soil characteristics. In the course of the study, 37 genotypes were identified among 42 barley varieties, which showed biological salt tolerance but could not cope with the re-cultivation of barley. However, out of these 37 genotypes, 13 varieties were isolated, which had true salt resistance and continued to grow and develop even under stressful conditions of repeated sowing. It is worth noting that these selected varieties are widely used as testers in hybrid crosses and have many useful characteristics. Many local barley varieties were created based on these genotypes.

It was also found that different characteristics have different degrees of genetic variability. The number of grains in an ear and the weight of 1000 grains have a high genetic variability exceeding 49%, which indicates a significant influence of genetic aspects on their development. These traits also play a key role in the selection of plants to increase productivity and grain quality. On the other hand, the height of plants depends more on external conditions and interaction with the environment, which is reflected in the low level of genetic variability of this trait (12.3%). The high genetic variability of traits, such as yield and duration of the growing season, emphasises the need to consider genetic diversity in the selection of barley varieties, especially in the context of changing climatic conditions. Thus, the results obtained can help agricultural specialists and breeders to make more informed decisions when choosing barley varieties and determining optimal crop rotations to increase yields and agricultural efficiency.

The practical significance of the results lies in the fact that they allow agricultural producers to more accurately select barley varieties that best match local climatic and soil conditions. This can significantly increase productivity and product quality. The prospect of further research consists in analysing the genomes of barley varieties to identify specific genes and molecular mechanisms responsible for various characteristics, which can contribute to more accurate molecular breeding.

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None.

CONFLICT OF INTEREST

None.

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Оцінка сортів ячменю за рівнем генотипової мінливості кількісних ознак

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Анотація. Дослідження генетичної мінливості сортів ячменю особливо важливі в контексті мінливого клімату та необхідності забезпечення продуктивності сільського господарства в умовах екологічних викликів. Мета проведеного дослідження полягала в оцінці стійкості сортів ячменю до засолення ґрунту для виявлення найбільш продуктивних та адаптованих сортів. Для досягнення поставленої мети, було проведено діагностику солестійкості сортів ячменю та ідентифіковано сорти, що проявили високу стійкість до засолення. У результаті дослідження 45 сортозразків ячменю було виявлено, що 37 із них виявляли солевитривалість, але в міру зростання деякі з них не справлялися із засоленням і припиняли свій розвиток. З цих 37 сортів було обрано 13 генотипів, які мали справжню солестійкість і продовжували рости й розвиватися в стресових умовах, володіючи здатністю давати задовільний врожай, як порівняти з сортом-стандартом. Ці сорти успішно використовуються як тестери в гібридних схрещуваннях і мають безліч корисних характеристик, що робить їх цінними для сільськогосподарської практики. Також дослідження показало, що різні характеристики мають різний ступінь генетичної мінливості. Так згідно з отриманими даними, кількість зерен у колосі та маса 1000 зерен мають високу генетичну мінливість, вказуючи на важливість генетичних чинників у їхньому формуванні. Ці характеристики відіграють ключову роль у доборі рослин для збільшення врожайності та якості зерна. З іншого боку, висота рослин залежить від зовнішніх умов і взаємодії з навколишнім середовищем, що відображається в низькому рівні генетичної мінливості цієї ознаки (12.3 %). Отримані результати мають практичне значення для сільськогосподарських виробників, тому що вони можуть точніше обирати сорти ячменю, які найбільше підходять для місцевих умов. Це сприяє збільшенню врожайності та якості продукції, що є важливим для забезпечення продовольчої безпеки та економічної ефективності сільського господарства

Ключові слова: врожайність; солестійкість; добір; селекція; посушливість

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The bioindicative characteristics of the *Betula pendula* Roth species in the dendrocenoses of the solid household waste landfill's influence zone

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Abstract. Due to the constant inflow of toxic substances into the air, soil, and groundwater, landfills not only physically occupy huge expanses of land but also have an increasing negative impact on the ecosystem and its constituent parts. As such, the research relevance is determined by the problem of landfill expansion as well as the size in Ukraine getting worse by the minute. An example of morphometric alterations in leaf indicators of the species *Betula pendula* Roth is used to assess the effects of the municipal solid waste landfill in Zhytomyr on the nearby dendrocenoses. The

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most revealing morphometric indications were identified by examining the dimensions and characteristics of the venation of leaf plates at various distances from the dump up to a radius of one kilometre. Moreover, the length of the leaf's second vein of the second order was determined as the most stable parameter, while the difference in the lengths between the bases of the first and second veins of the second order was the most sensitive. Based on the data collected on the varying asymmetry of the leaf plates, it is concluded that variations exist in the morphometric indicators over the entire distance under investigation. These variations enable the determination of the environment within the range of "polluted" to "excessively polluted". These findings can serve as a quick way to gauge how much of an influence landfills have on the ecosystems around them when sanitary protection strips are established, municipal waste dumps are built and outfitted, etc

Keywords: veining; morphometric indications; birch; pollution; waste

INTRODUCTION

Landfills are an urgent problem nowadays, and the number of them is increasing annually. One of the primary causes of pollution in the environment is spontaneous landfills. Due to incorrect functioning, current landfills are in unsatisfactory condition. Landfills are gradually engulfing plantations, streams, and woods. Due to the lack of storage places, perimeter collapse, and conditions of the organization, garbage is frequently dispersed. The contamination that these landfills filter into the subterranean aquifer and incorporate into the cycles of chemicals has a detrimental effect on the health of the nearby ecosystems and, as a result, plant, and animal organisms. When solid household waste breaks down or burns, dangerous and occasionally cancer-causing chemicals are released into the atmosphere. The condition of ecosystems' permanent components has the biggest impact on all these factors. As a result, these ecosystem components serve as the most useful indicators of the ecological health of ecosystems.

The functioning of human society is related to environmental pollution. Forests, which act as natural cleaners and sorbents of pollution, play a special role in these processes. A significant proportion of pollutants settle and later accumulate in the phytomass of woody plants. In general, temperature, chemical pollution, and population density are known stressors to populations in ecosystems (Benítez *et al.*, 2020). Trees clean, moisturize, and enrich the atmosphere of cities with oxygen, influence radiation levels and temperature, and reduce wind impact and noise pollution (Pfeifer *et al.*, 2022). Sanitary-hygienic, architectural, economic, and other human activities severely impact green spaces. One of the types of extreme conditions of vegetation habitats is landfills (Vaverková *et al.*, 2019).

The situation that has developed around the landfill of solid household waste (Zhytomyr, Ukraine) has recently caused considerable concern. The low level of use of waste processing causes its accumulation in the surrounding natural environment and pollution. Hundreds of thousands of tons of household waste accumulate in city landfills every year. The location, arrangement, and operating conditions of most waste disposal sites do not meet regulatory requirements, which increases the

environmental hazard of these facilities. A large landfill borders 6 blocks of the forest of the State Enterprise "Zhytomyrske LG". The influence of waste and the gas composition of the air in landfills is reflected in the form of various anomalies in the development of dendrocenoses in adjacent landscapes (Skydan *et al.*, 2022).

Many studies state that there are many species of plants and animals in ecosystems that are the first to respond to the appearance or increase of anthropogenic influence in the form of pollution (Orlov *et al.*, 2023; Fedoniuk & Skydan, 2023). Dendrocenoses, in their majority, actively respond to technogenic load by changing their growth and development indicators. For example, Y. Petrushkevych and I. Korshykov (2020) noted a clear trend regarding the differences in the responses of plants from a relatively clean area and polluted areas: in control trees, the coefficient of variation was higher for the right half of the leaf (right-sided asymmetry), and in man-made area plants, a small left-sided asymmetry was present (Fedoniuk *et al.*, 2022). The reactions of plants in response to pollution vary greatly, from colour changes to changes in the size and shape of leaf plates, leaf asymmetry, crown asymmetry, etc.

L. Romanchuk *et al.* (2018) noted, that many woody plants with pronounced and easily visible responses to environmental pollution are often used as indicator plants that allow not only determining the fact of the presence of pollution but also characterizing their scale and origin. K. Hartikainen *et al.* (2020) noted that even a slight but realistic increase in environmental temperature can significantly change the structure of silver birch leaves. The effect of changes in the gas composition (emissions of biogenic volatile organic compounds) on the morphometric indicators of the *Betula* species was noted by F. Ndah *et al.* (2022). As a result, such species either disappear from such ecosystems or react in the form of morphological or physiological disturbances. In conditions of prolonged impact of an undesirable object, the search for contamination signs becomes difficult since some of the sensitive species could have already disappeared under the influence of adverse conditions. In this case, species that respond to the presence of adverse factors in the environment

in the form of morphological disturbances come to the fore, as can be successfully recorded.

As a bioindicator of the quality of the environment, the hanging birch has been used successfully for quite some time (*Betula pendula*) in research of M. Aničić Urošević *et al.* (2019) and M. Božym *et al.* (2021). They noticed that it is massive and widespread and is part of various biotopes (ecosystems); its area includes steppe and forest-steppe zones in Scandinavia, Central and Atlantic Europe, the Mediterranean, and the Balkans. Several questions regarding the use of birch as a bioindicator remain unanswered. There is insufficient information on the disturbance of development stability on the ecological periphery of the area. The regularities of the spatial distribution of the asymmetry coefficient of this type have not been studied. However, M. Vaverková *et al.* (2019) confirmed the possibility of determining environmental pollution under the influence of solid waste landfills by biotesting methods. This study demonstrated and proved the possibility of using

hanging birch populations (*Betula pëndula*), oak (*Quercus robur* L.), and alder (*Alnus glutinosa* (L.) Gaertn.) to assess the impact of landfills on the environment.

As such, the study aimed to analyse the ecological condition of trees in the dendrocenoses of the forest, which are developing in the area of the municipal solid waste landfill (MSW).

MATERIALS AND METHODS

Characteristics of the research object. The municipal solid waste dump in Zhytomyr city is situated 0.65 km from the city limits; 0.514 km from residential and public buildings; 0.05 km from agricultural land; 65-70-0.05 km from the State Enterprise “Zhytomyrske LG” forest massif; and 1200 m from the Kroshenka River, which is a left tributary of the Kamianka River, which is a left tributary of the Teteriv River (Fig. 1). The primary data source for this project was created using the “Dynamic World V1” product on the Google Earth Engin platform (n.d.).



Figure 1. Map scheme of the location of the municipal solid waste dump in Zhytomyr

(blocks 65-70 of the forest lands of the State Enterprise “Zhytomyr LH”) and the investigated forest ecosystems

Source: Google Earth Engin platform (n.d.)

Collecting plant material peculiarities. To investigate the effects of the Zhytomyr landfill on dendrocenoses, measurements were made of a hanging birch leaf's dimension. The investigated area was separated into groups according to varying distances from the solid waste border (0-99, 100-199, 200-299, 300-399, 400-499, 500-599, 600-699, 700-799, 800-899, 900-1000 m). A location inside a forest massif that was no closer than two kilometres to the closest highway (hydropark) was selected as the control area. Ten birch trees yielded ten leaves each. This resulted in a total of 100 leaves in each experimental region, sufficient for appropriate correlation analysis and statistical analysis of a small sample of values. Regarding measuring indications, the degree of plant asymmetry was considered from both the left and right sides concerning the two sides. The average rela-

tive difference for one attribute for each leaf is a crucial measure of development stability for a collection of traits. This was accomplished by measuring and determining each chosen leaf's curve. There was no discernible variation in the leaf tip's curvature in the studied sites. As a result, this parameter was ignored in the subsequent investigation. The material collection started following the conclusion of the time of intense leaf growth, which typically falls between late May and early June throughout the years 2020-2022.

Leaves were sampled for each interval from medieval woody plants by the route (tape transect) method (Loya, 1978). 100 leaves were measured to assess the ecological state of large areas. In the case of damage, another +10% was collected. The leaves were taken from the lower part of the crown, at the level of the

raised hand, from the maximum number of available branches (at the same time, they tried to use parts of the plant located in different directions, conditionally to the north, south, west, and east) (Fig. 2).



Figure 2. Leaf collection sites

Source: compiled by the authors

Birch leaves were used only from shortened shoots. About one leaf, the average size for this species, was selected. Damaged leaves were used in the study only if the areas from which the measurements would be taken were not damaged. Leaves from one tree were tied with a thread by the petioles and placed in a polyethylene bag. If the collected material was not processed immediately, it was placed on the bottom shelf of the refrigerator, such material was kept for a maximum of one week. For long-term storage, a fixative was used: 70% alcohol or 3% formalin.

To exclude subjective errors when taking measurements from biological samples, the following was set: if the measurements were carried out by several people, then any individual sample was completely processed by the same person. After the measurement results were input into the electronic database and processed using the Statistica 12.0 software, the asymmetry value of every hanging birch leaf was ascertained. After statistical processing of the results of the features of each leaf, the average relative difference per feature was determined for this sample of leaves in the study area "plot 0-99" according to the example:

$$X_{av} = \frac{X_1 + X_2 + X_3 + \dots + X_n}{100}, \quad (1)$$

where X_{av} – average relative difference per leaf feature; $X_1, X_2, X_3 \dots X_n$ – asymmetry value of every hanging birch leaf.

The Pearson coefficients were used to calculate the correlations between the birch performance indices and the distance from the landfill. Linear regression models were used to evaluate the relative changes in the performance indices in space.

Dimensions were measured from birch leaf plates.

Five factors were used to note indications from the left

and right sides of a single leaf (Fig. 3): half of the leaves' width. Folding the leaf in half, securing the top to the base, and then unfolding the leaves allowed for measurements along the created fold; the distance between the bases of the first and second veins of the second order; the length of the second vein of the second order to the leaf's base; and the separation between these veins' ends; the separation between the leaf's top and the end of the second vein of the second order; the angle formed by the base of the second-order leaf vein's main vein and secondary vein.

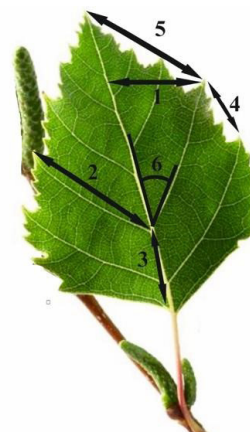


Figure 3. Measurement of the angle between veins

Source: compiled by the authors

The acquired result was equated with the degree of detection of deviations from the norm and their position within the general range of deviations in signs. The first four parameters were taken with a calliper, and the angle between the veins was measured with a protractor (Fig. 3). When measuring the angle, the protractor (1, Fig. 3) was held so that the centre of the base of the protractor window (2, Fig. 3) was at the branching point of the second vein of the second order (3, Fig. 3). Since the veins are not rectilinear but winding, the angle was measured as follows: the section of the central vein (3, Fig. 3), located within the window of the protractor (2, Fig. 3), was combined with the central beam of the protractor, which corresponds to 90°, and the section of the vein of the second order (3, Fig. 3) continued to the degree values of the protractor (3, Fig. 3) using a ruler.

The "bending" of the top of the leaf was recorded separately as "not bent", "bent to the left", "bent to the right", and "swallow's tail", which also potentially indicated that the leaves were subjected to technogenic influence. For the determination of parameters on the left and right sides, they were marked as X_l and X_r . For each of the 10 leaves of the same tree, the relative difference in the measurements of each of the 5 features on both sides of the leaf was determined using the formula:

$$FA_i = \frac{x_l - x_r}{x_l + x_r}, \quad (2)$$

where, FA_i – fluctuation asymmetry index; X_l, X_r – parameters on the left and right leaf sides.

Then, the average relative difference was calculated for each characteristic at each distance from the polygon. Fluctuation Asymmetry Integration Index (IIFA) values were then calculated for each leaf. To do this, the sum of the fluctuation asymmetry coefficients for each of the five sheet characteristics, divided by the number of measured characteristics, was calculated:

$$IIFA_n = \frac{FA_1 + FA_2 + FA_3 + \dots + FA_n}{n}, \quad (3)$$

where $IIFA_n$ – fluctuation asymmetry integration index; FA – fluctuation asymmetry index of each parameter.

This indicator characterizes the degree of asymmetry (Klingenberg 2015). If data sets demonstrated that fluctuating asymmetry exists, FA value was estimated using the protocol recommended by A. Palmer and Strobeck (2003). The last research step was to determine the level of air pollution in each area using a 5-point scale (Viscosi, 2015). To evaluate the level of disruption to the stability of plant development, a 5-point rating system was created. The first point (conditional norm), z_i fluctuates in the range from 0.040 to 0.054, the second point, from 0.055 to 0.059, the third point, from 0.060 to 0.064, the fourth point, and from 0.065 to 0.070 and above, the fifth point (critical state), are all within the range of values of the integral index of stability of development up to 0.070. The integral asymmetry index values that correspond to the first point are typically seen in a sample of plants that are growing in ideal conditions. If the plants are in extremely poor condition, the fifth point describes the critical state of the environment. The authors followed the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

One of the typical landfills in Ukraine is the solid waste landfill in Zhytomyr city. These landfills are typically run with little regard for environmental protection. In Zhytomyr City, all beforehand unsorted home waste is dumped in a landfill. This requires improvement as it has become a significant source of contamination for both groundwater and the atmosphere, thereby heightening the potential for an epidemic. Based on information presented during the 53rd session of the VII convocation of the Zhytomyr City Council (n.d.), from

the moment the municipal landfill opened in 1957, between 12 and 15 million m³ of various waste was dumped, with a layer height of around 30 meters. The storage site occupies 18.7 hectares, but the overall area is 21.6 hectares (the state act on the allocation of land states that the total size is 21.5670 hectares). According to the 53rd session Decision at the landfill, waste of the 3rd and 4th class of danger from the city's population and enterprises of all forms of ownership is stored. The sources of waste include waste from high-rise buildings (about 63%); waste from private residential construction (about 26%); and waste from commercial and other business entities (about 11%). Household waste, dumped in the landfill, has the following declared morphological composition: 33.1% is food waste; 5.9% is paper; 3.3% is metal; 13.2% is polymer packaging; 4.1% is wood; 13.5% is glass; 2% is rags; 1.4% is leather and rubber; 3.7% is construction waste; 11% is road debris; and other waste is 8.8%.

Nevertheless, the lack of a weight scale at the municipal solid waste storage site raises questions about the accuracy of this data and the stated initial average coefficient of the solid household waste ratio of mass to volume (density), which is 0.27 t/m³. The following environmental effects have been shown to have a significant negative impact: agricultural land alienation and landscape change; air pollution from the smouldering and burning of accumulated waste; potential harm from pathogenic microorganisms, dust, smells, and noise; noise pollution and pollution from the transportation of waste and the use of technical means; environmental thermal pollution; and pollution of surface and subsurface waters.

During research on the dendrology of the State Enterprise "Zhytomyrske LG" forests, the territory of which is closely adjacent to the territory of the Zhytomyr Municipal Solid Waste Landfill, the following species were discovered: *Birch pendula* Roth., *Populus alba* L., *Populus tremula* L., *Pinus sylvestris* L., *Salix caprea* L., and *Ashinus excelsior* L. The hanging birch was chosen as a research object since its effectiveness has been proven by Y. Petrushkevych and I. Korshykov (2020). As a result of the conducted research, the general indicator of asymmetry in the morphological parameters of the leaf plates of the *Betula pendula* species All data was divided into grades for better understanding and visualization of the data (Table 1).

Table 1. Gradations of the main parameters of *Betula pendula* leaves in samples from phytocenoses subjected to different levels of anthropogenic pressure

| Leaf plate parameter | Parameter grades | Share in the sample of leaf plates of certain grades, % | | | | | | | | | |
|----------------------|------------------|---|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| | | location | | | | | | | | | |
| | | 0-99 | 100-199 | 200-299 | 300-399 | 400-499 | 500-599 | 600-699 | 700-799 | 800-899 | 900-1000 |
| Leaf length, mm | ≤40.0 | 4.815 | | | | | | | | | |
| | 40.0-49.9 | 25.215 | 4.375 | 2.552 | 1.565 | 1.109 | | | | | |
| | 50.0-59.9 | 24.515 | 23.975 | 3.452 | 2.465 | 2.009 | 3.567 | 2.345 | 1.678 | 0.469 | |

Table 1. Continued

| Leaf plate parameter | Parameter grades | Share in the sample of leaf plates of certain grades, % | | | | | | | | | |
|--|------------------|---|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| | | location | | | | | | | | | |
| | | 0-99 | 100-199 | 200-299 | 300-399 | 400-499 | 500-599 | 600-699 | 700-799 | 800-899 | 900-1000 |
| Leaf length, mm | 60.0-69.9 | 21.315 | 25,530 | 17,252 | 13,335 | 12,879 | 9,651 | 14,568 | 13,098 | 10,034 | 12,456 |
| | 70.0-79.9 | 14.715 | 27,010 | 20,520 | 19,678 | 20,134 | 23,561 | 16,093 | 22,207 | 23,453 | 12,988 |
| | 80.0-89.9 | 9.430 | 10,580 | 27,130 | 26,143 | 26,599 | 32,992 | 30,021 | 33,524 | 31,008 | 31,455 |
| | 90.0-99.9 | | 7,150 | 15,290 | 24,986 | 25,442 | 24,780 | 26,287 | 21,165 | 26,577 | 33,455 |
| | 100.0-109.9 | | 1,380 | 10,250 | 9,263 | 8,812 | 4,447 | 8,456 | 7,098 | 5,457 | 4,679 |
| | ≥110.0 | | | 3,552 | 2,565 | 3,021 | 1,003 | 2,234 | 1,234 | 3,004 | 4,977 |
| Width, mm | 0.0-19.9 | 19.756 | 9,075 | 5,456 | 4,469 | 3,819 | 2,642 | 2,589 | 1,054 | 1,094 | 1,564 |
| | 20.0-39.9 | 26.031 | 32,974 | 9,123 | 8,136 | 7,486 | 6,789 | 8,965 | 7,567 | 6,541 | 7,789 |
| | 40.0-49.9 | 31.256 | 37,568 | 40,253 | 41,354 | 42,004 | 43,789 | 42,786 | 41,567 | 44,678 | 46,678 |
| | ≥50.0 | 22.956 | 20,463 | 45,257 | 46,046 | 46,696 | 46,780 | 45,660 | 49,812 | 47,687 | 43,969 |
| Elongation of the leaf | ≤1.50 | 1.874 | 1,256 | 1,025 | 0,038 | | | | | | |
| | 1.50-2.00 | 22.456 | 9,623 | 5,462 | 4,475 | 3,825 | 4,678 | 4,910 | 3,001 | 2,870 | 1,987 |
| | 2.00-2.19 | 45.698 | 30,265 | 25,690 | 25,301 | 26,657 | 18,907 | 14,631 | 14,321 | 12,568 | 15,324 |
| | 2.20-2.49 | 22.150 | 30,565 | 35,456 | 33,720 | 34,687 | 38,789 | 31,678 | 27,081 | 23,609 | 26,788 |
| | 2.50-2.66 | 5.648 | 20,263 | 22,412 | 25,331 | 24,537 | 26,987 | 29,001 | 35,890 | 27,810 | 22,102 |
| | 2.70-2.99 | 2.547 | 5,968 | 7,536 | 9,768 | 8,301 | 10,123 | 18,906 | 16,710 | 21,614 | 29,450 |
| Distance from the central to the first vein, mm | ≥3.00 | 0.652 | 2,100 | 2,354 | 1,367 | 2,000 | 0,516 | 0,874 | 2,997 | 11,529 | 4,349 |
| | ≤2.0 | 3.772 | 2,870 | 2,460 | 1,486 | 1,578 | 0,567 | 0,110 | | | |
| | 2.0-2.49 | 3.154 | 8,770 | 9,434 | 8,497 | 6,678 | 4,789 | 6,898 | 2,678 | 3,897 | 2,475 |
| | 2.50-2.99 | 5.440 | 11,521 | 8,780 | 7,793 | 8,678 | 12,679 | 22,648 | 21,899 | 20,678 | 16,567 |
| | 3.00-3.49 | 22.444 | 22,161 | 20,456 | 19,469 | 13,567 | 28,543 | 35,679 | 39,543 | 33,268 | 32,789 |
| | 3.5-3.99 | 47.596 | 32,163 | 31,256 | 30,291 | 30,032 | 25,678 | 31,568 | 32,019 | 33,600 | 35,676 |
| The distance between the first and second veins, mm | 4.00-4.49 | 15.050 | 18,910 | 23,456 | 25,598 | 26,789 | 21,897 | 20,500 | 20,165 | 18,562 | 24,808 |
| | 4.5-5.0 | 2.550 | 3,998 | 4,252 | 6,867 | 12,678 | 5,847 | 3,098 | 3,861 | 8,557 | 12,494 |
| | ≤4.00 | 3.202 | 2,226 | 1,890 | 0,903 | 0,673 | | | | | |
| | 4.00-4.49 | 2.584 | 6,056 | 8,864 | 7,934 | 7,704 | 5,690 | 8,668 | 6,989 | 8,679 | 3,678 |
| | 4.50-4.99 | 4.870 | 7,425 | 8,210 | 7,223 | 6,993 | 7,743 | 8,437 | 5,678 | 8,547 | 9,072 |
| | 5.00-5.49 | 21.874 | 22,587 | 19,886 | 18,132 | 17,902 | 16,567 | 22,678 | 25,989 | 22,099 | 26,567 |
| The distance from the base of the leaf to the edge of the leaf, mm | 5.50-6.00 | 45.156 | 35,146 | 30,126 | 31,234 | 31,464 | 30,466 | 33,678 | 32,678 | 29,678 | 36,679 |
| | 6.00-7.00 | 20.359 | 22,458 | 25,345 | 26,789 | 27,019 | 28,678 | 25,687 | 20,789 | 18,678 | 18,678 |
| | ≥7.00 | 1.980 | 4,459 | 5,896 | 7,789 | 8,245 | 10,857 | 0,852 | 7,877 | 12,320 | 5,326 |
| | ≤2.99 | 22.485 | 6,725 | 4,004 | 3,017 | 0,750 | 0,189 | 0,037 | 0,000 | 0,000 | 0,000 |
| | 3.00-3.49 | 25.273 | 28,475 | 6,288 | 5,301 | 6,069 | 5,052 | 6,825 | 4,223 | 5,149 | 2,713 |
| | 3.50-3.99 | 26.285 | 31,549 | 30,986 | 29,999 | 14,109 | 13,110 | 15,239 | 13,966 | 13,931 | 13,654 |
| Leaf apex numeric index | 4.00-4.49 | 18.835 | 23,737 | 32,888 | 31,901 | 22,052 | 27,966 | 22,581 | 30,871 | 26,325 | 26,306 |
| | 4.5-4.99 | 4.715 | 5,290 | 13,565 | 15,678 | 28,678 | 27,710 | 30,108 | 29,709 | 30,363 | 31,485 |
| | 5.00-5.49 | 2.158 | 3,575 | 7,645 | 8,678 | 20,703 | 20,233 | 21,698 | 19,221 | 19,618 | 24,312 |
| | ≥5.50 | 0.256 | 0,690 | 5,125 | 5,429 | 7,639 | 5,740 | 3,513 | 2,010 | 4,615 | 1,529 |
| | 1.01-1.26 | 4.490 | 2,059 | | | 0,600 | 0,151 | 0,029 | | | |
| | 1.27-1.49 | 16.354 | 6,159 | 1,659 | 0,672 | 5,077 | 4,042 | 5,460 | 3,378 | 4,119 | 2,171 |
| | 1.50-1.74 | 29.565 | 33,259 | 28,156 | 24,017 | 11,689 | 11,201 | 12,660 | 11,508 | 11,238 | 10,923 |
| Base numeric index | 1.75-1.99 | 38.257 | 25,145 | 63,154 | 62,167 | 20,217 | 24,303 | 25,437 | 27,316 | 23,067 | 24,981 |
| | 2.00-2.24 | 10.145 | 17,290 | 5,859 | 12,872 | 26,969 | 26,880 | 28,090 | 30,501 | 28,981 | 27,786 |
| | 2.25-2.49 | 1.259 | 13,256 | 1,259 | 0,272 | 21,882 | 22,785 | 23,362 | 22,082 | 21,896 | 25,741 |
| | 2.50-2.74 | | 2,859 | | | 13,565 | 10,638 | 4,962 | 5,215 | 10,699 | 8,398 |
| | 1.70-1.99 | 9.400 | 15,300 | | | | 4,675 | | | | |
| The apex shape asymmetry coefficient | 2.00-2.25 | 90.600 | 84,700 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 |
| | 0.25-0.49 | 61.524 | 57,980 | 74,300 | 75,587 | 75,070 | 72,770 | 74,425 | 71,598 | 73,357 | 72,347 |
| | 0.50-0.74 | 26.300 | 28,050 | 19,654 | 19,305 | 17,410 | 17,993 | 21,118 | 22,424 | 19,699 | 21,734 |
| | 0.75-0.78 | 11.400 | 9,300 | 6,100 | 5,113 | 7,521 | 7,128 | 3,754 | 4,188 | 6,944 | 3,110 |
| The base shape asymmetry coefficient | 0.79-0.99 | 0.700 | 4,900 | | | | 2,108 | 0,703 | 1,790 | | 2,809 |
| | less than 0.015 | 60.062 | 50,154 | 55,154 | 55,683 | 53,910 | 46,333 | 54,601 | 53,006 | 54,201 | 49,097 |
| | 0.015-0.029 | 29.150 | 25,419 | 35,150 | 36,567 | 30,439 | 32,486 | 30,409 | 30,875 | 29,406 | 31,306 |
| | 0.030-0.044 | 7.156 | 14,250 | 7,162 | 6,175 | 7,401 | 8,402 | 8,928 | 11,920 | 8,510 | 9,103 |
| | 0.045-0.059 | 2.156 | 6,362 | 2,562 | 1,575 | 4,823 | 3,199 | 5,670 | 4,120 | 6,987 | 7,901 |
| ≥0.060 | 1.595 | 3,862 | | | 3,427 | 9,580 | 0,392 | 0,079 | 0,896 | 2,593 | |

Table 1. Continued

| Leaf plate parameter | Parameter grades | Share in the sample of leaf plates of certain grades, % | | | | | | | | | |
|----------------------|------------------|---|---------|---------|---------|---------|---------|---------|---------|---------|----------|
| | | location | | | | | | | | | |
| | | 0-99 | 100-199 | 200-299 | 300-399 | 400-499 | 500-599 | 600-699 | 700-799 | 800-899 | 900-1000 |
| Integral index of FA | 0.025-0.034 | 13,216 | 3,500 | | | 0,675 | 0,170 | 0,033 | 0,000 | 0,000 | 0,000 |
| | 0.035-0.044 | 25,245 | 9,800 | 3,300 | 2,313 | 4,573 | 3,294 | 4,573 | 2,851 | 4,067 | 3,879 |
| | 0.045-0.054 | 51,400 | 39,800 | 19,568 | 18,581 | 19,893 | 23,421 | 23,045 | 26,870 | 23,030 | 24,340 |
| | 0.055-0.064 | 10,156 | 39,156 | 53,150 | 54,634 | 50,303 | 45,302 | 46,532 | 45,002 | 47,201 | 46,533 |
| | 0.065-0.074 | | 7,500 | 21,156 | 22,567 | 21,668 | 22,336 | 22,287 | 23,978 | 24,844 | 20,981 |
| | ≥0.075 | | 0,900 | 2,895 | 1,908 | 2,887 | 5,476 | 3,530 | 1,299 | 0,858 | 4,267 |

Source: compiled by the author's research results

According to the results of research on the analysis and processing of data on the magnitude of asymmetry according to 6 parameters of birch leaf plates, the most stable parameter was determined – the length of the

2nd vein of the 2nd order from the base of the leaf (0.028), which proves its insensitivity to environmental factors. The most noticeable difference was between the sizes of leaf plates in length (Fig. 4).

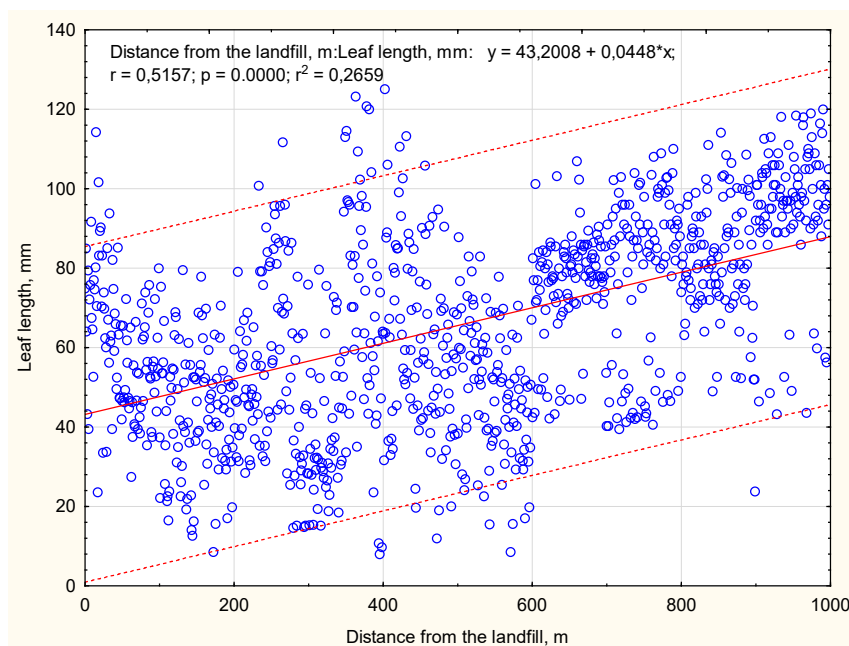


Figure 4. Peculiarities of the formation of the dimensions of leaf plates in length depending on the distance from the landfill

Source: compiled by the authors

It was noted that at a distance of up to 500 m from the landfill, the average size of leaf plates was smaller than at landfill at nearable distances. Thus, as follows from Figure 4, 80% of leaf plates in this range had dimensions from 30 to 80 mm, while at more than 500 m, these dimensions increased to 50-110 mm. This proves that the influence of toxic gases, leachate coming from landfills, and toxic substances in the soil has a significant negative impact on the surrounding dendrocnoses. Studies of the linear regression model showed that the coefficient correlation is 0.51, which indicates a medium-level relationship and characterizes the quality of the obtained regression line.

Based on the calculations in Figure 4, the regression equation is $y = 432008 + 0.0448x$, where x is the length of leaf plates, mm, and y – is the distance from the landfill.

The difference in the parameter of the width of the leaf plates was less pronounced. The processing of statistical data shows a less pronounced correlation dependence between the values of leaf width in closer and more distant areas from the border of the landfill. The collected data did not yield reliable correlation values (correlation coefficient: $r = 0.21$). As per the research program, the distance from the central vein to the first vein was also measured. In general, the range of value variations was from 1.2 to 5 mm. In general, it was noted that the distance of the first vein from the central one depends on the degree of distance from the landfill in dendrocnoses. Tangent to the limit, it is smaller and increases with distance. However, the correlation of these parameters can be characterized as directly proportional with a weak degree of closeness of the connection ($r = 0.25$).

The difference between the distances between the bases of the 1st and 2nd veins of the 2nd order was significant and maximal in comparison with other investigated parameters. In general, the values of the indicators varied in the range of 3.38 to 7.60 mm. At the same time, the values of asymmetry according to this indicator were the highest, and the value reached 0.16. Based on all the measurements that were taken, asymmetry coefficients were found, and their integral

index of fluctuation asymmetry was calculated by finding the average value of five different asymmetry measures for each leaf plate (Fig. 5). In general, the obtained values ranged from 0.012 to 0.077. At a distance of up to 500 m from the landfill, violations of the asymmetry of the studied leaf plates were noted. 80% of the values were in the range of 0.03 to 0.067. At a distance exceeding 500 m of the IIFI, 80% of the values were in a lower and narrower range, from 0.02 to 0.055.

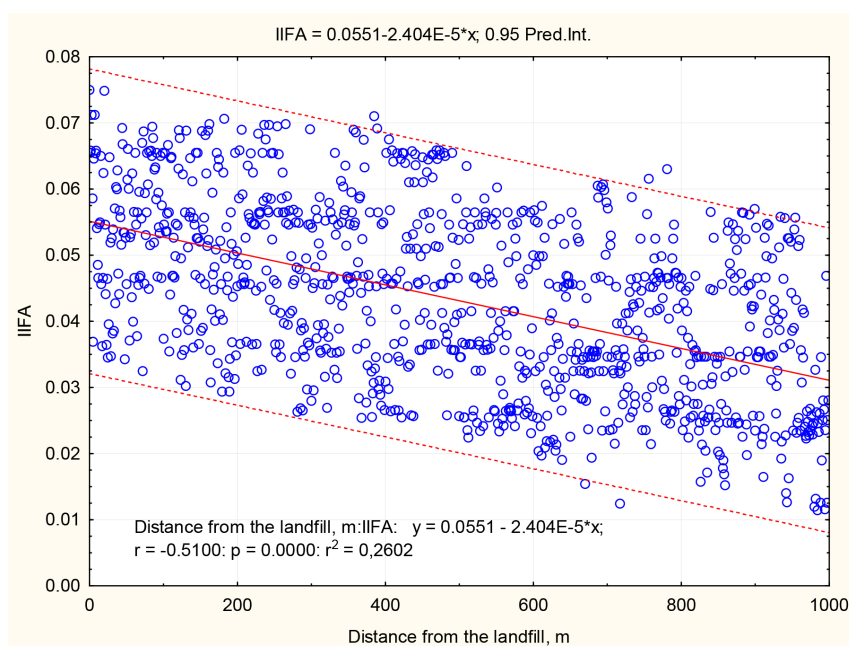


Figure 5: Fluctuation Asymmetry Integration Index (IIFA) at various distances from the landfill's edge (in meters)
Source: compiled by the authors

Linear regression model analyses revealed that the generated regression line's quality is characterized by a coefficient correlation of -0.51, indicating an inversely proportional link between the average level. The regression equation, where y is the

distance from the landfill and x is the IIFA value, is $y=0.0551+2.404E-5x$ based on the computations. The obtained IIFA values were equated to the threshold values for the stability of the development of dendrocenoses (Table 2).

Table 2. The degree of atmospheric air pollution in the zone of influence of the Zhytomyr landfill (by the degree of leaf asymmetry)

| The score and value of the stability indicator. Degree of air pollution | Distance from the edge of the landfill, m | IIFA, X |
|---|---|--------------|
| 1 point (up to 0.055) – clean air | beyond influence | 0.046±0.0398 |
| | ≥1000 | 0.067±0.0424 |
| 3 points (0.060-0.065) Air pollution | 900-999 | 0.067±0.0387 |
| | 800-899 | 0.068±0.0234 |
| | 700-799 | 0.060±0.0164 |
| | 600-699 | 0.062±0.0234 |
| | 500-599 | 0.062±0.0098 |
| 4 points (0.065-0.070) Heavily polluted air | 400-499 | 0.067±0.0067 |
| | 300-399 | 0.068±0.0123 |
| | 200-299 | 0.068±0.0378 |
| 5 points (more than 0.070) Excessively polluted | 100-199 | 0.072±0.0287 |
| | ≤99 | 0.083±0.0092 |

Source: compiled by the authors

The obtained data on IIFA levels were compared with air pollution scales, revealing that within a distance of up to 200 meters from the landfill border, the area was classified as “Excessively polluted”, while up to a distance of 0.5 kilometres, it was categorized as “Heavily polluted”. Starting from 500 m, the sheet plates also had certain deviations of asymmetry, which allows this territory to also be defined as “contaminated”. Since the impact on the environment in the zone of the Zhytomyr solid waste landfill is limited only to the activities of the landfill itself (due to the absence of industrial enterprises, highways, and other factors), it is possible to conclude that the solid waste landfill has a significant impact on the development of the leaf plates of the hanging birch.

The leaves of woody plants are considered one of the most flexible and sensitive plant organs (Gawronski *et al.*, 2017) as they are in direct and long-term contact with the environment (Crini & Lichtfouse, 2018; Rodríguez-Santamaría *et al.*, 2022). The conducted research fully confirms these statements as the results presented in this study demonstrated the deformations in the formation of leaf plates in trees exposed to negative anthropogenic influence. Such plants change at morphological or physiological levels under the influence of long-term anthropogenic influence. R. Popek *et al.* (2018) determined that the greatest frequency of pollutants from the atmospheric air is fixed in the leaves, disrupts photosynthesis, and thus affects the physiological parameters of the leaves. This study analysed the precise manner in which this influence manifests itself on morphometric indicators. As such, comparable information was obtained, although concerning the landfill's toxic effects. In the same study, a negative relationship between FA and distance from the pollution source was found for several species of trees. This result seems quite reliable, although the authors used small sample sizes from two birch trees. The studied areas show great variability both in terms of the amount and composition of pollutants – this is a pulp and paper enterprise, a metallurgical plant, etc. In the presented study, the sample size, which allowed us to obtain completely reliable results, was significantly increased.

Similar conclusions that the morphometric indicators associated with the asymmetry of plants and their parts are informative indicators of the state of the environment were reached by other scientists. Studies by O. Bala & A. Terentiev (2017), as well as by O. Chornobrov and O. Tkachova (2021) confirm that the greater

the deviation, the worse the conditions. This applies equally to both terrestrial and aquatic plants. Furthermore, more specific results were noted by M. Zbiljić *et al.* (2023). Their study indicated that the morphological diversification of leaves is another sign that shows how bad the conditions are. This is because it's considered one of the most crucial methods for assessing alterations in the plate's shape. Based on this study, this indicator has also been used for the presented research but did not get reliable results. Given this, this issue requires a more detailed study regarding the identification of environmental components that cause the deformation of the tips of leaf plates. Simultaneously, literature studies did not identify the distances between leaf veins as key indicator parameters.

CONCLUSIONS

By using degradation indicators to track the condition of dendrocenoses in the area under the influence of solid household waste landfills, this study addressed a real scientific and practical issue. While doing research, the following tree species were found in the forests right next to the Zhytomyr Municipal Solid Waste Landfill: *Pinus sylvestris* L., *Salix caprea* L., *Betula pendula* Roth, and *Populus alba* L. The technique of measuring the anthropogenic load near the solid waste dump using bioindicators – plates containing *Betula pendula* leaves, was effective. The accuracy of the procedure is demonstrated by the statistical estimations and the bioindicator results' resemblance to data collected by other authors.

The length of the second vein of the second order from the base of the leaf (0.028) was found to be the most stable of the five parameters of birch leaf plates. This shows that it is not affected by environmental factors. The difference between the distances between the bases of the 1st and 2nd veins of the 2nd order, where the asymmetry values exceeded 0.16, was defined as the maximum in the study. Further research should consider more indicator species since not all phytocoenoses contain the same list of species. Expanding the species diversity of indicator plants will help to be more flexible in monitoring ecosystems that are potentially subject to negative anthropogenic influence.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Біоіндикаційні особливості виду *Betula pendula* Roth у дендроценозах зони впливу полігону твердих побутових відходів

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Анотація. Проблема зростання чисельності та розмірів сміттєзвалищ в Україні зростає щомиті, оскільки окрім фізичного зайняття значних площ землі, сміттєзвалища впливають на навколишнє середовище та його компоненти через постійне надходження токсичних речовин у повітря, ґрунт і підземні води. Отже, метою роботи було дослідження екологічного стану дерев у дендроценозах, що розвиваються навколо полігону твердих побутових відходів (ТПВ). З огляду на це, у статті оцінено вплив полігону твердих побутових відходів м. Житомир на навколишні дендроценози на прикладі морфометричних змін показників листя виду *Betula pendula* Roth. Для цього досліджені розміри та особливості жилкування листкових пластинок на різній віддалі від полігону в межі до 1 км, а також визначені найбільш інформативні морфометричні показники. При цьому визначено, що найбільш стійким визначений параметр – довжина 2-ї жилки 2-го порядку від основи листка, а максимально чутливим – різниця між відстанями між основами 1-ї та 2-ї жилок 2-го порядку. На підставі отриманих даних щодо флуктуаційної асиметрії листкових пластинок узагальнено, що на усій досліджуваній віддалі є відхилення у морфометричних показниках, що дозволяють визначати середовище у діапазоні від «забруднене» до «надто сильно забруднене». Дані роботи можуть бути використані у якості експрес-методу оцінки масштабів впливу сміттєзвалищ на навколишні екосистеми при створенні санітарних захисних смуг, будівництві та обладнанні полігонів побутових відходів тощо

Ключові слова: береза; забруднення; відходи; жилкування; морфометричні показники

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The influence of soil-drying inputs on the soil and the productivity of crops

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Abstract. In Kazakhstan, agricultural land has been degraded for decades, leading to an overall decline in crop yields. The purpose of the study is to conduct an environmental assessment of the current state of Kazakhstan's soils to increase crop yields using soil protection methods. The following methods were used in the study: cartographic, analysis and synthesis, systematization, abstraction, specification, and forecasting. Agriculture accounts for 86% of Kazakhstan's land. Active land use has led to various forms of degradation, resulting in 90 million hectares of eroded soils, of

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which 29.3 million hectares are almost completely eroded. In 2023, the average yield of grain crops was 9.3 c/ha, oilseeds – 7.1 c/ha, and vegetables – 275.4 c/ha. It is noted that the yield of grain crops in 2023 is 28% lower than in the previous period of 2020-2022, despite the increase in sown areas. Drought and soil degradation are the main reasons for the decline in grain yields. It is noted that the main biological constraints to grain production are soil drought, windstorms, degradation and extreme temperatures, especially in rainfed irrigated farming systems in arid lands such as southern Kazakhstan. In the northern and central parts of Kazakhstan, agricultural land is dominated by black and chestnut soils, and in the south by brown semidesert soils. The largest areas of eroded agricultural land are located in Almaty, Atyrau and Turkestan regions – over 30%, and the smallest – in Akmola, Karaganda, Kostanay and North Kazakhstan regions – 5%. Productive grain growing requires soil monitoring for the main mobile elements that affect plant yields. The average values for the Republic of Kazakhstan are: nitrogen content – 37.5 mg/kg, phosphorus – 16.8 mg/kg, potassium – 419.5 mg/kg, humus – 2.8%. The practical significance of the study is to expand and supplement the theoretical basis of research in the field of soil degradation, and the results obtained are proposed for a comprehensive environmental assessment of soils in Kazakhstan

Keywords: agrochemical analysis; nativeness; rational land management; humus; nitrogen; phosphorus

INTRODUCTION

The use of fertilizers, intensive farming, and high-yielding varieties contribute to successfully overcoming food shortages. These factors eventually lead to soil fertility problems. Stable development of agriculture, growth of production and the welfare of the population largely depends on soil fertility, but over the last few decades there has been a steady degradation of agricultural land and loss of its productivity, which leads to an overall decrease in crop yields and efficiency of crop production. Rational use of nutrients and maintenance of soil fertility is increasingly recognized, especially in countries with high demographic pressure on land resources.

Environmental problems in the Republic of Kazakhstan (RK), are the primary causes of soil degradation, namely reduced humus content, toxicity, erosion, salinization, waterlogging, pollution and desertification. As described in the data of S.B. Kenenbaev *et al.* (2023), the main causes of declining soil fertility are: weakening of vegetation productivity in the apparent absence of pests and diseases; change of soil structure with the appearance of cracks; overabundance of water-soluble chloride, sulphate and carbonate salts with increase of acidity; reduction of organogenic elements by more than 15-20%; reduction of useful microorganisms, worms, insects; development of pathogenic fungi.

Anthropogenic activity imposes an imprint on natural conditions, lack of crop rotations, use of outdated technologies and insufficient application of organic fertilizers. Soil protection measures in RK are based on interrelated principles, namely: avoidance or minimization of mechanical disturbance of soil productivity; constant maintenance of soil covers with plant residues and living cover crops (including legumes used as green fertilizer), which reduces moisture loss and soil erosion; protection from extreme harsh climate conditions through crop rotation and the use of a wide range of new crop varieties and hybrids.

S.M. Farahat *et al.* (2022) noted that agricultural land management is a complex system involving land

use forecasting, land supervision and physical monitoring as the development of agricultural areas is directly dependent on their land and resources. One fifth of RK lands are not cultivated, which requires diagnosing new signs of types and kinds of soil degradation. The study of L. Kuanova *et al.* (2023) shows that the area of the RK agricultural land fund is 37.6% of the total area of 102.6 million ha, including arable land – 24.3 million ha, irrigated land – 1.7 million ha, fallow land – 2.6 million ha, hayfields – 2 million ha, pastures – 70 million ha. The qualitative composition of land suitable for farming is as follows: 16.1 million ha of arable areas, 58.2 million ha of solonetz soils, 43.1 million ha of scrubby soils, 35.3 million ha of saline soils, while the genetic and geographical features of soil degradation in RK remain unidentified.

As noted by M.A. Ansari *et al.* (2023), monoculture adoption usually leads to soil degradation and reduced crop yields, while the concept of conservation agriculture aims at obtaining acceptable profits while preserving the environment, therefore, double cropping with reduced tillage and utilization of crop residues is recommended. S. Turebayeva *et al.* (2022) report that proper and rational use of fertilizers can improve soil fertility and crop yields, while haphazard application of mineral fertilizers can have a negative impact. The main measure to protect the soil from contamination by mineral fertilizers and related compounds is scientifically justified fertilizer application at the optimal time. The intensive farming system involves the use of large quantities of mineral fertilizers, pesticides and other products of the chemical industry. Soil-protective measures are based on strengthening natural biological processes, by eliminating to a minimum chemical means of protection, fertilizers of mineral or organic origin. To improve soil degradation zoning of the RK territory, it is necessary to carry out continuous soil monitoring, as well as bonitet, soil-ecological and economic assessments.

The aim of the study is to assess the ecological state of RK soils and use soil-protective methods to increase crop yields.

LITERATURE REVIEW

Ecological problems of soils take place not only in RK, but also on a world scale, as can be seen from the data of world congresses in Europe, America, Turkey, China and near abroad, devoted to degradation, pollution, desertification, soil and environmental protection. A.M. Fortuna *et al.* (2023) report that soil is a unique natural resource that is utilized by mankind in agriculture and forestry for food independence, livestock rearing and industrial raw materials. Indicators of soil analysis include percentage of organic matter, biotic and microbial biomass, carbon amount, enzymatic activity, pH, electrical conductivity, cation exchange capacity of nitrogen, phosphorus, potassium, sulphur available to plants, porosity, aggregate stability, infiltration, bulk density, water available in soil. Topography has a significant influence on the formation of climate, soils, natural landscape and land cover. As reported by T. Darbayeva *et al.* (2020), the geological structure of the RK territory is complex and diverse: from low surface elevations to glacial highlands.

As noted in the data of A. Tokbergenova *et al.* (2018), more than 70 million ha of land in RK suffers from erosion, which is 26% of the territory of the republic, of which more than 52 million ha suffered from wind erosion and 17 million ha from water erosion. Wind erosion is widespread in the plains' region, especially in dry steppe areas, and it is most pronounced on soils of light mechanical composition in Zhambyl, Mangistau and Pavlodar oblasts. R. Zhu *et al.* (2023) report that water erosion is the result of unsystematic human use of land resources, it occurs during prolonged rainfall and snowmelt, when moisture does not have time to soak into the soil, washes out soil particles and forms potholes. Strong water flow forms deep gullies, reducing the area of cultivated land and creating inconvenience for field cultivation. According to K. Khosravi *et al.* (2023), important parameters such as maximum water absorption and plasticity number decrease with increasing degree of soil washing. The fertility of such soils is lower than that of non-washed soils and is one of the major causes of agricultural production losses due to erosion. In a study by M. Koza *et al.* (2021) noted that the total amount of trace elements – copper, zinc, cobalt, and manganese – as well as the amount of chelates of these elements available to plants decreases in highly eroded medium- and high-treated layers of chernozem.

Practically all agrophysical parameters deteriorate due to loss of power fraction and run-off as a result of soil erosion, as well as indicators of pesticides. A.I. Derepaskin *et al.* (2023) point out that in eroded soils, the number of permeable aggregates larger than 1 mm is almost twice as large as in fully formed soils.

As a result of loss of silt particles and humus, the physical and hydraulic properties of soil deteriorate, eroded soil becomes less water-holding and permeable. Specific and volumetric masses increase as humus content decreases and coarse dust content increases. In typical arable layers of chernozem and chestnut eroded soils, the content of silt and physical clay decreases by 5-6%, while the content of coarse dust increases by 4-5%. D.L. Corwin (2021) evaluates soil protection measures in agriculture, which are aimed at maintaining optimal phytosanitary conditions for crops, in particular, at protecting crops from weeds. The number of weed seeds in the arable layer ranges from 20 million to 5 billion seeds/ha, with a weed threshold of 10-20 seeds/m² for spring crops and 2-3 seeds/m² for perennial crops.

In their studies, S.T. Shah *et al.* (2022) report that destruction of the most fertile topsoil, deterioration of agrochemical and hydrophysical characteristics of soil inevitably leads to significant reduction in yields of cultivated crops in all regions. Soil estimation of humus content noted by K. Kunanbayev *et al.* (2022), informs about the availability of nitrogen, phosphorus, and potassium in the arable layer of the North-Kazakhstan region and shows that the yield of major grain crops (wheat, barley, oats, and maize) on slightly eroded soils decreases by 15-18%, on moderately eroded soils – by 30-40%, on highly eroded soils – by 40-50% compared to the yield on unaffected soils. Soil conservation measures have the potential to reduce the impact of climate change, in particular by regulating greenhouse gas emissions. As reported by R. Lal (2020), agricultural activities increase the stock of soil organic matter that can sequester carbon from carbon dioxide and store it safely for long periods of time, e.g. 25-50 years, before soil carbon saturation reaches a new stabilization level.

The benefits of proper crop rotation are increased yields and reduced costs; it is an integral part of the farming system. W. Grzebisz *et al.* (2022) found that a well-planned crop rotation not only enhances insect, disease and weed control, but also helps to maintain and improve soil structure and organic matter content. H. Li *et al.* (2023), in turn, characterized the crop diversity that can be used to reduce the negative impact of weeds, evenly distribute the load and prevent soil erosion, reduce biotic and abiotic stresses, and reduce economic risks.

MATERIALS AND METHODS

Fundamental and conceptual developments of the problem of determining the state of soil cover and its suitability for solving various tasks of agricultural production served as the basis of the scientific research. The following methods were used in the research: cartographic, analysis and synthesis, systematization, abstraction, concretization, forecasting.

The method of cartographic analysis was used to consider the soil cover of eroded agricultural lands as

RESULTS

one of the largest reclaimed groups in terms of area. According to the East National Technology Support Centre (ENTSC), the Soil Management Assessment Framework (SMAF) was evaluated. Soil quality within the farmland was characterized by certain levels of performance, namely the ability to provide crops with moisture, macro- and micronutrients. RK soils were classified on a latitudinal basis and were represented by: chernozem in the northern part of the country, chestnut, brown semidesert and desert sandy soils in the south. Soil structure in the RK territory was determined by the thickness of humus horizon, humus content, pH, hydrolytic acidity, nitrogen, phosphorus, and potassium content. Using the method of systematization, the RK soil structure was formed, which allowed collecting and analysing data based on the principles of state regulation of potential resources and to determine the productivity of high quality crop and livestock production at different levels of development.

The work was based on the main factors of soil fertility depletion: wind and water erosion, pollution, reduction of biological productivity of natural pastures, secondary salinization and waterlogging of irrigated areas, desertification, and use for construction. On the basis of soil degradation and fertility losses, the factors of water and wind erosion were determined. The development of soil erosion processes is caused by a combination of natural conditions (such as climate, relief, mechanical composition of soils and other natural conditions), but the increased level of anthropogenic impact and the degree of intensity of land use, especially agricultural land, significantly accelerates degradation. To substantiate the planning of land management in RK, methods of analysis and synthesis have been used to determine the prospects for the use of land funds in the regions, determining the efficiency and effectiveness of agricultural land use, based on analysed and processed information of the Bureau of National Statistics (2023).

Natural and climatic conditions of RK have a significant impact on the yield and growth period of grain crops, ensuring high yields, as well as improving the quality of marketable products and raw materials. The noticeable effects of RK climate change are signalled by the occurrence of severe droughts that manifest with high intensity. According to United Nations (2013) climate parameters were set: summer high temperatures of 24-35°C with dust storms; winter low temperatures and snowstorms, with average temperatures of 13°C. In the research system, SWOT-analysis of RK agricultural land by soil condition and plant productivity was made. SWOT-analysis allowed finding out the optimal parameters of land use for building a model of sustainable development of the agro-industrial complex. Soil survey materials, materials on redistribution of agricultural land, land cadastre data, materials on socio-economic development and nature protection were used as input data for the survey.

The peculiarity of the RK ecological and geographical position is low stability of the natural environment to anthropogenic impacts. Four soil-geographical zones are distinguished on the RK plains: middle humid forest-steppe, middle arid steppe, dry desert steppe and desert. Geographical boundaries of natural zones correspond to the size of soil zone types. In RK 86% of the area falls on plains, where three main types of soils are present: chernozem, chestnut, grey-brown loamy soils, as well as in some areas' riverside soils – fluvisols and marsh soils – histosols. According to Sh. Smagulova *et al.* (2022) it is established that the scale of actively used agricultural land in RK as of 2022, is: 38.5%, of which more than 70% of arable land is in Akmola, Kostanay, Pavlodar and North-Kazakhstan oblasts, more than 60% of irrigated arable land in Almaty and South-Kazakhstan oblasts, as well as small areas of pastures in Karaganda – 18.8% and Almaty – 44.1% oblasts.

Reduction of soil degradation is ensured by the use of sustainable land use practices, as traditional tillage with intensive ploughing destroys soil structure and leads to soil degradation. In contrast, no-till or minimum tillage systems increase organic matter content, retain moisture and minimize soil degradation. Crop rotation prevents degradation; it is the alternation of crops of different families on the same plot to control pests and diseases, increase fertility and reduce the risk of nutrient deficiencies. Strip farming is the alternation of legumes and cover crops with cereals and continuous crops to prevent soil degradation. Precision efficient irrigation, such as drip irrigation, can prevent a range of negative impacts, especially secondary salinization and sanding of fields. Satellite imagery can be used to analyse crop conditions and determine the right amount of fertilizer to be applied to a particular area, helping farmers get the desired yields without damaging nature. Organic farming with natural fertilizers helps prevent soil degradation, and the use of integrated crop protection methods avoids the application of chemicals that pollute the environment. Planting cover crops with living mulch protects the soil from damage, improves soil structure, increases nutrients and provides effective weed control. Contour ploughing using earthen ridges or dikes to collect water prevents fields from eroding and flooding.

Identifying soil erosion hotspots is the first step in improving environmental remediation strategies. Various methods can be used, including analysing aerial photographs, using soil erosion models and more detailed scaling. D. Malakhov *et al.* (2022) report a large volume of soil, reclamation, soil-erosion and soil-geochemical surveys with a number of thematic soil maps. The main volume of RK soil surveys totalled: 96.4 million ha or 52.1% of the total surveyed area in the period up to 1990; 3.2 million ha each in 2014-2015; 2.3 million ha in 2016; 5.2 million ha in 2017, 7.2 million ha in 2018, 7.3 million ha in 2021, and 7.8 million ha in 2022.

The agricultural lands of RK are characterized by the presence of chernozem, chestnut soils in the northern part, brown semidesert soils are marked to the south. Chernozem are subdivided into leached soils with humus content of 3-6%, ordinary soils and southern soils. Regions with chernozem include Northern, Kostanay, Akmola, Pavlodar, Aktobe and West Kazakhstan regions

and occupy 25.5 million ha or 9.5% of the country's territory. Unlike other types of soils, chernozem are characterized by a high level of natural fertility, thick humus layer, significantly higher content of humus and total nitrogen in inclusions, which gradually decreases by soil layers, detailed agrochemical analysis of chernozem is considered in Table 1.

Table 1. Chernozem – agrochemical properties

| Subtype | Humus horizon thickness, cm | Humus, % | Salt extract, pH | Acidity (hydrolytic) meq/100 g | Absorption capacity meq/100 g |
|----------|-----------------------------|----------|------------------|--------------------------------|-------------------------------|
| Ordinary | 65-135 | 5.5-8.5 | 7-7.8 | 0-1 | 40-50 |
| Leached | 75-145 | 9-9.4 | 5.4-6 | 2-4 | 45-55 |
| Typical | 100-175 | 8.5-12 | 6.4-7.1 | 0.5-3 | 50-60 |
| Southern | 45-85 | 3-6.5 | 7.2-8.1 | 0-0.5 | 25-35 |

Source: compiled by the authors based on M.K. Zhumagulova et al. (2022)

Chestnut soils are subdivided into dark chestnut, chestnut, and light chestnut soils, they occupy most of the plains of the central RK, the northern part of the Caspian lowland and East Kazakhstan oblast, covering 90.6 million ha or 34% of the country's territory.

Chestnut soils are widespread in Northern, Central, Eastern and Western Kazakhstan.

Humus content in chestnut soils is 2-3%, detailed agrochemical analysis of chestnut soils is considered in Table 2.

Table 2. Chestnut soils – agrochemical properties

| Subtype | Humus horizon thickness, cm | Humus, % | Nitrogen, % | Phosphorus, % | Salt extract, pH | Total number of cations, meq/100 g |
|----------------|-----------------------------|----------|-------------|---------------|------------------|------------------------------------|
| Dark chestnut | 36-46 | 4-5 | 0.22-0.28 | 0.15-0.25 | 6.8-7.2 | 30-35 |
| Chestnut | 30-40 | 3.5-4 | 0.18-0.22 | 1.13-0.18 | 7.2-7.5 | 20-13 |
| Light chestnut | 25-30 | 2.5-3 | 0.11-0.16 | 0.09-0.13 | 7.4-8.2 | 12-15 |

Source: compiled by the authors based on A.B. Kaldybekov et al. (2022)

Brown and grey-brown soils are located to the south of chestnut soils and cover an area of 120 million ha, or 44% of the RK territory. Morphological features of brown soils include an upper humus layer of lighter colour, predominantly brown in the profile.

The humus layer is 12-15 cm thick, weakly stratified, structureless, loose, light brown. The humus content in brown soils varies in the region of 1-2%, so it is suitable only for use in livestock areas, and farming is possible only under irrigation, which is clearly shown in Table 3.

Table 3. Gray-brown soils – agrochemical characteristics

| Subtype | Salt extract, pH | Humus horizon thickness, cm | Humus, % | Transitional phosphorus mg/100 g soil | Transitional potassium mg/100 g soil |
|------------|------------------|-----------------------------|----------|---------------------------------------|--------------------------------------|
| Gray-brown | 4-5.8 | 20-30 | 1.2-2 | <5 | <10 |
| Brown | 4.3-4.8 | 15-20 | 1-2 | 5-8 | 10-15 |

Source: compiled by the authors based on K. Kunanbayev et al. (2022)

When assessing soil degradation in the context of damage to agriculture due to climate change, the most frequent focus is on crop production, which is increasingly affected by the unevenness of precipitation over the year. However, livestock production is equally affected by climate change, leading to degradation of pastures, low productivity of hayfields – and as a consequence, the inability to keep livestock in many regions of RK. Reducing conventional tillage and the correct use of herbicides can significantly improve weed control ef-

ficiency, reduce chemical costs and reduce the risk of environmental pollution. For better utilization of moisture, spring soil preparation techniques are of great importance: one or two cultivations with harrowing, also timely carrying out of these operations improves moistening of the sowing layer, ensures active sprouts and weed control. Data on land quality characteristics in RK counts 90 million ha of eroded soils, of which 29.3 million ha are almost completely eroded. Figure 1 illustrates the extent of eroded soils.

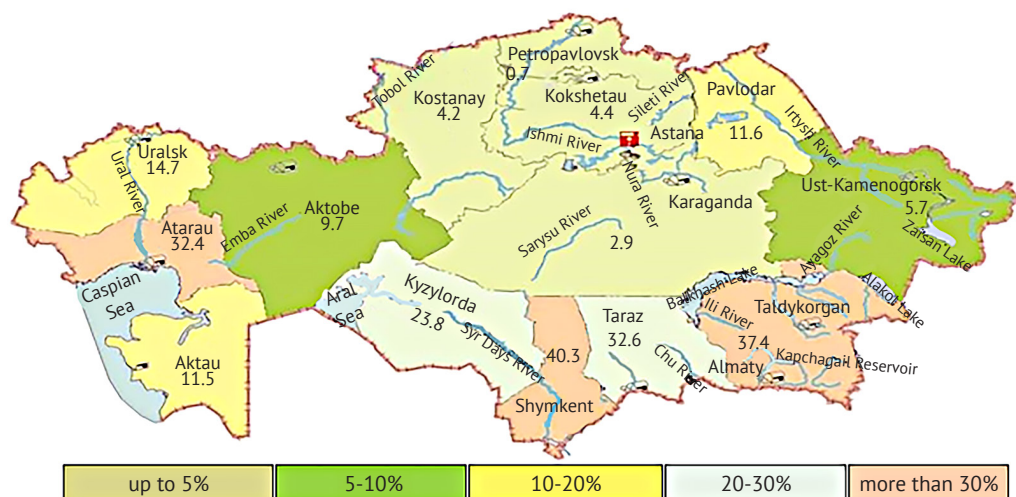


Figure 1. Rhodinated soils of the Republic of Kazakhstan

Source: compiled by the authors based on S.K. Makenova et al. (2023)

The largest share, more than 30% of eroded agricultural land from the total area falls on Almaty, Atyrau and Turkestan oblasts, on the contrary the smallest share up to 5% on Akmola, Karaganda, Kostanay and North-Kazakhstan oblasts. The effectiveness of agricultural technologies is assessed by plant productivity, which depends on a number of factors, including the growing season and weather conditions of the previous autumn, winter, and spring. The vegetation in RK is distributed by zones: the wet northern zone is located in the forest-steppe zone, the arid southern zone is located in the steppe, semidesert and desert zones. Due to the diversity of soil vegetation and relief within each zone, in addition to the characteristic zonal vegetation scattered throughout Kazakhstan, there is striped vegetation – for example: riparian forests, desert buckthorn and other wetlands. The current RK flora includes trees – 68 species, shrubs – 266, semi-shrubs – 433, perennial – 2598, annual – 849 herbs.

Drought and temperature extremes are the main biological constraints to cereal production, especially in rainfed dry farming systems such as in the southern part of RK. The average yield of cereals in 2023 was 9.3 kg/ha, oilseeds 7.1 kg/ha, and vegetable crops 275.4 kg/ha. During the 2021-22 harvest period, Kazakhstan harvested 22 million tonnes of grain, which is 34% more than in 2021, of which: wheat – 16.4 million tonnes, barley – 3.3 million tonnes. In 2023, RK's average grain yields are 28% lower than the previous 2020-2022 figures. The reason for the fall in cereal

yields was atmospheric and soil drought, dry spells and soil degradation. One of the main problems of crop production in RK is unstable crop yields due to progressive soil degradation. According to M. Kazlauskas et al. (2022), it was found that the yield of winter wheat on moderately podzolic soils with non-washed loamy turf was 31.7 c/ha, on moderately washed soils – 15.3 c/ha, on heavily washed soils – 2 c/ha.

A large amount of research is devoted to the use of mineral fertilizers, microelements and growth regulators, as well as their effect under different treatments and conditions. RK is developing technologies of direct sowing and pre-sowing tillage for winter wheat without main tillage in three-field crop rotation under rainfed conditions. Wheat is a strategic crop for the RK economy and the issue of resource efficient winter wheat production technologies in the south of the country is one of the strategic priorities that are being developed, tested and adapted. More detailed research is needed, especially in arid climatic conditions with erratic rainfall and temperature regimes. At the time of maize sowing, the best moisture reserves are in the one and a half metre layer of soil and are observed after winter wheat. Significantly less moisture in the soil ball by 30-50 mm is observed after sunflower, barley, Sudan grass, sugar beet. Provision of soils with three main mobile elements, which affect plant yields on the example of cereals, on average in RK the content of humus on arable areas is 2.8%, nitrogen – 37.5 mg/kg, phosphorus – 16.8 mg/kg, potassium – 419.5 mg/kg, which is noted in Table 4.

Table 4. Composition of humus and productivity of grain crops by regions of the Republic of Kazakhstan

| Regions | Humus, % | Nitrogen, mg/kg | Phosphorus, mg/kg | Potassium, mg/kg | Grain yield in 2022/23, c/ha |
|------------------|----------|-----------------|-------------------|------------------|------------------------------|
| North Kazakhstan | 4.6 | 47.5 | 16.1 | 454.1 | 20.9 |
| Kostanay | 4.2 | 49.2 | 18.2 | 483.7 | 9.1 |
| East Kazakhstan | 3.8 | 36.4 | 21.3 | 404.7 | 23.6 |

Table 4, Continued

| Regions | Humus, % | Nitrogen, mg/kg | Phosphorus, mg/kg | Potassium, mg/kg | Grain yield in 2022/23, c/ha |
|-----------------------------|----------|-----------------|-------------------|------------------|------------------------------|
| West Kazakhstan | 3.7 | 35.1 | 18.9 | 563.3 | 13.8 |
| Akmola | 2.6 | 48 | 12.4 | 424.3 | 14.1 |
| Aktobe | 2.9 | 36.9 | 15.5 | 276.8 | 9.2 |
| Pavlodar | 2.5 | 33.6 | 15.4 | 464.6 | 12.7 |
| Turkestan | 2.5 | 15.8 | 19.1 | 323.3 | 31.4 |
| Karaganda | 2.4 | 56.4 | 10.6 | 433.6 | 12.9 |
| Kyzylorda (irrigated lands) | 2.1 | 57.9 | 9.9 | 344.1 | 13.1 |
| Zhambyl | 1.9 | 16.7 | 23 | 456.8 | 29.1 |
| Almaty | 1.3 | 16.5 | 20.8 | 399.8 | 28.8 |

Source: compiled by the authors based on A. Rau et al. (2023)

Nitrogen is the main element of soils, as it has the greatest influence on plant growth and is the building material for new cells. The leaders in terms of nitrogen content in soil are: Karaganda region – 56.4 mg/kg, Kostanay region – 49.2 mg/kg, Akmola region – 48 mg/kg, North Kazakhstan region – 47.5 mg/kg. The main importance of phosphorus is acceleration of metabolic processes in cells, which determines the speed and quality of crop maturation, as well as resistance to plant diseases. In terms of phosphorus content prevails: Zhambyl region – 23 mg/kg, East Kazakhstan region – 22.5 mg/kg, Kyzylorda region – 20.4 mg/kg, Almaty region – 19.5 mg/kg, West Kazakhstan region – 19.4 mg/kg. Potassium is involved in the process of photosynthesis, as well as in the movement of carbohydrates, protein synthesis, provides resistance to fungal diseases of plants. In the case of potassium deficiency, plants develop and grow slowly, leaves turn yellow, stems thin, seeds lose germination energy. According to the content of potassium in the soil are leading: West Kazakhstan region – 563.3 mg/kg, as well as Zhambyl region – 456.8 mg/kg, Kostanay region – 483.7 mg/kg, Pavlodar region – 464.6 mg/kg, North Kazakhstan region – 454.1 mg/kg. Correlation with the percentage of humus content is noticeable in the content of nitrogen, phosphorus, potassium, as these elements of plant nutrition are contained in humus.

The formation of energy plantations of bush willow biomass *Salix Viminalis* prevents soil erosion and contributes to the improvement of the environment, this project is ideal for seedlings on RK lands consisting of low-productive and polluted in terms of crop cultivation, as well as in erosion control measures to strengthen soils, a natural filter to clean the soil from pesticides. Soil-forming plant growth activators are presented in the form of potassium and sodium humates of biological metabolites in dilution of 5-10 ml per litre of water, with the rate of application of the preparation 2-4 l/ha. Preparations based on potassium and sodium humates stimulate the growth of the root system, simultaneously increase yield and mobilize the immune system, in combination with herbicides they reduce stress for the main crop, increase the efficiency of photosynthesis, nitrogen uptake by plants, participate in the accumulation of sugars and protein synthesis. M.A. Abdelfattah et al. (2021) reported that humates contain less than 200 g/l dry matter, humic, citric, succinic, ascorbic organic acids, vitamin complexes B1, B3 and B1 less than 80 g/l; potassium and sodium salts of humic acid more than 60 g/l, carbon more than 35 g/l, complexes of macro- and microelements. The most comprehensive tool for analysing agricultural land for sustainable farming in RK is SWOT-analysis, it is a general method of assessing various phenomena and factors, presented in Table 5.

Table 5. SWOT analysis of the formation of sustainable land use in the Republic of Kazakhstan

| Strengths | Weaknesses |
|--|--|
| <ul style="list-style-type: none"> • waterlogging of the soil due to mulching; • absence of water and wind erosion; • formation of an active microbiota with the presence of micro- and macroelements; • accumulation of carbon in the soil; • reduction of carbon dioxide emissions into the atmosphere. | <ul style="list-style-type: none"> • treating fields with pesticides before sowing and during the growing season. |
| Opportunities | Threats |
| <ul style="list-style-type: none"> • natural accumulation of humus in soils; • improvement of agrophysical and agrochemical properties of soils; • diversification of resource-saving technologies; • marketing of agricultural products; • modernization of agricultural machinery. | <ul style="list-style-type: none"> • infestation by pests and diseases; • economic damage from a lack of fertilizers and a decrease in soil fertility. |

Source: compiled by the authors based on B. Hnatkivskyi et al. (2022)

The phenomena and factors of SWOT-analysis are divided into four categories: Strengths, Weaknesses, Opportunities, Threats. The SWOT-analysis allowed identifying internal and external factors of development, determined the best standards of land use organization and formed the basis of the sustainable land use model in RK.

DISCUSSION

The formation of crop yields in RK is influenced by natural soil fertility, as well as climate, organic and mineral fertilizers, seeds, tillage, fertilizers, ameliorants, plant protection products. It is noted that the average yield of cereal crops in RK in 2023 is low at 9.3 kg/ha. L. Rayichuk *et al.* (2023) report that wheat ranks third among cereals in terms of production, behind only rice and maize. But it should be taken into account that the world leaders in wheat yield, are characterized by high productivity indicators: Germany – 75.3 c/ha, France – 68 c/ha, Egypt – 64 c/ha, China – 57 c/ha. From the reviewed facts, it is found that only application of soil protection measures can raise plant productivity in RK.

Firstly, it is necessary to introduce innovative farming systems in RK: water accumulation, regulation of water exchange, gas exchange and heat exchange processes. Obtaining high and stable yields of grain crops in severe hydrothermal conditions requires taking into account soil-climatic zonality: in the north of RK agricultural lands are represented by chernozem and chestnut soils, and in the south – brown semidesert soils. Unforeseen weather conditions and drought lead to loss of fertility. To ensure the sustainability of crop yields, it is necessary to carry out reclamation measures with the application of organic and synthetic mineral fertilizers. According to D.S. Peixoto *et al.* (2020), in order to conserve natural resources, maintain water, air and soil quality, and stabilize crop yields, it is necessary to implement soil-protective resource- and moisture-saving farming methods: No-Till, Strip-Till, Mini-Till, Conservation Agriculture. These technologies envisage preservation of integral, intact structure, leaving on the field stubble and mulch of shredded plant residues, and are also applied in the form of soil-protective crop rotations, terracing of slopes, snow retention, improvement of conservation planting, hydraulic engineering construction. It should be agreed that the alternate application of the most effective No-Till, Strip-Till and Mini-Till tillage technologies in RK will improve soil fertility and crop yields with minimal environmental impact.

Soils contain more carbon than the atmosphere and all vegetation in general, and the introduction of crops such as legumes and cereals into the farming system allows it to be biologically sequestered into organic matter, as well as balancing the nitrogen content of the soil. W.P. Zhang *et al.* (2023) noted that stems, stubble, roots, and leaf litter of crops are important additions of nutrients to the soil, but crops such as root

crops and fruiting vegetables leave very little nutrients in the soil. Also, in the work of K.K. Shah *et al.* (2021), an improved crop rotation system that significantly improves soil structure, physical and chemical properties and increases the availability of nitrogen, phosphorus, potassium and other elements in the soil are described. Certainly, this study confirms the importance of this intervention in maintaining soil fertility.

Different crops are adapted to different types of extreme weather events, and crop rotation effectively reduces the risks of yield loss as well. RK has developed a technology of direct seeding and pre-sowing tillage without main tillage for winter wheat in a three-field rotation in rainfed conditions. A.P. Pinto *et al.* (2023) take into account the basic principles of building dynamic rotations of conservation agriculture: avoiding the alternation of crops of similar origin; respecting the optimal return period of crops on the same site; consideration of soil-ecological groups, soil peculiarities; availability of machinery, farm evaluation, economic conditions. As an additional confirmation, it is noted that modern harmonious crop rotation combines the ecological possibility of reducing the use of synthetic mineral fertilizers and pesticides in the soil with the economic aspect of profit maximization through the growth of highly profitable yields.

In RK, new methods of bio-agriculture, including cover crops, plant growth stimulators, liquid fertilizers in the form of humates, organic acids and B vitamins are used to increase crop production. To date in RK, conservation technologies have reached about 7.5 million ha of agricultural land, but the main problem is the annual removal of essential nutrients from the soil after harvesting. Productive cultivation of food crops in the soil assumes the presence of the main mobile elements affecting plant yield, namely nitrogen – 37.5 mg/kg, phosphorus – 16.8 mg/kg, potassium – 419.5 mg/kg. In the case of unfertilized sowing, only 15-20% of nutrients taken up by plants with harvesting are returned to the soil, therefore, it is necessary to apply a large amount of mineral and organic fertilizers. According to S. Sharma *et al.* (2022), nitrogen and potassium should be returned to the soil by 80%, and phosphorus – by 85%, so potassium fertilizers are recommended to be applied to grain crops from autumn in the amount of 90-120 kg/ha, and phosphorus fertilizers at seed sowing – 60-80 kg/ha due to the introduction of synthetic mineral fertilizers. It is worth refuting this opinion, but the use of synthetic mineral fertilizers is an effective way to ensure constant yields, although it contradicts the concept of soil-saving agriculture. And the work of T. Bayu (2020) pointed out effective ways to restore soil fertility through intensification of agricultural production using organic fertilizers and plant growth regulators. It is also found that the combined application of manure and mineral fertilizers is more economical to maintain sustainable agricultural productivity. Maximum sus-

tainable crop yield of 2.88 t/ha is obtained by applying 69 kg of mineral fertilizer with 10 t/ha of manure. As a result, it can be agreed that organic matter in soil is of fundamental importance in providing nutrient elements to plants, especially under the conditions of continuous increase in potential yield of RK degraded soils. Consequently, it is possible to agree with the statement that organic matter in soil has fundamental importance in providing plants with nutrient elements, especially under conditions of necessity of constant increase of potential crop yields for RK degraded soils.

To increase humus levels in RK soils, it is necessary to create a dense cover of plant material, with gradual application of organic, organomineral fertilizers that disperse surface run-off, attenuating the force of winds under contour ploughing and strip farming. Assessing the quality of agricultural land requires a significant amount of soil sampling for humus content. Monitoring estimates of humus content in the arable layer of chernozem ranges from 3% to 12%; in chestnut soils from 2.5 to 5%; grey-brown soils from 1 to 2%. L. Kang *et al.* (2021) report that in order to preserve and reproduce soil fertility, in particular its main indicator – humus, it is necessary to apply crop rotations with annual and perennial grasses, and to apply organic fertilizers. It is worth agreeing with this statement, because the mineral fertilizer system does not provide stabilization of humus content in grain and fallow crop rotation, irrespective of the method of main tillage.

Energy plants are natural filters for soil purification, in RK there are prerequisites for mass use of modern methods of cultivation and processing of such biomass. Of particular relevance are arrays of energy willow, which can be used as buffer zones in places of accumulation of biological wastes of farms and become natural filters for removal of agro-industrial wastes. As noted in the work of S. Jain & A.R. Tembhurkar (2022), the development of bioenergy technologies will diversify the country's energy supply, improve soil and air ecology, and promote local employment. In addition, plantations are effectively used in anti-erosion measures to strengthen the soil, enrich the soil with macro- and microelements and nutrients of natural origin. It is difficult to disagree with this study, as bioenergetics is a promising branch of agriculture, for radiation-contaminated, unproductive and degraded lands, plantations of energy plants, which become the only cost-effective and safe maintenance of land fertility.

Diversification of agriculture is done by planning and ensuring a high level of land use through specialized digital maps with photo images corresponding to the current state of the land, which should cover 100% of the RK territory. The results of RK soil surveys, indicate environmental problems and risks of agricultural land use related to landscape degradation, especially for arable land. According to Y. Cai *et al.* (2022), modern assessment of soil profile status and potential

is impossible without the application of Geographic Information System (GIS) land use indicators, which determines the net amount of carbon assimilated by photosynthesis and autotrophic respiration over a certain period of time for biological production of fibre and protein. It is impossible to disagree that in this study, the main emphasis is placed on the construction of balance relationships in the agro-landscape, their use for the optimization of natural-anthropogenic systems aimed at raising the level of productivity of farms with low yields.

CONCLUSIONS

Soil research, which was conducted, has shown that soil erosion has a detrimental effect on the economy, as the gradual degradation of fields inevitably leads to lower crop yields. Regular monitoring of fields helps to detect the first signs of problems. Intensive farming aims to generate as much profit as possible through the use of fertilizers and pesticides, intensive and extreme land use with significant inputs, abundant irrigation, extensive cropping, high-yielding varieties and expansion into new areas. At the same time, the potential of degraded fields is significantly reduced and more attention needs to be paid to their management practices, including ways of applying additional mineral organic fertilizers to increase productivity. Despite the length and complexity of the process, it is also necessary to analyse the short-term effects of soil erosion using vegetation indices. Establishing a natural crop rotation can effectively improve soil physical and chemical properties while increasing soil enzyme activity, fertility and ultimately soil stability in the process of resisting RK weather extremes.

Modern agricultural technologies allow not only achieving significant success in preventing soil erosion and its consequences, but also finding rational solutions to this problem. At the same time, the choice of optimal methods and strategies depends on effective management decisions, climatic conditions, resource availability and soil utilization plans. Soil erosion monitoring and control can be adapted to the requirements of specific agribusinesses. For example, digital mapping of fields based on satellite images and the use of mathematical models allows analysing the current state of soils and taking appropriate protective measures. In the process of climate change and global warming, modern agriculture is far from classical methods that ensure adequate storage and utilization of soil moisture, as even on fertile soils plant productivity may not give the expected yield due to lack of soil moisture.

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CONFLICT OF INTEREST

None.

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Анотація. У Казахстані сільськогосподарські землі деградували протягом десятиліть, що призвело до загального зниження врожайності сільськогосподарських культур. Метою дослідження є проведення екологічної оцінки сучасного стану ґрунтів Казахстану для підвищення врожайності сільськогосподарських культур з використанням ґрунтозахисних методів. Під час проведення дослідження використовувалися такі методи: картографічний, аналізу і синтезу, систематизації, абстрагування, конкретизації, прогнозування. Під сільське господарство використовується 86 % земель Казахстану. Активне землекористування призвело до різних форм деградації, внаслідок чого налічується 90 млн га еродованих ґрунтів, з яких 29.3 млн га практично повністю розмиті. У 2023 році середня врожайність зернових культур становила 9.3 ц/га, олійних – 7.1 ц/га, овочевих – 275.4 ц/га. Зазначено, що врожайність зернових культур у 2023 році нижча на 28 %, ніж у попередньому періоді 2020-2022 рр., незважаючи на збільшення посівних площ. Посуха та деградація ґрунтів є основними причинами зниження врожайності зернових культур. Зазначено, що основними біологічними обмеженнями для виробництва зернових культур є ґрунтова посуха, суховії, деградація та екстремальні температури, особливо в богарних зрошуваних системах землеробства на посушливих землях, таких як південь Казахстану. У північній і центральній частині Казахстану угіддя сільськогосподарського призначення представлені чорноземами і каштановими ґрунтами, а на півдні бурими напівпустельними. Найбільші площі еродованих сільськогосподарських угідь розташовані в Алматинській, Атирауській і Туркестанській областях – понад 30 %, а найменші – в Акмолинській, Карагандинській, Костанайській і Північно-Казахстанській областях – 5 %. Для продуктивного вирощування зернових культур необхідний моніторинг ґрунту за основними рухомими елементами, які впливають на врожайність рослин. Середні значення для Республіки Казахстан становлять: вміст азоту – 37.5 мг/кг, фосфору – 16.8 мг/кг, калію – 419.5 мг/кг, гумусу – 2.8 %. Практична значущість дослідження полягає в розширенні та доповненні теоретичної бази досліджень у галузі деградації ґрунтів, а отримані результати пропонуються для комплексної екологічної оцінки ґрунтів Казахстану

Ключові слова: агрохімічний аналіз; природність; раціональне землекористування; гумус; азот; фосфор



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Ecological aspects in the use of soil enzymes as indicators of anthropogenic soil pollution

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Abstract. In the contemporary era, with rapid industrial growth and urbanisation, analysing the impact of human activities on soil enzyme activity becomes crucial. The purpose of this study is to assess the influence of anthropogenic pollution on enzyme activity in soil. Research on enzyme activity levels in the soil in the city of Karabalta, Chuy Region, Kyrgyz Republic, was conducted using biochemical analyses and specific enzymatic tests. The results revealed significant diversity in catalase activity in

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different soil samples. Some samples exhibited high activity, while others showed low activity. These differences may be associated with oxidative stress and the ability of soil microorganisms to decompose hydrogen peroxide. Urease analysis indicated the highest activity in soil samples after 2 hours, particularly near the protective barrier of the tailings pond, suggesting intensive chemical reactions, especially near pollution sources. Research has also revealed the diversity of protease activity in soil ecosystems, where samples with high activity may more effectively break down proteins compared to samples with low activity. To achieve ecological stability of soil resources, it is necessary to develop a management strategy, including monitoring and restoring priority areas considering local characteristics, supporting biodiversity, applying sustainable agricultural methods, and combating soil erosion. Important steps also include forming a community emphasising the importance of soil resources, funding research, and collaborating with local authorities, scientists, and the business community. The results of the study can be used in developing strategies to prevent the negative consequences of soil pollution, contributing to improved ecological resilience, especially for environmental protection agencies

Keywords: catalase; urease; protease; ecosystem; ecological stability; sustainable development

INTRODUCTION

Soil is an integral part of biogeocenoses and the biosphere as a whole, performing important environmental functions. It sustains life on Earth, participates in the cycling of substances and energy in the biosphere, and contributes to ecosystem stability. However, under increasing anthropogenic pressure on the planet, soil undergoes degradation due to human activities. This affects all components of the biosphere and underscores the importance of assessing the state of the soil and its potential rehabilitation (Bartkowiak *et al.*, 2020).

Enzymes in the soil play a key role in biochemical processes, determining its functionality. They act as biocatalysts, facilitating the decomposition of organic matter and the circulation of biogenic elements in the soil. These enzymes can be produced by various organisms, as their activity creates complex biochemical systems in the soil (Doolotkeldieva *et al.*, 2021). The analysis of enzymatic activity in the soil is a powerful tool for assessing anthropogenic impact. It reflects the dynamics of essential biochemical processes, such as the decomposition of organic material and nitrification. These processes are crucial for maintaining soil health and the overall ecosystem (Totubaeva *et al.*, 2019).

Research on enzymatic activity allows evaluating the degree of ecosystem degradation and developing soil rehabilitation strategies. They can also help establish a quantitative relationship between the physicochemical properties of the soil and enzyme activity, contributing to a deeper understanding of changes occurring in the soil due to anthropogenic influence. Soil enzymes are a powerful tool for diagnosing contaminated soils and ecosystems. They reflect changes in the soil under the influence of pollutants such as oil, metals, and pesticides. Studies show that enzymes are sensitive indicators of pollution, and their activity may change depending on the type of pollutant and its concentration (Cui *et al.*, 2021).

In particular, enzymes such as urease, catalase, and dehydrogenase can be used to detect oil-contaminated soils. Urease often increases its activity in the

presence of oil, associated with the growth of ammonifying microorganisms. However, after the completion of oil degradation processes, urease activity decreases, and catalase activity increases. These changes in enzyme activity can serve as indicators for diagnosing the state of the soil after oil contamination (Doolotkeldieva *et al.*, 2018). The use of soil enzymes as indicators of anthropogenic soil pollution in industrial cities of the Kyrgyz Republic is of great importance for assessing the environmental situation and soil health in the country. Like many other countries, the Kyrgyz Republic faces soil pollution issues in industrial regions, where intensive industrial activities can lead to emissions of various pollutants. This is particularly crucial for industrial cities, where the intensive use of soil and emissions from industrial enterprises can have a negative impact on soil quality (Severinenko *et al.*, 2023).

In this regard, researching enzyme activity in polluted soils provides an opportunity to diagnose and assess the degree of soil contamination by various pollutants such as oil, metals, or pesticides. Soil enzymes are sensitive to changes in the environment and can serve as indicators to detect the presence and nature of pollution. This enables taking measures to control and manage contaminated areas and developing strategies for their rehabilitation. Research on enzyme activity in polluted soils is also important in the context of climate change and the development of rehabilitation strategies for pollution. In addition, enzyme activity is linked to soil quality and its impact on human health through food products, making it relevant from a public health perspective. Thus, studies on enzyme activity have practical significance for addressing environmental, economic, and health issues in the modern world.

The purpose of this study is to assess how anthropogenic pollution affects enzyme activity in the soils of the industrial city of Kara-Balta. To achieve this purpose, the following tasks were set and implemented: evaluate the level of enzymatic activity in the soil in Kara-Balta, and develop recommendations for the

management and monitoring of soil resources to preserve and restore environmental sustainability.

MATERIALS AND METHODS

The object of the study was the city of Kara-Balta, located in the Chui region, serving as the centre of the Jayyl district of the Kyrgyz Republic. The city is situated in the Chui

Valley along the Kara-Balta River and is positioned on the route of the road connecting Bishkek, Taraz (Kazakhstan), and Tashkent (Uzbekistan). Located at an altitude of 780 m above sea level, the city is 62 km west of the capital Bishkek and 122 km from the regional centre of Tokmok. Various sampling points were selected in different parts of the city for soil sample collection (Table 1).

Table 1. Points of selection of soil samples

| No. | Soil sampling points in the city of Kara-Balta | Coordinates of points |
|-----|--|------------------------|
| 1 | 300 m from Djunda, in an agricultural area | 42°47'42"N 73°50'34"E |
| 2 | 100 m from the security zone | 42°47'56"N 73°52'58"E |
| 3 | 10 m from the security zone | 42°47'56"N 73°53'00"E |
| 4 | 200 m from the tailings tank | 42°47'004"N 73°50'20"E |
| 5 | 100 m from the tailings tank | 42°47'15"N 73°50'11"E |
| 6 | 50 m from the tailings tank | 42°47'13"N 73°50'07"E |
| 7 | At the border of the protective barrier of the tailings pond | 42°47'14"N 73°50'06"E |
| 8 | Inside the tailings pond | 42°47'15"N 73°50'08"E |
| 9 | 200m from Kara-Balta Mining and Metallurgical Plant (KMMP) | 42°46'28"N 73°50'01"E |
| 10 | KMMP from a distance of 100m | 42°46'28"N 73°50'01"E |
| 11 | Acreage 150m from KMMP | 42°46'14"N 73°50'18"E |
| 12 | 400m from KMMP | 42°46'26"N 73°50'47"E |
| 13 | Control sample 1 km from KMMP | 42°46'23"N 73°51'14"E |

Source: compiled by the authors

Samples were taken at a depth of 0-20 cm from a test area measuring 1×1 m at 5 different points, which were then combined into a single composite sample weighing 400-500 g. The following methodologies were employed to determine soil indicators:

1. Soil pH was determined using a universal ionomer EV-74.
2. Humus content in the soil was determined using a modified Tyurin method.
3. Soil moisture was determined by the gravimetric method, where samples were dried in an oven at a temperature of 105°C.
4. Soil particle size distribution was determined using the sieve method, using sieves of various sizes ranging from 0.001 to 10 mm.

For catalase activity determination, a method based on the formation of a complex of intact hydrogen peroxide with potassium iodide was used. Catalase activity was calculated using the formula: $A=D/0.02$, where A represents the catalase activity in the sample; D – optical density of the investigated sample; 0.02 – the conversion coefficient of catalase into arbitrary units.

For urease activity determination, an express method was employed. This involved placing 50 g of soil sample in a Petri dish and adding 0.5 g of urea dissolved in a small amount of water. The soil and urea were thoroughly mixed, moistened with distilled water to a paste-like state, and evenly distributed on the bottom of the dish. The dish was covered, and the

incubation time was determined based on soil biological activity (2-3 hours, up to 4 hours in cold weather).

For protease activity determination, a modified photometric method was used, conducted in the laboratory of the fertility of hydromorphic and acidic soils of the Institute of Soil Science and Agrochemistry named after O.N. Sokolov. This method is based on the Mishustin method for determining protease activity, utilising photographic film, and an improved method for calculating protease activity using Adobe Photoshop.

The obtained research results were processed for reliability using a multifactor analysis of variance (ANOVA) with the help of Microsoft Excel and the Statistica 10 software package. Differences in the obtained results were considered significant at a significance level of $P \leq 0.05$ according to the Student's t-test criterion.

RESULTS

The city of Kara-Balta is characterised by the presence of several large industrial enterprises and has a tailings storage facility. The Zhongda Oil Refinery, located in Kara-Balta, was built in 2009 and started production in 2014. The owner of the refinery is the Chinese company China Petrol Company Zhongda LLC, and Kyrgyzstan does not have a share in its ownership. The refinery specialises in the production of various oil products, including gasoline, diesel fuel, mazut, and liquefied gas. About 89% of the produced products are sold on the domestic market, while the remaining 11%

are exported to countries such as China, Tajikistan, Belarus, and Uzbekistan. The refinery's operations have been suspended since October 2020.

The tailings storage of the Kara-Balta Mining Combine is located in the Jayyl district of the Chui region. This site has been used for storing radioactive waste since 1955 and is located only 1.5 km from the city of Kara-Balta, which has a population of over 50 thousand. Since 2008, the complex has belonged to the private enterprise "Uran-Platina Holding." The total volume of radioactive waste here is about 37 million m³, although the designed capacity of the storage is almost twice as large – 63.5 million m³. Some sections of the waste storage are undergoing constant rehabilitation. However, due to the complex economic situation at the Kara-Balta Mining and Metallurgical Plant (KMMP), the quality of supervision over the storage has deteriorated, posing an increased risk to the environment and the population in densely populated areas. The waste storage in Kara-Balta is considered one of the most dangerous objects in

the Kyrgyz Republic and is the largest landfill of its kind in the world. The potential contamination zone extends to a radius of 10 km from this facility.

Agrochemical indicators of soil samples are crucial for understanding its condition in a region with industrial load. The analysis of agrochemical soil characteristics helps not only in determining the physical and chemical properties of the soil but also in developing strategies to improve its quality and increase productivity. It is important to emphasise that agrochemical soil indicators have a significant impact on agriculture and the environmental condition of the studied region. According to the obtained data, soil samples have different levels of acidity (pH), but most of them are in the neutral or slightly alkaline range, which is often favourable for agriculture. The humus content varies from low values around 2% to higher values around 6.5%. Samples with higher humus content can provide better soil fertility. Cation exchange capacity also varies among samples, which can affect the soil's ability to retain nutrients (Table 2).

Table 2. Agrochemical indicators of the studied soil samples

| No. | pH | Humus, % | Absorption capacity, mg equiv per 100 g of soil |
|-----|------|----------|---|
| 1 | 7.2 | 1.98 | 13.4 |
| 2 | 7 | 2.96 | 14 |
| 3 | 7.55 | 3.22 | 16 |
| 4 | 7.7 | 3.22 | 18.4 |
| 5 | 7.85 | 2.5 | 14.6 |
| 6 | 7.55 | 3.28 | 17 |
| 7 | 7.6 | 3.38 | 18 |
| 8 | 7.8 | 3.22 | 18 |
| 9 | 7.2 | 5.04 | 22 |
| 10 | 7.3 | 3.9 | 18 |
| 11 | 7.95 | 3.38 | 17.2 |
| 12 | 7.2 | 6.55 | 23 |
| 13 | 6.9 | 2.65 | 16 |

Source: compiled by the authors

The analysis of the mechanical composition is an important stage of the study, as it allows determining the percentage of various particles in the soil by their size. These data are of significant importance for evaluating the soil's textural characteristics, its ability to retain moisture and nutrients, and determining its agrochemical properties. The mechanical composition of the soil, including the proportions of sand, silt, and clay, determines its textural characteristics. In the

conducted study, various soil samples exhibit different mechanical compositions. The soil at 10 m from the protected zone has a high content of the fraction sized 1-0.25 mm (24.79%), while the soil at the boundary of the tailings storage protective barrier has a higher content of the fraction 0.25-0.05 mm (32.2%). The soil sample from the sowing area at 150 m from KMMP has a significant content of the fraction <0.01 mm (26.12%) (Table 3).

Table 3. Mechanical composition of the studied soil samples

| No. | Fraction content, % (particle size mm) | | | | | | | Sum of particles <0.01 |
|-----|--|--------|-----------|-----------|------------|-------------|--------|------------------------|
| | >1 | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | <0.001 | |
| 1 | | 14.72 | 12.4 | 41.48 | 1.44 | 16.24 | 13.72 | 31.4 |
| 2 | | 12.21 | 9.41 | 32.2 | 11.12 | 19.56 | 15.4 | 46.08 |
| 3 | | 18.61 | 24.79 | 22.56 | 4.48 | 19.92 | 9.64 | 34.04 |
| 4 | | 10.21 | 18.79 | 29.92 | 8.08 | 17.52 | 15.45 | 41.08 |

Table 3, Continued

| No. | Fraction content, % (particle size mm) | | | | | | Sum of particles <0.01 | |
|-----|--|--------|-----------|-----------|------------|-------------|------------------------|--------|
| | >1 | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | | <0.001 |
| 5 | | 12.9 | 17.58 | 28.92 | 10.68 | 17.24 | 12.68 | 40.6 |
| 6 | | 21.74 | 21.86 | 24.56 | 8.64 | 12.8 | 10.4 | 31.84 |
| 7 | | 11.99 | 19.13 | 32.2 | 8.48 | 16.36 | 11.84 | 36.68 |
| 8 | | 15.4 | 18.2 | 30.76 | 9.84 | 13.44 | 12.36 | 35.64 |
| 9 | | 13.18 | 13.38 | 35.04 | 10 | 17.04 | 11.36 | 38.4 |
| 10 | | 16.91 | 14.97 | 29.56 | 11.24 | 14.64 | 12.68 | 38.56 |
| 11 | | 20.33 | 17.11 | 36.44 | 4.32 | 12.88 | 8.92 | 26.12 |
| 12 | | 20.66 | 19.5 | 24.72 | 7.88 | 14.88 | 12.36 | 35.12 |
| 13 | | 20.76 | 33.56 | 31.84 | 9.08 | 14.46 | 10.56 | 34.6 |

Source: compiled by the authors

The catalase activity is an important indicator that can help determine the impact of anthropogenic changes on the soil. Locations with increased catalase activity may have mechanisms to protect against oxidative stress, while in other locations, the soil may be less resistant to this stress. The study of the activity of catalase and other soil enzymes is crucial for monitoring soil conditions and detecting anthropogenic impacts. This data can assist in developing environmental protection strategies and maintaining ecosystem stability in industrial cities.

As a result of the study, it was found that catalase activity varies significantly among samples, covering a wide range of values from 15.9 to 86.6. This indicates

the different ability of soil samples to decompose hydrogen peroxide. Soil samples from 200 m from the tail tank and inside the tailings storage exhibit the highest catalase activity values. This may indicate their high capability to decompose hydrogen peroxide, potentially linked to greater resistance to oxidative stress. Soil samples from 50 and 100 m from the tail tank have the lowest catalase activity values, suggesting limited capability to decompose hydrogen peroxide. This may indicate higher vulnerability to oxidative stress, possibly related to anthropogenic influences. Other samples have activity values between these extremes, indicating diversity in their ability to decompose hydrogen peroxide (Table 4).

Table 4. Catalase activity

| No. | D | A |
|-----|-------|-------|
| 1 | 0.41 | 20.5 |
| 2 | 0.318 | 15.9 |
| 3 | 0.851 | 42.55 |
| 4 | 0.933 | 46.65 |
| 5 | 0.246 | 12.3 |
| 6 | 0.245 | 12.25 |
| 7 | 0.318 | 15.9 |
| 8 | 1.732 | 86.6 |
| 9 | 0.862 | 43.1 |
| 10 | 0.838 | 41.9 |
| 11 | 0.749 | 37.45 |
| 12 | 0.842 | 42.1 |
| 13 | 0.739 | 36.95 |

Note: D is the optical density of the test sample; A is the catalase activity in the sample

Source: compiled by the authors

Results of urease activity measurements in different samples over time (1 hour, 1.5 hours, and 2 hours) show that the enzyme's activity varies among samples and changes over time. Initial values range from 3.5 to 5, and final values after 2 hours range from 6.5 to 8. This suggests various chemical processes occurring in the solutions, which can be a crucial factor in examining chemical reactions and the time impact on environmental parameters.

Significant increases in soil samples from 200 m from the tail tank and the control sample 1 km from KMMP may indicate chemical processes affecting the acidity or alkalinity of the solutions. Changes in urease activity over time indicate that chemical processes in the soil develop and change over time. This dynamic may be related to various factors such as microorganisms, the presence of organic substances, and environmental conditions. Thus, soil samples at the boundary

of the tailings storage protective barrier and in the control sample demonstrate the highest urease activity

values after 2 hours, potentially linked to more intense chemical reactions (Fig. 1).

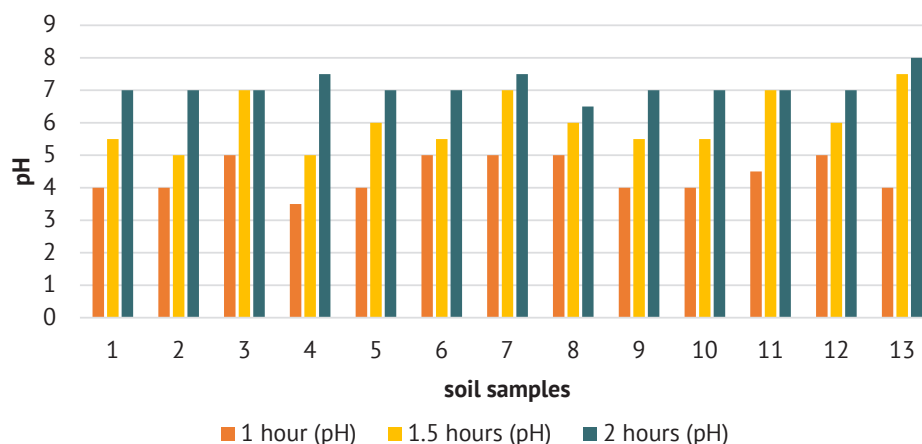


Figure 1. Urease activity

Source: compiled by the authors

Significant changes in soil samples, especially near pollution sources, may indicate the influence of anthropogenic chemical processes on soil acidity or alkalinity. This can have long-term effects on soil and biota and the quality of soil resources. The research results emphasise the importance of regular monitoring of soil enzymes, such as urease, in industrial city areas. This helps identify changes in the soil ecosystem and react promptly to anthropogenic impact. Information about changes in the soil ecosystem, occurring under the influence of anthropogenic factors, using the activity of protease enzymes as an indicator, was determined by the area of the decomposed gelatine layer – $S(g)$. Values of $S(g)$ vary significantly among the investigated samples. The minimum value is 0.267, while the maximum value is 7.318. This indi-

cates diverse activity of protease enzymes in different soil samples.

Soil samples at 50 m from the tail tank and at the boundary of the tailings storage protective barrier stand out with the largest area of the decomposed gelatine layer. This may indicate higher activity of protease enzymes in these samples, possibly related to more intensive biochemical processes. Soil samples at 200 m from the tail tank and inside the tailings storage have the lowest $S(g)$ values, indicating reduced activity of protease enzymes in these soils. This could be associated with the impact of anthropogenic factors that may slow down or restrict biochemical processes in the soil. Other samples have $S(g)$ values between these extreme values, indicating diversity in the activity of protease enzymes in soils (Table 5).

Table 5. Assessment of changes in the soil ecosystem under anthropogenic influence based on the activity of protease enzymes

| No. | $S(g)$ |
|-----|--------|
| 1 | 4.542 |
| 2 | 1.952 |
| 3 | 2.258 |
| 4 | 0.554 |
| 5 | 1.773 |
| 6 | 5.954 |
| 7 | 7.318 |
| 8 | 0.84 |
| 9 | 0.267 |
| 10 | 3.385 |
| 11 | 1.652 |
| 13 | 4.67 |

Note: $S(g)$ – area of the decomposed gelatine layer

Source: compiled by the authors

Protease activity is directly related to the soil's ability to decompose organic material, including plant and animal residues. These processes play a crucial role in the nutrient cycle and soil stability. Therefore, changes in protease activity can affect soil quality and its ability to support plant and animal life. Analysing protease activity in different samples or conditions allows the following observations: the data demonstrate diversity in protease activity in samples, with minimum activity at 0.0002% and maximum reaching 0.04%. Such diversity indicates varying abilities of samples to decompose protein compounds. The soil sample at 300 m from the China Petrol Company Zhongda oil refinery, in the agricultural

area, and the control sample 1 km from KMMP exhibit the highest protease activity. This may indicate a higher capacity for breaking down protein compounds in these samples, suggesting healthier soils in these locations.

Soil samples at 200 m from the tail tank, inside the tailings storage, and at 200 m from KMMP have the lowest protease activity. This indicates a reduced ability to decompose protein compounds in such samples, possibly due to pollutant impact and changes in soil conditions. The obtained data can be essential for understanding biochemical processes in the soil and other ecological systems and for assessing the soil's ability to decompose organic material (Table 6).

Table 6. Protease activity, %

| | |
|----|--------|
| 1 | 0.03 |
| 2 | 0.01 |
| 3 | 0.02 |
| 4 | 0.0005 |
| 5 | 0.001 |
| 6 | 0.005 |
| 7 | 0.006 |
| 8 | 0.0007 |
| 9 | 0.0002 |
| 10 | 0.02 |
| 11 | 0.01 |
| 13 | 0.04 |

Source: compiled by the authors

In general, the study confirms that soil enzymes can serve as important indicators of anthropogenic impact on soils in industrial cities. This not only helps understand the environmental conditions but also enables measures to improve ecological sustainability in such areas. Recommendations for the management and monitoring of soil resources to preserve and restore ecological sustainability:

1. Develop a soil resource management strategy that includes goals and priorities for managing and restoring soil resources, considering local characteristics and environmental needs.

2. Monitor soil quality in vulnerable and ecologically important areas.

3. Preserve biodiversity by applying conservation and restoration methods, such as soil vegetation restoration and creating locations for animal migration.

4. Adopt sustainable agricultural practices, such as organic farming, and reduce the use of chemical fertilisers and pesticides.

5. Develop erosion stabilisation methods.

6. Educate and inform the public, agricultural workers, and all stakeholders about the importance of soil resource management and methods for preserving ecological sustainability.

7. Finance and support research aimed at studying soil processes, monitoring changes in soil ecosystems,

and developing new methods for soil resource restoration.

8. Incorporate legislation and regulations that promote sustainable soil resource management, including penalties for soil damage and illegal construction on vulnerable soil sites.

9. Collaborate with local authorities, scientists, and the business community to develop and implement joint programmes for soil resource management and monitoring.

These recommendations form the basis for developing a comprehensive approach to soil resource management with the goal of preserving and restoring ecological sustainability. Effective soil management plays a crucial role in ensuring a healthy environment and sustainable development.

DISCUSSION

Soils are an essential component of ecosystems, supporting vegetation, filtering water, and participating in the nutrient cycle. However, industrial activities in cities often result in high levels of anthropogenic soil pollution. This pollution includes various chemical compounds such as heavy metals, organic compounds, petroleum products, and other harmful substances that can cause serious damage to soil ecosystems and human health.

According to Y. Cui *et al.* (2019), various methods and tools are employed to assess the degree of anthropogenic soil pollution in industrial cities. One of such methods is the use of soil enzymes as indicators. Soil enzymes are proteins that play a key role in the biochemical processes occurring in the soil. They can be sensitive to changes in the soil environment and serve as indicators of anthropogenic impact on the soil. The application of enzymes also contributes to the development of measures to restore soils affected by human activities, correlating with the conducted research and its findings. The study also reflects the opinion of S.H. Lee *et al.* (2020) that anthropogenic pollutants can affect the activity and structure of enzymes, which can be used to assess the pollution level. Metals such as copper, nickel, and mercury can inhibit the activity of various soil enzymes, depending on their concentration and the enzymes' properties. These metals can have diverse effects on soil biochemical processes.

Furthermore, the activity of soil enzymes can be influenced by pesticides, and this impact depends on their chemical structure and bioavailability. The chemical structure of pesticides can affect how they interact with soil enzymes. Some pesticides may inhibit or destroy the activity of specific enzymes, leading to disruptions in processes related to the decomposition of organic matter or nutrient cycling. This can lead to a deterioration in soil quality and a decrease in its fertility (Masikevych *et al.*, 2022). According to C. Michan *et al.* (2021), substances entering the soil due to anthropogenic influence can alter enzymatic activity, serving as an indicator of pollution. Toxic trace elements and petroleum hydrocarbons can have a negative impact on the activity of soil enzymes, affecting the soil's ability to support life and ecosystem functions, as also noted in the conducted study.

Confirmation of the conducted research can also be found in the works of R. Nunes *et al.* (2021), who argue that soil enzymes can be used for conducting ecotoxicological studies to assess the impact of pollutants on biological systems in the soil. The use of soil enzymes also facilitates monitoring anthropogenic soil pollution in industrial areas, which can be useful for taking measures to improve soil quality and environmental protection, as also reflected in the conducted study. Moreover, studies on soil enzyme activity help assess the health of an entire ecosystem, and the functionality of the soil and its ability to support life in the ecosystem are linked to enzyme activity. Changes in enzyme activity may indicate alterations in biological diversity and the structure of soil microorganisms, which, in turn, influence ecosystem processes. Such research allows not only the evaluation of the current state of the biogeocenosis but also the prediction of its ability to recover after potential pollutant impacts. These studies help make informed decisions in environmental protection and strategy development to minimise pollutant impact

on natural ecosystems, as reflected in the arguments presented in the current study (Maphuhla *et al.*, 2020; Maini *et al.*, 2020).

C.M. Raffa and F. Chiampo (2021) emphasise the importance of understanding how soil pollution levels, chemical and biological properties influence the synthesis, activity, and stability of enzymes, their release into the environment, and distribution in the soil under increasing human impact on soil ecosystems. This knowledge plays a key role not only in soil enzymology and microbiology ecology but also in determining the effectiveness of soil restoration methods affected by anthropogenic influences. R. Ochoa-Hueso *et al.* (2021) confirm the results of the study that soil-forming factors, such as soil composition, influence the nature and formation of enzymes. Soil represents a complex biological and physicochemical system, complicating the study of microbiological processes occurring in it. This highlights the need for collaboration among specialists from different fields to more accurately determine the impact of various factors on biochemical processes in different soil types and climatic conditions (Nazarkulova *et al.*, 2019; Keller *et al.*, 2021).

Advancements in the use of soil enzymes are crucial for environmental protection and natural resource management. Soil enzymes can catalyse the decomposition of pollutants, such as chemicals and heavy metals, into less toxic products. This can be highly valuable for soil restoration and the cleanup of contaminated areas. Soil enzymes can be used for real-time pollution level monitoring and assessing the effectiveness of methods for rehabilitating polluted soils. It also helps determine the necessary measures for restoring soil resources (Koković *et al.*, 2021; Wyszowska *et al.*, 2023). Numerous studies by authors, particularly M.A. Severinenko *et al.* (2023), Y. Tepe *et al.* (2022), also emphasise the significant role of soil enzymes in processing tissues contaminated with various chemical substances. Soil enzymes exhibit high activity and the ability to catalyse specific reactions necessary for breaking down both natural and synthetic compounds into less hazardous substances. Soil enzymes also perform diverse functions, such as decomposing organic substances, mineralising nutrients, and detoxifying harmful compounds, as also demonstrated in the conducted studies.

According to the data from N. Totubaeva *et al.* (2019), the use of the soil enzyme urease as an indicator of anthropogenic soil pollution in industrial cities provides crucial information about the state of the environment and the impact of human activities on soil ecosystems. The study shows that urease activity varies among different soil samples. This variation may be related to different pollution factors, such as industrial emissions, the presence of toxic substances, and changes in soil conditions. The diverse dynamics of urease activity over time indicate that anthropogenic influence and chemical processes in the soil are not static but evolve over

time. This can be linked to the continuous impact of pollutants and changes in environmental conditions, as confirmed in the study.

Considering the mentioned studies by the authors and the results of this study, it can be asserted that the use of soil enzymes as indicators of anthropogenic soil pollution in industrial cities is an essential tool for assessing the state of soil ecosystems and developing measures for their restoration. This approach not only helps identify issues related to soil pollution but also contributes to improving the resilience of urban ecosystems and ensuring a healthy environment for residents. Furthermore, it is crucial to continue research in this field and develop more precise methods for assessing the activity of soil enzymes and their relationship with anthropogenic impacts to more effectively address environmental issues associated with soil pollution.

CONCLUSIONS

The use of soil enzymes as indicators of anthropogenic pollution in industrial cities is of great significance for assessing the environmental condition and taking measures to improve the quality of the environment and human health. These indicators not only help identify pollution but also provide information for the development of sustainable development and environmental protection strategies.

The study disclosed that the examination of catalase activity shows significant diversity in the ability of different soil samples to decompose hydrogen peroxide. Some samples exhibit high activity, while others have low activity. This variation may be associated with differences in oxidative stress and the ability to biochemically break down hydrogen peroxide. Observations of the highest urease activity in soil samples after

2 hours, especially at the border of the tailings storage protective barrier, indicate more intensive chemical reactions, particularly in areas located in close proximity to the pollution source. This may be related to biotic and abiotic factors, including microorganisms and changes in soil composition. The analysis of protease activity in the soil ecosystem also shows diversity in the ability of different soil samples to decompose protein compounds. Samples with high protease activity may more effectively break down proteins, while samples with low activity may be less capable of doing so.

To achieve ecological sustainability of soil resources, it is important to develop a management strategy that includes monitoring and restoring priority areas, considering local characteristics. This involves ensuring high-quality monitoring of soil conditions, maintaining biodiversity, adopting sustainable agricultural methods, and combating soil erosion. Public education on the importance of soil resources and funding research play a crucial role in this process. In addition, legislative consideration and collaboration with local authorities, scientists, and the business community help ensure effective management and monitoring of soil resources, contributing to their sustainability and preservation for future generations. Further studies can focus on developing more efficient methods for monitoring soil enzymes, allowing for a more accurate and timely determination of the degree of pollution and the soil's condition.

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CONFLICT OF INTEREST

None.

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Екологічні аспекти використання ґрунтових ферментів як індикаторів антропогенного забруднення ґрунтів

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Анотація. У сучасній епосі, коли спостерігається швидке зростання промислових секторів та урбанізація, аналіз впливу людської діяльності на активність ґрунтових ферментів набуває особливого значення. У межах цього дослідження було встановлено мету – провести оцінку впливу антропогенного забруднення на активність ферментів у ґрунті. Для досягнення поставленої мети проведено дослідження рівня активності ферментів у ґрунті у місті Кара-Балта Чуйської області Киргизької Республіки, який вимірювався за допомогою біохімічних аналізів та спеціальних ферментативних тестів. Результати досліджень показали значне розмаїття активності каталази в різних ґрунтових зразках. Деякі зразки виявляють високу активність, тоді як інші низьку. Ці відмінності можуть бути пов'язані з окислювальним стресом та здатністю ґрунтових мікроорганізмів до розкладання пероксиду водню. Аналіз уреазі показав найвищу активність у ґрунтових зразках через 2 години, особливо на межі захисного бар'єру хвостосховища, вказуючи на інтенсивні хімічні реакції, особливо поблизу джерел забруднення. Дослідження також виявили різноманітність активності протеази в ґрунтовій екосистемі, де зразки з високою активністю можуть ефективніше розкласти білки порівняно зі зразками з низькою активністю. Для досягнення екологічної стійкості ґрунтових ресурсів необхідно розробити стратегію управління, включаючи моніторинг та відновлення пріоритетних ділянок з урахуванням місцевих особливостей, підтримувати біорізноманіття, застосовувати стійкі методи сільського господарства та боротися із ґрунтовою ерозією. Важливими кроками також є утворення спільноти щодо важливості ґрунтових ресурсів, фінансування досліджень, а також співпраця з місцевими органами влади, науковцями та бізнес-спільнотою. Результати дослідження можуть бути використаними при розробці стратегій запобігання негативним наслідкам забруднення ґрунтів, сприяючи покращенню екологічної стійкості, особливо для державних структур з охорони навколишнього середовища

Ключові слова: каталаза; уреазі; протеаза; екосистема; екологічна стійкість; сталий розвиток

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Assessment of ecological sustainability of the landscape of the Prypiat River basin within the Volyn region

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Abstract. The relevance of the research lies in the fact that, in the context of the global concept of sustainable development, one of the leading tasks is to maintain the sustainability of natural ecosystems by finding optimal strategies for the development of socio-economic systems. The purpose of the research is to assess the environmental sustainability of the landscapes of the Prypiat River basin within the territorial communities of the Volyn Oblast in the current conditions of the region's development. The methods used to achieve this goal included the calculation of the landscape

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ecological sustainability coefficient based on the systematization of statistical reporting data, followed by comparative geographical analysis and environmental mapping using ArcMap and ArcGIS Pro. The main results of the research show that the coefficient of ecological stability of landscapes in the Prypiat River basin is in the range of 0.22-5.39 and assesses landscapes from the level of “unstable with pronounced instability” to “stable, with pronounced stability”. The distribution of land areas in the territorial communities located in the Tsyur sub-basin determines the landscape characterization at the level of “stable, with pronounced stability”. Within the territorial communities of the Vyzhivka sub-basin and the upper reaches of the Prypiat River, the landscapes are “conditionally stable” – “stable”. Within the communities of the Turia sub-basin – from “unstable” to “stable, with pronounced stability”. Within the communities of the Stokhid sub-basin – from “unstable” to “stable, with pronounced stability”. The territorial communities of the middle part of the Styur sub-basin are represented by landscapes ranging from “unstable, with pronounced instability” to “stable, with pronounced stability”. In general, more ecologically stable landscapes are located in the northern part of Volyn Oblast, due to the large areas of forested land. Environmental instability of landscapes is typical for the southern part of the region due to large areas of ploughed land. The practical value of the work lies in obtaining regional variations in the assessment of ecological stability of landscapes, which is important to consider when developing coordinated concepts between communities and environmental management bodies on a basin basis to achieve sustainable development goals in socio-ecological systems

Keywords: river basin; sub-basin; land use; ecosystem services; management decisions

INTRODUCTION

The river basin with its constituent components (channel, floodplain, terraces, slopes) is a self-regulating system that is able to function regardless of the impact of external factors. The basin approach to water resources management involves the creation of organized management entities that intervene in individual ecosystem components and the landscape structure of the basin. In particular, the redistribution of water and land resources in terms of quantity and quality negatively affects the sustainability of landscapes, which can lead to errors in management decisions. As a result, there is a need to determine the limits of permissible economic use of river basin areas and assess their current state in order to optimize water and land management for the formation, use, and protection of the landscape.

Modern researchers agree that the ecological sustainability of a river basin landscape refers to the ability of this basin to maintain its natural functions, biodiversity, ecosystem services, and ability to recover from anthropogenic impacts (Abalo *et al.*, 2021; Ma *et al.*, 2023). K.G. Sreeja *et al.* (2015) find that most anthropogenic factors within a river basin are caused by agriculture through the reconfiguration of landscape elements. In particular, agriculture requires significant space for growing crops and grazing livestock. This leads to the reduction of natural ecosystems such as forests, meadows, and marshes and their replacement with arable land and pastures. The misuse of land for agriculture can lead to soil erosion, desalination, waterlogging and other forms of degradation that alter soil structure and lead to loss of fertility. E. Soulé *et al.* (2023) note that the use of pesticides, herbicides, mineral fertilizers and agricultural waste can lead to water pollution in river channels, and changes in landscape structure due to agriculture can lead to a decrease in the biodiversity of many plant and animal species.

An equally significant impact of agriculture on river basins is the loss of natural ecosystem services of the landscape. Agriculture can lead to the loss of natural ecosystem services, such as air and water purification, erosion prevention, soil fertility and other processes that are important for ecosystem health. Some authors suggest increasing the area of forests as an eco-compensation for agricultural land use within river basins. For example, using the example of the Grain-for-Green Programme (GFGP) in China, B. Xu and J. Pan (2022) showed that adjusting the structure and scale of forest and grass plantations in the Jinghe River basin during 2000-2015 reduced sediment yield and removal by 36.2% and 60.7%, respectively, and increased carbon storage by 2.4%.

Y. Li *et al.* (2023) found that the spatial spillover effects of urbanization exacerbate the spatial heterogeneity of biogeochemical, physical, ecological and hydrological processes in their basins. The studies provide convincing evidence that catchment urbanization significantly increases the potential for riverine CH₄ emissions. Recent studies by J. Liu *et al.* (2021) also show that urbanization and anthropogenic disturbance of natural landscapes are increasing the amount of allochthonous organic matter entering aquatic ecosystems. And domestic and industrial wastewater inhibits the self-purification capacity of rivers by introducing significant amounts of nutrients, heavy metals, microplastics, medicines, etc.

Depending on the scale and intensity of landscape transformation, these changes can have serious consequences for the ecological sustainability of the river basin. According to A. Tønnesen, *et al.* (2023) argue that avoiding such consequences depends on sustainable land and resource management at the level of urban and rural communities. The tools of such approaches include accounting and mapping of different contexts of community territories to make spatial decisions in landscape

planning, outlining potential impacts on river basin ecosystem services, identifying cause-and-effect relationships with socio-ecological benefits and local as well as global development goals (Schmidt *et al.*, 2022).

The scientific approaches analysed above show that there is currently no single, universal methodology for assessing the ecological sustainability of landscapes at spatial and temporal scales. In each case, researchers use different approaches, but what they have in common is the analysis of complex interrelationships between environmental conditions and anthropogenic factors. Taking into account the interests of territorial communities (TCs) in such cases, the distribution of natural elements that support the sustainable functioning of the entire ecosystem (meadows, forests, wetlands, etc.) and elements that meet the socio-economic needs of communities (arable land, pastures, buildings, etc.) is assessed. Ultimately, this allows for modelling scenarios of environmental change in river basins to support the optimal distribution of landscape elements and ensure a balance

between conservation and development throughout the region. The aim of the study was to assess the environmental sustainability of the landscapes of the Prypiat River basin and its tributaries in the context of the administrative boundaries of territorial communities of Volyn Oblast, as one of the regions of Ukraine that is actively changing in the current conditions of the state's development in accordance with the Sustainable Development Strategy and support of its goals.

MATERIALS AND METHODS

The study area of the Prypiat River basin is located in two parts of the south-western part of the Eastern European Plain – Polissya and Podillya. The northern part of the basin is located within the Volyn Polissya physiographic region, and the southern part is located within the Volyn Upland. According to the administrative division, the study area belongs to the Volyn region, which is divided into 4 rayons, comprising 54 territorial communities (Passport of Volyn region. 2022) (Fig. 1).

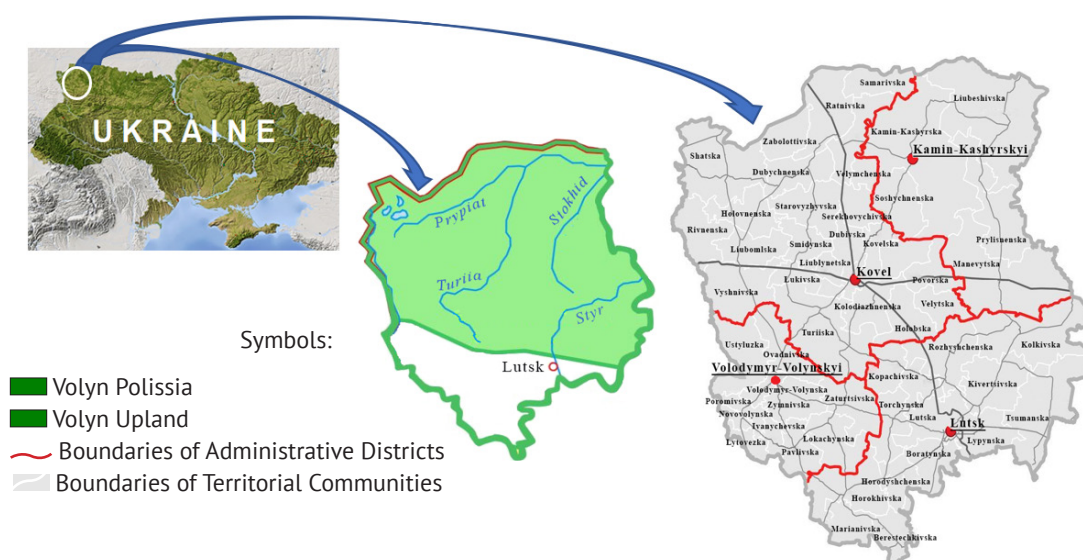


Figure 1. Physico-geographic characteristics and administrative units of the territory of the Prypiat River basin within the Volyn region of Ukraine

Source: based on author's research

The Prypiat River originates from its source near the village of Budnyky in the Kovel district of Volyn region. On the territory of the Kamen-Kashyrskiy and Kovel districts, the river flows in a southeasterly direction. Not far from the village of Senchytsi in the Varash district of Rivne region, the Prypiat River crosses the state border of Ukraine with the Republic of Belarus. Within that territory, the river flows through the Polissya Lowland, which is represented by the poorly defined valley of the Pinsk bogs. The last 50 km of the Prypiat riverbed are located within the Kyiv region of Ukraine, in the lower reaches of the terrain. The mouth of the Prypiat River is located near the town of Chornobyl, where it flows into the Kyiv Reservoir on the Dnipro Riverbed (Khilchevskiy *et al.*, 2022).

The total length of the river is 775 km, of which 254 km is in Ukraine. The Prypiat River basin covers 114.3 thousand km², of which 68.37 thousand km² is in Ukraine. According to the hydrographic zoning of Ukraine (2016), the Prypiat River is a separate sub-basin of the Dnipro River basin. A part of the Prypiat riverbed in Volyn Oblast, with a total length of 72 km, has been transformed into the main channel of the Upper Prypiat drainage system, which is one of the largest in Europe (Khilchevskiy *et al.*, 2019).

The environmental sustainability of the landscape of the study area was assessed based on the methodology of E. Klementova and B. Geynige (1995), the essence of which is to determine the coefficient of ecological sustainability of landscapes k_{ESL1} by the distribution of

areas occupied by different landscape elements, taking into account their positive or negative impact on the environment:

$$k_{ESL1} = \frac{\sum_{i=1}^n F_{stb\ i}}{\sum_{j=1}^m F_{stb\ j}}, \quad (1)$$

where $F_{stb\ i}$ is the area of agricultural plant species that have a positive impact on the landscape (stable landscape elements): forests, green plantations, natural meadows, areas of nature conservation status, hayfields and arable land used for growing perennial grasses – alfalfa, clover, grass mixtures, etc., ha; $F_{stb\ j}$ is the area of land with low environmental sustainability, represented by landscape elements of unstable structure: actively exploited arable land, areas with high density of overgrowth, land with little grass cover, street and road network, silted and overgrown water bodies, mining sites and other lands subject to anthropogenic impact, causing environmental tension that can negatively affect landscape sustainability, ha.

The calculated values of k_{ESL1} were used to provide a qualitative description of the ecological stability (territorial integrity) of the landscape on the scale “unstable, with pronounced instability” – $k_{ESL1} \leq 0.51$; “unstable” – $k_{ESL1} = 0.51-1.0$; “conditionally stable” – $k_{ESL1} = 1.0-3.0$; “stable” – $k_{ESL1} = 3.01-4.5$; “stable, with pronounced stability” – $k_{ESL1} \geq 4.5$.

The initial data for the calculations were statistical reports of the Department of Ecology and Natural

Resources and the Department of Agricultural Development of the Volyn Oblast State Administration, which constituted a database for solving environmental problems (Stock Materials, n.d.), both in the Prypiat River basin and in Volyn Oblast in particular, within the framework of the implementation of the National Target Programme for the Development of Water Management and Environmental Improvement of the Dnipro River Basin for the Period up to 2021 and the Regional Environmental Programme “Ecology 2016-2022” (Passport of Volyn region, 2022) consolidated database of relevant data and calculations was also used for spatial analysis and environmental mapping of the distribution of different types of landscapes within the study area, using geographic information software MapInfo and ArcGIS Pro.

RESULTS AND DISCUSSION

The mapping of the hydrographic network of the study area shows that most of the territorial communities of the Volyn Oblast are located within the upper reaches of the Prypiat River basin. In particular, the upper reaches of the basin in the Volyn Oblast include sub-basins of the Prypiat River tributaries: the Tsyry, Vyzhivka, Turia, Stokhid, Styry, and the Prypiat River itself. The territorial communities located along the north-western and western borders of the region, in hydrographic terms, belong to the Western Bug River basin (Fig. 2).

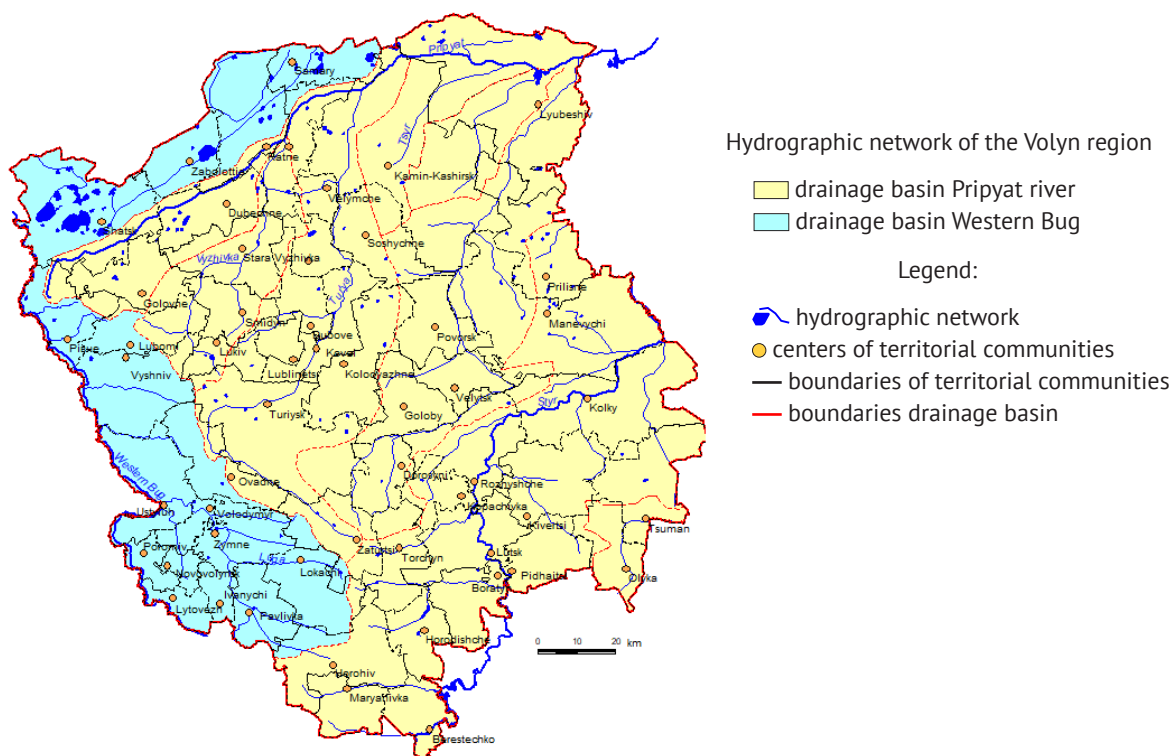


Figure 2. Hydrographic network of the upper reaches of the Prypiat River basin

Source: based on author's research

An analysis of the structure of land within the territorial communities of the study area revealed that the areas occupied by unstable landscape elements (annually cultivated arable land, land with unstable grass cover, under buildings and road networks, mining sites,

etc.) are overwhelmingly located in the southern part of the basin. A significant part of the area of most territorial communities is occupied by agricultural land. At the same time, there is an uneven distribution of arable land between different parts of the region (Fig. 3).

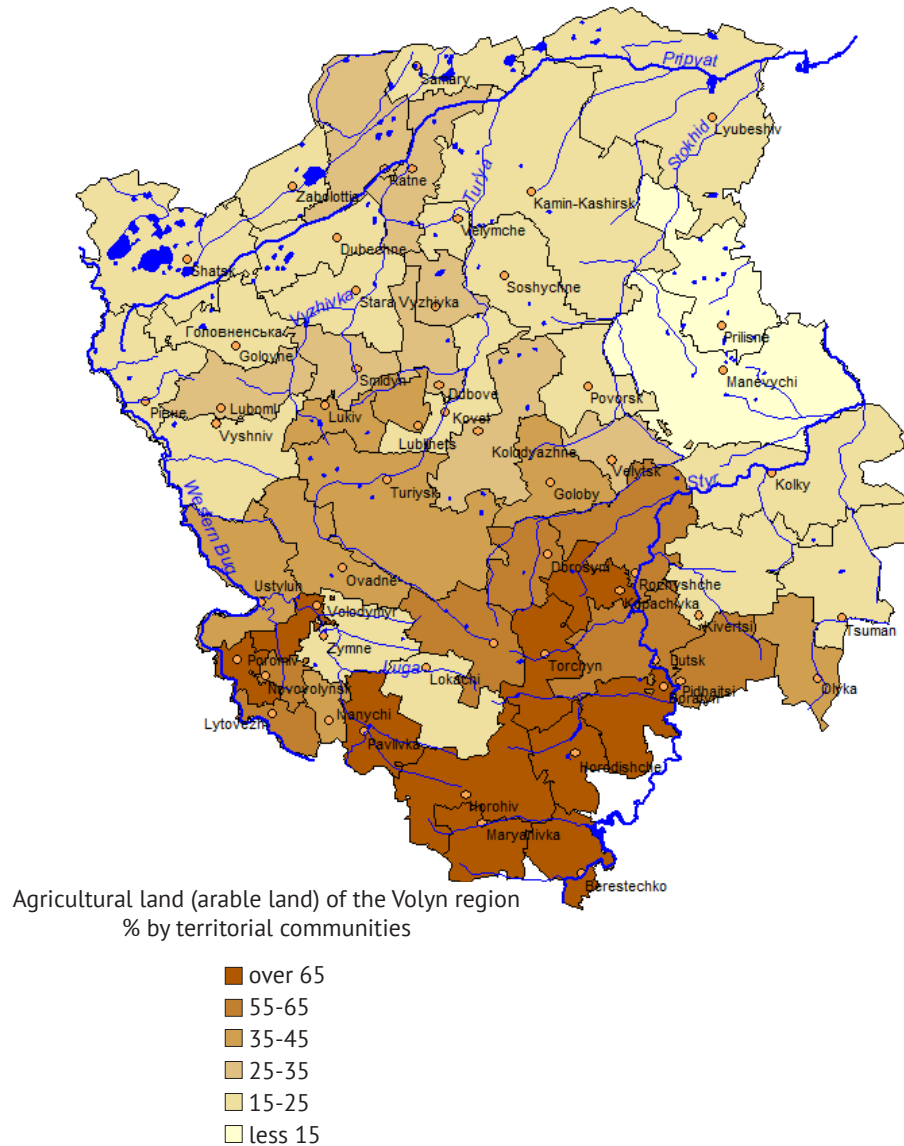


Figure 3. Agricultural land (arable land) of the Volyn region in the section of the TC

Source: based on author's research

Thus, the land allocated for arable land in the communities of the northern part of the region does not exceed 35%. In the central part of the region, there is an increase in the area of arable land, which ranges from 35 to 65% in the spatial distribution. Territorial communities located in the southern part of the study area are characterized by the highest level of agricultural land development. In particular, the ploughed area of their territories exceeds 65%. It is worth noting that it is here, within the Volyn Upland, that the tributaries of the Prypyat River originate.

The areas under plant communities that have a positive impact on the landscape (forests, green spaces, natural meadows, nature reserve fund (NRF) objects, perennial grasses, etc.) are mostly located in the northern part of the basin within the Polissya Lowland where the mouths of tributaries are located – the Vyzhivka River, the Turia River, the Tsyra River, the Stokhid River and the source of the Prypyat River itself. In particular, there is a clear tendency for forested landscapes to gravitate towards the northern and central-eastern parts of the Volyn Oblast (Fig. 4).

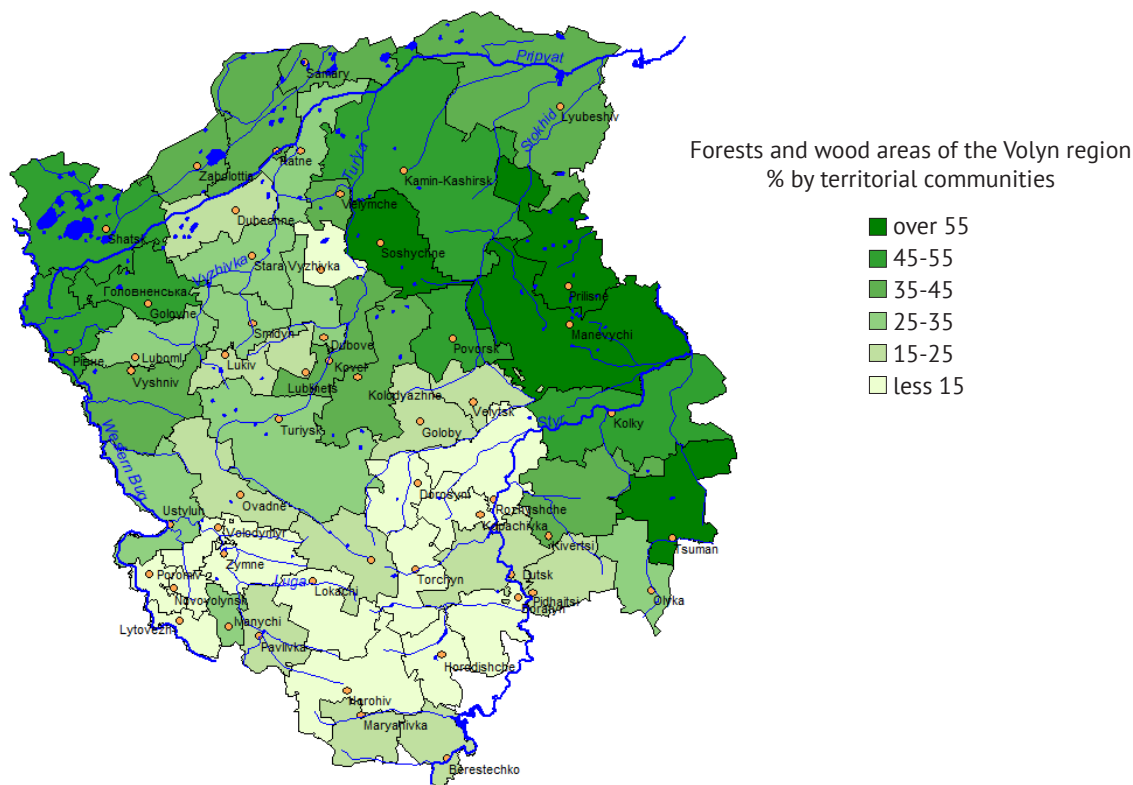


Figure 4. Forests and wooded areas of the Volyn region in the section of the TC

Source: based on author's research

In terms of spatial distribution, forests cover 45 to 55% or more of the area of territorial communities located in the northern and central-eastern parts of the region. In particular, more than 55% of the area is covered by forests within the Manevychi, Tsumanska, Prylisenka and Sochyshnenska territorial communities. The calculation of the quantitative assessment of the ecological stability

of landscapes in the Prypiat River basin revealed that the value of the k_{ESL1} coefficient within individual territorial communities ranges from 0.22 to 5.39. That is, the landscapes of the basin can be assessed from “unstable, with pronounced instability” to “stable, with pronounced stability” according to the administrative boundaries of territorial communities (Table 1).

Table 1. The results of determining the ecological stability of the landscapes of the Prypiat River basin within the Volyn region (in terms of administrative entities of the TC)

| Territorial community | Area, ha | k_{ESL1} | Landscape stability | Territorial community | Area, ha | k_{ESL1} | Landscape stability |
|-----------------------|----------|------------|--------------------------------------|-----------------------|----------|------------|----------------------|
| Berestechko | 22198.40 | 0.54 | Unstable | Zaturtsi | 36399.30 | 0.90 | Unstable |
| Boratyn | 28194.00 | 0.34 | Unstable with pronounced instability | Ovadne | 35726.10 | 1.27 | Conditionally stable |
| Horohiv | 49455.80 | 0.28 | Unstable with pronounced instability | Velymche | 11087.50 | 2.66 | Conditionally stable |
| Dorosyni | 23490.30 | 0.72 | Unstable | Velytsk | 21157.50 | 1.69 | Conditionally stable |
| Kivertsi | 47061.00 | 2.83 | Conditionally stable | Goloby | 29815.70 | 1.3 | Conditionally stable |
| Kolky | 76449.15 | 2.99 | Conditionally stable | Golovne | 32473.60 | 4.35 | Stable |
| Kopachivka | 17923.68 | 0.49 | Unstable with pronounced instability | Dubechne | 24643.70 | 2.1 | Conditionally stable |
| Lutsk | 38457.60 | 0.74 | Unstable | Dubove | 20322.90 | 1.82 | Conditionally stable |
| Maryanivka | 22977.00 | 0.76 | Unstable | Zabolottia | 20406.10 | 3.6 | Stable |
| Olyka | 27030.20 | 1.01 | Conditionally stable | Zabrody | 33423.60 | 2.57 | Conditionally stable |
| Pidhaitsi | 28443.39 | 0.75 | Unstable | Kovel | 26849.90 | 3.02 | Stable |

Table 1, Continued

| Territorial community | Area, ha | k_{ESL1} | Landscape stability | Territorial community | Area, ha | k_{ESL1} | Landscape stability |
|-----------------------|-----------|------------|--------------------------------------|-----------------------|----------|------------|----------------------|
| Rozhshyche | 46105.52 | 0.99 | Unstable | Kolodyazhne | 46630.10 | 2.19 | Conditionally stable |
| Senkevychivka | 21213.70 | 0.22 | Unstable with pronounced instability | Lukiv | 16277.90 | 1.18 | Conditionally stable |
| Torchyn | 26439.70 | 0.38 | Unstable with pronounced instability | Lublinets | 11460.00 | 1.34 | Conditionally stable |
| Tsuman | 44708.00 | 4.46 | Stable | Povorsk | 29721.40 | 3.49 | Stable |
| Kamin-Kashirsk | 142527.60 | 3.86 | Stable | Ratne | 48066.10 | 2.53 | Conditionally stable |
| Lyubeshiv | 123949.00 | 5.39 | Stable, with pronounced stability | Serehovichi | 16767.00 | 1.43 | Conditionally stable |
| Manevychi | 110363.15 | 5.16 | Stable, with pronounced stability | Smidyn | 22697.10 | 1.72 | Conditionally stable |
| Prilisne | 52694.30 | 8.0 | Stable, with pronounced stability | Stara Vyzhivka | 28434.10 | 3.61 | Stable |
| Soshychne | 39699.90 | 4.37 | Stable | Turiysk | 86478.30 | 1.48 | Conditionally stable |
| Luboml | 29659.80 | 2.18 | Conditionally stable | Shatsk | 75074.92 | 4.11 | Stable |

Source: based on the author's research

Thus, in the sub-basin of the Tsy River, from the source to the mouth, there are Kamen-Kashyrska and Lyubeshivska TC. The territories of these communities are characterized by a landscape stability coefficient (k_{ESL1}) value in the range of 4.90-5.39. The corresponding qualitative characteristic of the ecological sustainability of landscapes is defined as "stable, with pronounced stability".

In the sub-basin of the Vyzhivka River and the upper reaches of the Prypiat River, there are Lyuboml, Rivne, Lukivka, Holovne, Smidyn, Dubeche, Starovyzhivka and Ratniv TCs. Within their boundaries, k_{ESL1} varies from 1.18 to 4.35, which assesses the ecological sustainability of landscapes from "conditionally stable" to "stable". In particular, the ecological condition of the landscapes in the upper, lower reaches and near the mouth of the Vyzhivka River is classified as "conditionally stable", with k_{ESL1} values not exceeding 2.35, and in the upper reaches of the Prypiat River – as "stable".

The Turia River sub-basin includes the Zaturtsivska, Ovadnenska, Turia, Liublynetska, Kovelska, Kolodyazhchenska, Soshychnenska, Velymchenska, Starovyzhivska, and partially Smidynska and Kamen-Kashyrska TCs. Their landscape stability coefficient (k_{ESL1}) varies from 0.90 to 4.90. Accordingly, the qualitative characteristics of the ecological sustainability of the landscapes of these TCs are defined by the levels from "unstable" to "stable, with pronounced stability". In particular, the ecological state of landscapes in the upper reaches of the Turia River is assessed by the value of k_{ESL1} 0.90 and is classified as "unstable". The landscapes in the middle reaches of the river are characterized by k_{ESL1} values ranging from 1.72 to 3.61, which classify them as "conditionally stable" and "stable". The landscapes of the lower reaches and mouth of the Turia River have a k_{ESL1}

value of 3.86 and are classified as "stable". The sub-basin of the Stokhid River includes Lyubeshivska, Povorska, Velytska, Holobska, Dorosynivska and partially Kamen-Kashyrska, Manevytska and Zaturtsivska TCs. The stability coefficient of their landscapes (k_{ESL1}) varies from 0.90 to 5.39, which corresponds to the levels of qualitative characteristics from "unstable" to "stable, with pronounced stability". The ecological condition of the landscapes in the upper and lower reaches of the Stokhid River is assessed with k_{ESL1} values ranging from 0.72 to 0.90, which classifies them as "unstable". The stability of the middle reaches of the river is assessed with k_{ESL1} values ranging from 1.69 to 3.86, which classifies their quality characteristics as "conditionally stable" to "stable". The landscapes of the lower reaches and the mouth of the Stokhid River are characterized by k_{ESL1} values of 5.39, which classify their quality characteristics as "stable, with pronounced stability". Thus, the Stokhid sub-basin contains 4 types out of 5 types of ecological sustainability of landscapes.

The Sty River sub-basin is located in Volyn Oblast only within the middle reaches, where Horodyshe, Horokhiv, Maryaniv, Torchyn, Boratyn, Pidhaitsi, Lutsk, Kivertsi, Kopachiv, Rozhshyche, Olytsia, Kolkiv, Prylisne and Manevychi TCs are located. The coefficient of landscape stability (k_{ESL1}) in their territories varies from 0.28 to 5.16. Accordingly, the levels of qualitative characteristics of environmental sustainability of landscapes range from "unstable, with pronounced instability" to "stable, with pronounced stability". The assignment of the boundaries of the territorial communities of the Volyn Oblast to the sub-basins of the Prypiat River tributaries allowed tracing certain features of the ecological stability of landscapes and visualizing the data in spatial location as of 2022 (Fig. 5).

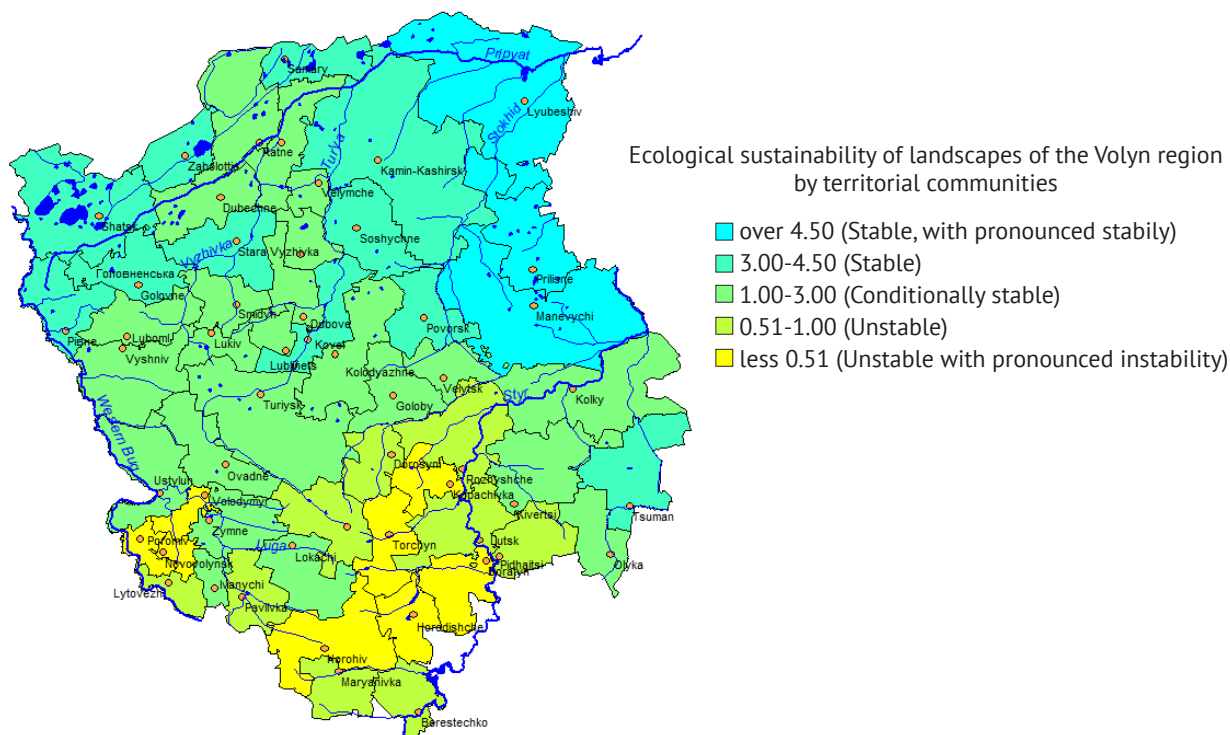


Figure 5. Ecological sustainability of landscapes of the Volyn region in the section of TC (2022)

Source: based on the author's research

For example, the southern part of Volyn Oblast is represented by landscapes in an “unstable state, with pronounced instability”. Here are the TCs (Gorokhiv, Maryaniv, Rozhyshe, Horodyshe, Boratyn) with the largest percentage of agricultural land, namely arable land, which is over 65%, and the smallest part of forests and forested land – no more than 15-25%. In the middle part of the region (Kolkivska, Horobska, Velytska, Turyska, Ustyluzka, Liubomylska TCs), the ecological condition of the landscapes is gradually changing to “conditionally stable”. In the northern part of the region, the ecological stability of the landscapes becomes “stable, with pronounced stability”, which is ensured by small areas of arable land (15-25%) and significant areas of forests and forest-covered land (from 45% to over 55%), as well as a sufficient number of protected areas, in particular in the Tsumanska, Manevytska, Prylissenska and Kolkivska TCs.

The results of the spatial distribution of stable and unstable landscape elements in the upper reaches of the Prypiat River basin obtained in the course of the study allow generalizing that the basis of economic development of the territory is agricultural and forestry land use. This was facilitated by the natural conditions of the Prypiat River basin, which resulted in a diverse and unique landscape structure. This is also confirmed by modern ecological and geographical works by I. Myskovets & Ya. Molchak (2022), who shows that the landscape diversity of the upper Prypiat River basin is formed by zandra lowlands, sandy terraces, forest and

meadow-marsh floodplains that have undergone significant agrogenic transformation.

In the south and east of the Prypiat River basin, agricultural use of natural resources prevails within the territorial communities of Volyn Oblast. This is due to the fragmented location of zandra lowlands in the structure of landscape formations, which form a flat-wavy land surface with a predominance of sod-podzolic and sod soils. The dominance of the agricultural type of natural resource use within the zandra lowlands is noted in the research of C. Gao *et al.* (2020), who explains this by the presence of fertile soils on their surface, which were formed in the post-glacial period on sand and gravel deposits.

The large-scale drainage reclamation that took place in the Volyn region during the second half of the 20th century led to the loss of the original appearance of natural watercourses, such as the Vizhivka River, Turia River, Tsyri River, Korostianka River, and Stokhid River. As a result, the landscape structures of the area have also changed, represented by lowland marshes, which occupy about 30% in the east and north of the study area of the upper Prypiat River basin. This is also evidenced by the studies of R. Koptiuk *et al.* (2023), who recorded the reduction of riverbeds in the region as a result of their transformation into main channels of drainage systems, which, against the background of climate change and a lowering of the groundwater table, has significantly changed the moisture supply of the soil and negatively affected its fertility. S. Tomscha *et al.* (2023) confirm the

importance of preserving natural wetland complexes, which constitute an important ecological component of the environment and contribute to landscape stability and ecosystem services, and are essential for the conservation of water resources, carbon stocks, and the preservation of plant and animal diversity. The significant impacts of climate change on the baseline environmental situation in river basins are also proved by M. Ben-Daoud *et al.* (2021), H. Ma *et al.* (2023), who outline that climate change affects the river flow regime by increasing or decreasing precipitation, which affects the stability of ecosystems within river basins and significantly complicates water management.

The results obtained indicate that the intensity of agricultural use of natural resources, in particular ploughed land, spatially ranges from 35 to 65% within the upper reaches of the Prypiat River basin. A similar situation is noted in the work of P. Volk *et al.* (2023), who believe that in order to preserve soil ecosystem services, including food services, within the Volyn region's TCs, adaptive measures of agro-melioration, agrotechnical and hydrotechnical directions should be introduced to optimize the functioning of drainage systems and the possibility of balanced management of moisture reserves on drained lands against the background of climate change. Keshtkar *et al.* (2023) also note that in recent decades, agricultural intensification, expanding urbanization, technological progress and economic growth, combined with the effects of climate change, have significantly altered the balance of relations between humans and nature and led to serious consequences and risks for landscape ecosystem services. The results of this study show that these issues are particularly acute and must be addressed for Pavlivka, Horokhiv, Maryanivka, Horodyshche and Torchyn communities, as well as other communities in the central and southern part of Volyn Oblast.

Within the Prypiat River valley and in the valleys of its tributaries, forest and meadow-marsh floodplains on alluvial deposits are quite common. These floodplains usually have more fertile soil than the surrounding areas and a greater diversity of vegetation. Research by J. Opperman *et al.* (2022) confirms the highest natural diversity of tree, shrub and herbaceous plants within such floodplains, which is explained by the intensive accumulation of organic material that supports the ecosystem services of the landscape. However, as a result of long-term urbanization and economic development of floodplains in the Prypiat River basin, the sustainability of landscapes is sometimes unstable, due to a number of environmental problems. A. Volchak *et al.* (2016) explain that the impact of artificially changing the conditions of river flow formation over decades has led to periodic floods and floods, and due to the flooding of settlements and agricultural land, a large amount of pollutants enters the rivers. A. Konoplev *et al.* (2021) observed that flooding of territories causes

secondary contamination of surface waters in the Prypiat River basin with radionuclides that are still present in the soil profile after the Chernobyl nuclear power plant accident. Similar confirmations are provided by observations of Y. Grokhovska and S. Konontsev (2022), who prove that due to irrational use of natural resources within the Prypiat River catchment, regulation and straightening of small river channels, soil erosion is intensifying, siltation of channels occurs, water quality and the vital activity of aquatic organisms are changing.

K. Wang *et al.* (2023) confirm that in recent decades, agricultural intensification, expanding urbanization, technological advances and economic growth, combined with the effects of climate change, have significantly altered the balance of relations between humans and nature and led to serious consequences and risks for landscape ecosystem services. Taking into account the multitude of natural and anthropogenic factors in the Prypiat River basin, the impossibility of applying unified approaches to assessing the ecological sustainability of landscapes, as observed in the scientific literature, is confirmed. In addition, the presented experience shows that the completeness of the assessment model largely depends on the availability of data and their orderliness. Thus, in order to assess the environmental sustainability of the Prypiat River basin landscape within the Volyn Oblast, data within individual territorial communities were used, which are officially reported for environmental purposes.

The mapping of the assessment results on the administrative boundaries of the TC contributed to a clear visualization of the current environmental sustainability of the region in administrative and spatial terms. This situation coincides with the data of J. Jóźwik & D. Dymek (2021), who argue that landscape sustainability studies should be repeated periodically, as in the future this will allow communities to identify in advance natural structures that require preservation or restoration based on environmental conditions. Proposals X. Qiao *et al.* (2023) to optimize land use patterns in river basins by taking into account landscape structure are similar to the approaches used in this study. However, such assessments within river basins and sub-basins, which could facilitate management decisions on practical projects to preserve or restore their ecological status, are currently difficult in Ukraine due to the peculiarities of statistical reporting. These gaps can be filled by tracking the extent of anthropogenic landscape changes within territorial administrative units, while analysing the natural features of river catchment areas. Modern environmental mapping technologies can provide the necessary regional-scale variations in the environmental sustainability of landscapes, which will facilitate the development of coordinated concepts between communities and public environmental management bodies to achieve sustainable development goals in socio-ecological systems.

CONCLUSIONS

Based on the determinations of the coefficient of ecological sustainability of landscapes (k_{ESL1}) of the Prypiat River basin in the context of territorial communities of the Volyn Oblast, it was found that the landscapes of the study area have a qualitative characteristic ranging from “unstable with pronounced instability” to “stable, with pronounced stability”. The ecological mapping showed that in the Tsyry sub-basin, from the source to the mouth, where Kamen-Kashyrska and Lyubeshivska TCs are located, the k_{ESL1} value is 4.90-5.39, which assesses the landscapes as “stable, with pronounced stability”. In the Vyzhivka River sub-basin and the upper Prypiat River (Rivne, Holovnenska, Shatska, Zabolotnenska, Ratnivska TCs), k_{ESL1} varies from 1.18 to 4.35, which assesses the sustainability of the landscapes as “conditionally stable” – “stable”. In the Turia River sub-basin (Turia, Lyublyntsi, Kovel, Sochyshne, Velymche TCs), k_{ESL1} ranges from 0.90 to 4.90, which means that the ecological sustainability of the landscapes is assessed as “unstable” to “stable, with pronounced stability”. In the sub-basin of the Stokhid River (Prylisenka, Kamyn-Kashyrska, Lyubeshivska TCs), k_{ESL1} has a value of 0.90-5.39, which means that the ecological sustainability of the landscapes ranges from “unstable” to “stable, with pronounced stability”. In the middle part of the Styr sub-basin (Horodyshche, Lutsk, Torchyn, Horokhiv, Kivertsi, Kolkiv, Manevychi TCs), k_{ESL1} varies from 0.28

to 5.16, which assesses the ecological sustainability of landscapes as “unstable, with pronounced instability” to “stable, with pronounced stability”. In general, the land areas of the TC administrative units in the Prypiat River basin within Volyn Oblast are represented by unstable landscape elements mainly in the southern part of the basin, within the Volyn Upland, where the tributaries of the Prypiat River originate. The areas under agricultural crops and plant communities that have a positive impact on the landscape are located mainly in the northern part of the basin within the Polissya Lowland, where the mouths of the tributaries (Vyzhivka, Turia, Tsyry, Stokhid) and the source of the Prypiat River itself are located. The variations in landscape stability obtained in the course of ecological mapping have the prospect of continuing such assessments to expand the spatial and temporal dimension of research. This will help to align the interests of socio-economic development of communities with the management decisions of state environmental agencies to preserve the stability of landscapes in river basins, maintain and restore their ecological condition.

None.

None.

ACKNOWLEDGEMENTS

CONFLICT OF INTEREST

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Оцінка екологічної стійкості ландшафту басейну річки Прип'ять у межах Волинської області

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Анотація. Актуальність досліджень полягає в тому, що в розрізі глобальної концепції сталого розвитку, одним із провідних завдань є підтримання стійкості природних екосистем через пошук оптимальних стратегій розвитку соціо-економічних систем. Мета досліджень – оцінка екологічної стійкості ландшафтів басейну річки Прип'ять у межах територіальних громад Волинської області в сучасних умовах розвитку регіону. Методи, що використовувались для досягнення мети, включали розрахунок коефіцієнту екологічної стійкості ландшафту на основі систематизації статистичних звітних даних, з наступним порівняльно-географічним аналізом і проведенням екологічного картографування засобом ArcMap та ArcGIS Pro. Основні результати досліджень свідчать, що коефіцієнт екологічної стабільності ландшафтів у басейні р. Прип'ять знаходиться у межах 0,22-5,39 і оцінює ландшафти від рівня «нестабільні з яскраво вираженою нестабільністю» до «стабільні, з яскраво вираженою стабільністю». Розподіл площ земель у територіальних громадах, які знаходяться у суббасейні р. Цир, зумовлює характеристику ландшафтів на рівні «стабільні, з яскраво вираженою стабільністю». У межах територіальних громад суббасейну р. Виживка та верхів'я р. Прип'ять – «умовно стабільні» – «стабільні». У межах громад суббасейну р. Турія – від «нестабільні» до «стабільні, з яскраво вираженою стабільністю». У межах громад суббасейну р. Стохід від «нестабільні» до «стабільні, з яскраво вираженою стабільністю». Територіальні громади середньої частини суббасейну р. Стир представлені ландшафтами від «нестабільні,

з яскраво вираженою нестабільністю» до «стабільні, з яскраво вираженою стабільністю». У цілому, більш екологічно-стабільні ландшафти розміщені в північній частині Волинської області, що завдячує великим площам лісовкритих земель. Екологічна нестабільність ландшафтів характерна для південної частини області через значні площі розораних земель. Практична цінність роботи полягає в отриманні регіональних варіацій оцінки екологічної стабільності ландшафтів, що важливо враховувати при розробці узгоджених концепцій між громадами та органами управління природокористуванням за басейновим принципом, для досягнення цілей сталого розвитку в соціоекологічних системах

Ключові слова: річковий басейн; суббасейн; землекористування; екосистемні послуги; управлінські рішення

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Analysis of cassava farming efficiency as a supporter of post-COVID-19 rural economic changes in wonogiri regency

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Abstract. Cassava farming, as an important commodity in agriculture in Wonogiri Regency, is necessary for structural changes in the rural economy of Wonogiri Regency in post-COVID-19 conditions. This study aims to determine the level of efficiency and analyse the elasticity of cassava farming. The Data Envelopment Analysis is used in analysing the efficiency of cassava farming, while multiple linear regression analysis is used in analysing production elasticity. The results of Data Envelopment Analysis with an input-oriented model in the study show that farmers have a level of technical efficiency of 64.6%, allocative efficiency of 47.1%, and economic efficiency of 30%. Farmers who are not efficient can increase their efficiency value by using cassava farming inputs. The elasticity of the production of seedlings, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, pesticides, and labour is positive. The scale of business results show that farming is in a condition of increasing returns to scale. The addition of production factors has a positive effect on cassava production. However, if production factors are not considered, it will result in additional inputs, decreasing yields. Optimal use of inputs can increase the production scale of cassava farming and increase efficiency. This study can be helpful for the farmers to increase the efficiency level through the efficient use of inputs. They can be helpful for the government in the formulation of rural development plans with farming development and implementing policies to increase the efficiency

Keywords: input; elasticity; rural development; Cobb-Douglas; Data Envelopment Analysis

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INTRODUCTION

The structure of agricultural businesses in Indonesia is dominated by small-scale agriculture in rural areas. Rural change or transformation in rural areas is not only from the agricultural side but needs to pay attention to the aspirations of rural communities, which play an important role in shaping their desires. Therefore, to develop a rural economy, it must start from the community's aspirations through production, distribution, consumption, and investment activities. In the current conditions, transformation is needed because most small-scale (subsistence) agriculture can no longer meet the community's economic needs, especially food needs. Understanding rural dynamics is one of the main keys to formulating agricultural development policies and regional economic development. In line with the ongoing development process, the rural economy is experiencing dynamic structural changes post-COVID-19. The impact of Covid-19 has deepened the vulnerability of small producers, including in the agricultural sector (FAO, 2020).

In agriculture, economic production is closely related to natural processes. Hence, the restrictive measures imposed during the COVID-19, in particular, negatively impacted farmers' productive employment, rural household budgets, and the functioning of the rural social environment. area, etc. The background of this research is that cassava is a leading commodity in Wonogiri Regency and in Central Java. The production of cassava in Wonogiri Regency is 857,432 tons/year, but the productivity is low compared to other regions. They always increase natural resources while maintaining sustainability and the rural economy. The level of productivity can be seen from the use of inputs as a resource in farming (Badan Pusat Statistik, 2022). Based on the concept of resilience, M. Meuwissen *et al.* (2019) define it as the ability of an agricultural to be able to adapt to all impacts that occur, be able to study the conditions that occur, and be able to transform to change the agricultural system. For some local farmers in research by I. Scoones *et al.* (2020), transformation is related to resistance to development forces to achieve sustainability.

A research study in the first year of E. Rahayu *et al.* (2021) found that cassava agribusiness impacts the economy of Wonogiri Regency from the dynamic cassava supply chain, which was able to increase revenue by Rp. 7,972,155.03/Ha compared to COVID-19, which was only 4,909,935.52/Ha. Although there was an increase in costs by 17.79%, there was an increase in revenue by 62.36%, so it still gave a positive increase. The results of P. Mugabe *et al.* research (2022) also show that COVID-19 has had an impact on agriculture, where as many as 45% of farmers have experienced a decrease in agricultural output, and among them, as many as 60% have experienced a decrease of 25% while the rest (40% of farmers) have experienced a decrease of 50%.

Cassava in Wonogiri Regency is used as a supplier of raw materials for tapioca factories, with a

proportion of more than 50% of the total raw materials needed, and this has caused the demand for cassava raw materials to continue to increase. Unlike the previous decades, where cassava was only consumed directly, direct consumption will continue to decrease, and F. Rozi *et al.* (2023) said that it will be offset by increased demand for cassava as an industrial raw material for processed industries, as well as new and renewable energy material. Cassava can be processed into various kinds of derivative products, which are produced in small-scale and large-scale industries, both in terms of production and the technology used, including in Wonogiri Regency. In Wonogiri Regency, cassava is widely cultivated by the community and used as raw material for the flour industry (Banowati *et al.*, 2020). In Wonogiri Regency, there have been two units of tapioca flour industry, and it is estimated that in the future, it will increase. Farmers prefer to sell cassava to wholesalers and contract systems with factories or processing industries because the prices offered by wholesalers are greater than those offered by the market, increasing the competitiveness of cassava at the farmer level.

Post-COVID-19, the economy of cassava is used as a reference in changing the rural economy. Post-COVID-19 conditions provide an opportunity to think about all actions in making decisions regarding the agricultural system that will be developed, including decisions on how to use optimal inputs (Lioutas & Charatsari, 2021). In cassava production conditions, it has not been balanced with farmers' knowledge of using the right production factors. Farmers do not understand the principles of the relationship between inputs and outputs, so farmers often use inputs that do not follow recommendations. The use of inputs that are not optimal results in the production produced is also not optimal. Therefore, T. Luttiana & Y. Hariyati (2019) stated that knowing what factors can affect a farm to be used as efficiently as possible is necessary.

There is a need for studies on economic activities, especially from cassava production and farming in Wonogiri Regency based on cassava agribusiness, where cassava is the dominant commodity that develops as a rapidly growing and productive economic sector. Cassava agribusiness activities, it is expected to be a trigger in the rural economy that is balanced and develop into the industry, both cassava product development industries and non-cassava impacts on rural economic development, namely the increase in income levels and welfare of cassava agribusiness. Revenue from the cassava agribusiness affects the economic dynamics in rural areas in terms of food consumption and non-food consumption (education, health, quality of labour, etc.). Therefore, the purpose of this study was to determine the efficiency and elasticity of cassava production in the Wonogiri region.

MATERIALS AND METHODS

This research survey was conducted from May to June 2022 in three districts with high cassava production, namely Ngadirojo District, Tirtomoyo District, and Jatiroto District. The research method in this study is a closed survey method. The survey was conducted offline through direct interviews with cassava farmers related to data on the use of cassava farming inputs consisting of the use of cassava seeds, manure, SP36 fertilizer, urea fertilizer, pesticides, and labour use, with the price of each input. As well as questions about output in the form of production from cassava farming. In the interview, farmers are willing to voluntarily become respondents with prior permission and ensure the protection of respondents' data by not misusing data obtained from respondents.

The selection of districts and villages as research samples (in Fig.1) was carried out by multi-stage stratify random sampling. The population data of cassava farmers in Wonogiri Regency is unknown, so the determination of the number of samples uses the formula of P. Levy and S. Lemeshow (2013):

$$n = \frac{Z^2 1 - \alpha / 2P(1-P)}{d^2}, \quad (1)$$

where n is the number of samples; Z is the z score at 95% level of confidence = 1.96; P is the maximum estimate = 0.5; and d is alpha (0.10) or sampling error = 10%. Through the formula above, the number of samples to be used is:

$$n = \frac{Z^2 1 - \alpha / 2P(1-P)}{d^2},$$

$$n = \frac{1,96^2 - 0.5 / (1-0.5)}{0.01}, \quad (2)$$

$$n = 96.04,$$

The risk of data loss is often faced by researchers, one of which is because there is a chance that respondents do not answer ranging from 5-25% of the total respondents. If respondents do not answer a maximum of 25% of the total sample (96 farmers), then the total sample that does not respond is 24 farmers. For the total sample to be optimal, the risk of unresponsive samples is added to the total sample of the initial calculation, thus the total sample used in this study amounted to 120 cassava farmers who were divided proportionally into 3 sub-districts, namely each sub-district consisting of 40 cassava farmers as research samples.

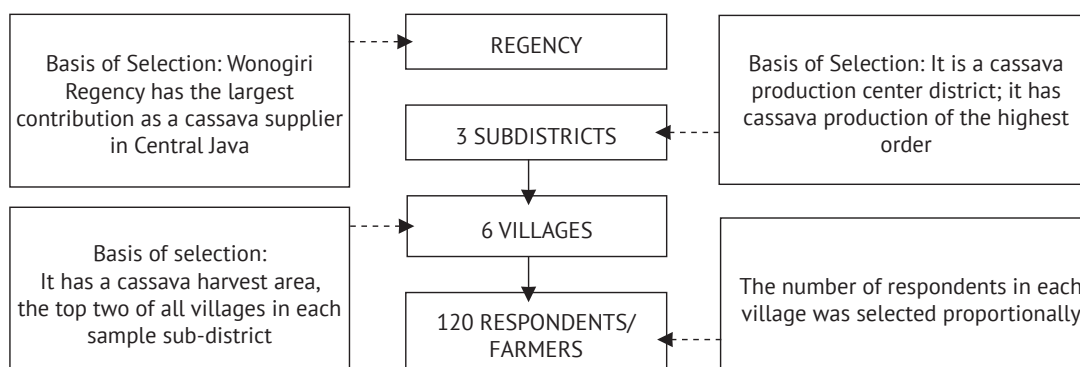


Figure 1. Research Sample Determination Scheme

Source: formed by authors

The data analysis method to determine the level of efficiency uses the Data Envelopment Analysis (DEA). The concept of efficiency used in this study refers to efficiency proposed by T.J. Coelli *et al.* (2005), where efficiency is classified into technical, allocative, and economic efficiency. The DEA model used in this study is input-oriented because farmers can control input variables more easily than the output produced. Technical efficiency relates to the managerial ability of farmers in allocating production inputs. In calculating technical efficiency, it is assumed that there are K inputs and M outputs for each period N and at the i moment will be represented by factors x_i and y_i . The input matrix, X , and output matrix, Y , represent data for the entire period N . The formulation of input orientation and assumption of Variable Returns to Scale (VRS) can be formulated:

$$\begin{aligned} & \text{Min}_{\theta, \lambda} \theta \\ & \text{Subject to: } -y_i + Y\lambda \geq 0; \\ & \theta x_i - X\lambda \geq 0; \\ & N1\lambda = 1; \\ & \lambda \geq 0, \end{aligned} \quad (3)$$

where θ is the technical efficiency score, y_i is the vector of the amount of cassava production. x_i is the vector of the input, Y is the output of the production in kilogram, X is the input (the use of cassava seeds (X_1), manure (X_2), SP36 fertilizer (X_3), Phonska fertilizer (X_4), urea fertilizer (X_5), pesticides (X_6) and labour (X_7)), and λ is the $N \times 1$ vector of the weightier. An efficiency score of ≤ 1 with a value of 1 indicates an efficient Decision-Making Unit (DMU). An efficiency score of 1 indicates a point on the frontier where a farmer run by a cassava farmer

(DMU) is already efficient, while an efficiency score of <1 indicates a point where a farmer run by a farmer has not been efficient. Allocative efficiency measurement can be done with input price information and cost minimization assumptions. Assuming VRS and cost minimization, the equation becomes as follows:

$$\begin{aligned} & \text{Min } \lambda, \text{ xi } \text{Pixi}^* \\ & \text{Subject to } -y_i + Y \lambda \geq 0; \\ & \theta \text{ xi} - X \lambda \geq 0; \\ & N \text{ } 1 \lambda = 1; \\ & \lambda \geq 0, \end{aligned} \tag{4}$$

where, Pi is the input price vector for the i time and xi* is the cost minimization vector of the input quantity for the i time, with the output rate yi. According to Soekartawi (2003), economic efficiency (EE) is the product between all price efficiency (allocative) of all input factors or between technical efficiency (TE) and allocative efficiency (AE). The economi efficiency can be expressed as EE = TE×AE, with criteria if EE = 1,

$$\text{LnY} = \text{Ln } a + \beta_1 \text{LnX}_1 + \beta_2 \text{LnX}_2 + \beta_3 \text{LnX}_3 + \beta_4 \text{LnX}_4 + \beta_5 \text{LnX}_5 + \beta_6 \text{LnX}_6 + \beta_7 \text{LnX}_7 + e \tag{6}$$

The elasticity of output towards the input used can be seen from the coefficient value of each input (βi).

RESULTS AND DISCUSSION

Efficiency analysis is carried out to determine how cassava farming management is managed efficiently. The results of DEA Variable Return to Scale (VRS) in Table 1.

then the use of input is efficient, and if EE < 1, then the use of input is inefficient. The data analysis method of the production elasticity is multiple linear regression analysis based on the Cobb-Douglas production function as follows:

$$Y = a X_1^{\beta_1} X_2^{\beta_2} X_3^{\beta_3} X_4^{\beta_4} X_5^{\beta_5} X_6^{\beta_6} X_7^{\beta_7} e, \tag{5}$$

where Y is cassava production (kg), a is the constant value. X₁ is the use of cassava seedlings (stems), while X₂ is the use of manure (kg). X₃ is the fertilizer SP36 (kg), X₄ is the fertilizer Phonska (kg), and X₅ is the urea fertilizer (kg). X₆ is using pesticides for cassava farming (litres) and X₇ is using labour(man-day). While β₁, β₂, β₃, β₄, β₅, β₆, and β₇ are estimated parameters, which output the elasticity of each input used, and e are error terms.

After the data is logarithm, it is possible to use multiple linear regression analysis to find the next equation. The results of the equation are then transformed into a natural logarithm equation (Ln) so that the equation becomes:

show that the average farmer has a technical efficiency level of 0.646 or 64.6%, therefore there are 35.4% technically inefficient uses of input. The percentage of farmers who are fully efficient (1,000) on the VRSTE assumption is 29 farmers (24.2%), and the majority of farmers, namely 34.2%, have an efficiency value in the range of 0.250-0.499, which shows that they have a low-efficiency value.

Table 1. Distribution of Technical, Allocative, and Economic Efficiency of Cassava Farming

| Range | Technical Efficiency | | Allocative Efficiency | | Economic Efficiency | |
|-----------------|----------------------|-------|-----------------------|-------|---------------------|------|
| | Freq | % | Freq | % | Freq | % |
| 0.250-0.499 | 41 | 34.2 | 57 | 47.5 | 96 | 80.0 |
| 0.500-0.749 | 34 | 28.3 | 50 | 41.7 | 21 | 17.5 |
| 0.750-0.999 | 16 | 13.3 | 12 | 10.0 | 2 | 1.7 |
| 1,000 | 29 | 24.2 | 1 | 0.8 | 1 | 0.8 |
| Total | 120 | 100 | 120 | 100 | 120 | 100 |
| Mean | | 0.646 | | 0.471 | | 0.30 |
| Min. Efficiency | | 0,118 | | 0 | | 0 |
| Max. Efficiency | | 1 | | 1 | | 1 |

Source: compiled by authors using Data Envelopment Analysis (2023)

The results of DEA with an input-oriented model in research show that farmers who are not yet efficient. Technical efficiency levels range from 11.8% to 100%, which implies an opportunity to improve technical efficiency. A. Akpaeti and N. Frank (2021), B. Sherzod et al. (2018) research that farmers can increase the technical efficiency with the current production resources. Increasing agricultural productivity ranks highly as a path to poverty alleviation and reducing vulnerability to poverty for changes towards improving the economy of rural communities, which in T. Mallawaarachchi &

D. Rahut's research (2023) can be approached with technical changes in agricultural systems supported by knowledge transfer.

Cassava farmers in Wonogiri Regency have an allocative efficiency rate of 0.471 or 47.1% (in Table 14), which shows that farmers can reduce current average production costs by 52.9% to achieve potential minimum production costs. The allocative efficiency shows that only 0.8% of farmers are fully allocative efficient, while most farmers (47.5%) have low or inefficient efficiency. Allocative efficiency relates to the price level

of each input issued by farmers. The majority of farmers do not make purchases of seedlings. The need for seedlings is obtained from stem cuttings from previous cassava plants. The problem mainly occurs in the price of NPK Phonska fertilizer and urea, which affects the input costs incurred by farmers because there is a price difference between subsidized and non-subsidized fertilizers. Not all cassava farmers can access subsidized fertilizers for cassava farming. The availability of subsidized fertilizer does not follow when the fertilizer is needed for cassava farming, so it requires farmers to buy non-subsidized fertilizer so that farming continues to run by meeting the nutrient needs of cassava plants.

There is a need for adequate support in the form of agricultural subsistence, because, according to S. Singh *et al.* (2020), the agricultural sector can contribute to the recovery and strengthening of countries, stimulate rural development, increase food security, and influence price stabilization on global markets. E. Nchanji *et al.* (2021) proposed subsidy provisions for agricultural inputs as post-COVID-19 policy recommendations in their research. Subsidies for agricultural inputs can affect the amount of expenditure or costs incurred by farmers so that the use of inputs can be carried out optimally without any availability restrictions and price limits. The economic efficiency rate of cassava farming is 30% and almost all cassava farmers in Wonogiri Regency have not been efficient because only 0.8% of farmers have just achieved economic efficiency with a value of 1,000. W. Kaye-Blake

(2022) states that resilience cannot develop without supporting resources. Therefore, achieving resilience depends on how resources can be used efficiently.

Good management of agricultural systems and natural resources can increase sustainability towards a sustainable agricultural system (Piñeiro *et al.*, 2020). The availability of natural resources is very meaningful for the sustainability of production activities to the consumption of rural communities. Natural resources as factors of production must be used efficiently to produce optimal production output (Ajayi & Olutumise, 2018). A good understanding of the relationship/interaction of production activities and their efficiency drives changes in rural economic dynamics that broadly impact the life sector of farmers and the surrounding community. The mechanism is expected to improve the farmer's economy and more dynamic rural economic dynamics after COVID-19. In line with the ongoing development process in Wonogiri Regency, the rural economy is undergoing dynamic structural changes after COVID-19. The pandemic of COVID-19 has changed rural life, including agricultural and food conditions (Mayuzumi, 2023), where the existence of COVID-19 as a whole affects agricultural output.

Cassava farming inputs include seeds, fertilizers, and pesticides. Seeds are needed in farming so that cultivation can be carried out. Fertilizer aims to provide nutrients to plants to meet the nutritional needs of plants. Fertilizers used in cassava farming consist of manure, SP36 fertilizer, Phonska fertilizer, and urea fertilizer.

Table 2. Average Cost of Production Facilities in Cassava Farming in Wonogiri Regency in 2022

| Description | Average Usage/MT | Average Cost/MT (Rp) |
|-----------------------|------------------|----------------------|
| Seed | 393.38 stem | 2,083.33 |
| Fertilizer | | |
| a. Manure | 271.92 kg | 0 |
| b. SP36 Fertilizer | 7.73 kg | 26,229.17 |
| c. Phonska Fertilizer | 27.83 kg | 100,416.67 |
| d. Urea Fertilizer | 57.12 kg | 161,933.33 |
| Pesticides | 0.02 litres | 1,916.67 |
| Total | 292,579.17 | |

Source: compiled by authors based on the survey data results

Based on the average use of cassava farming inputs, an analysis of the elasticity of cassava production can be carried out. In business activities, producing production activities aims to maximize profits. This condition is achieved by utilizing some inputs at the optimum level. Two conditions are needed to achieve maximum profit: necessary and sufficient. The necessary condition is objective in that it is fulfilled when there is no longer the possibility of achieving greater production using the same inputs or when the elasticity of production is between zero and one ($0 \leq \epsilon \leq 1$). The level of production elasticity of each input used can be seen from the results of multiple linear regression analysis to analyse the influence of inputs or production factors.

Tests with multiple linear regression models must meet the rules of classical assumptions to show whether there is bias in the research data results used in multiple linear regression tests. Classical assumptions are assumptions that are met to meet the criteria of BLUE (Best Linear Unbiased Estimator). Classical assumption testing consists of Normality, Multicollinearity, and Heteroscedasticity Tests. The normality test is needed to test the dependent variable and independent variables, whether the residuals are normally distributed or not. In this study, the normality test was carried out by looking at the histogram and normal probability plot graphs. Based on the results in Figure 2, it gives a pattern that does not

deviate left or right, and the data spread following the direction of the histogram graph, thus meeting the normality test. Based on the normal probability

plot test results in Figure 3, the points or data are near or following the diagonal line, so the residual values are normally distributed.

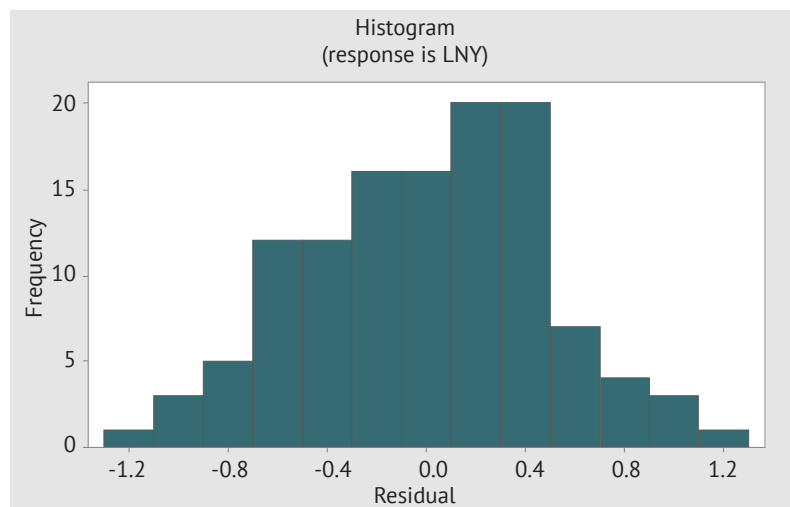


Figure 2. Histogram Graph

Source: regression output with Minitab based on survey data results

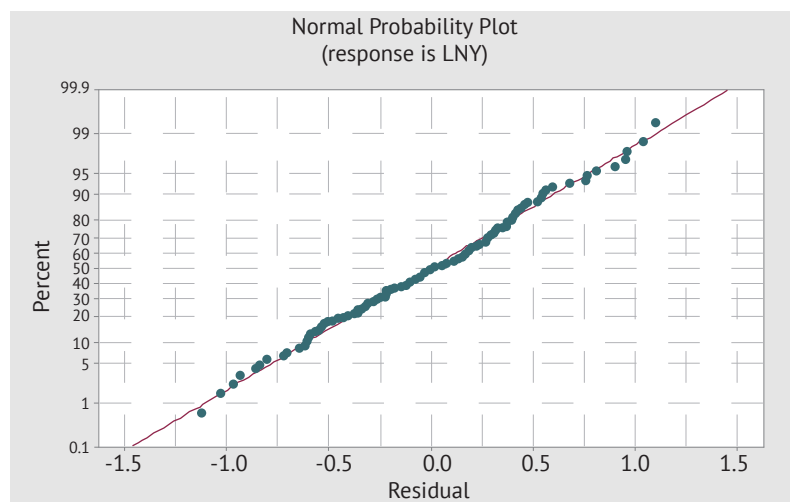


Figure 3. Normal Probability Plot Graph

Source: regression output with Minitab based on survey data results

Multicollinearity is a condition with a linear relationship between two or more independent variables (Chan *et al.*, 2022). The method used is seen from the Variance Inflation Factors (VIF). The VIF limit is 10, so multicollinearity does not occur if the VIF value ≤ 10 per independent variable. Based on Table 3, the VIF

value of each independent variable (seedlings, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, pesticides, and labour) is less than 10. It can be concluded that each variable has been free from the problem of multicollinearity or multicollinearity has not occurred.

Table 3. VIF Value

| Term | VIF |
|---------------------------|------|
| Constant | |
| LNX1 (Seed) | 1.78 |
| LNX2 (Manure) | 1.93 |
| LNX3 (SP36 Fertilizer) | 1.33 |
| LNX4 (Phonska Fertilizer) | 1.18 |

Table 3, Continued

| Term | VIF |
|------------------------|------|
| LNx5 (Urea Fertilizer) | 1.46 |
| LNx6 (Pesticide) | 1.20 |
| LNx7 (Labour) | 1.20 |

Source: compiled by authors using Minitab based on survey data results

The heteroscedasticity test is used to test whether there is an imbalance of variance in a regression model. If the variance of one observation is different from other observations, this indicates heteroscedasticity is occurring. Based on the scatterplot diagram, it is known that the pattern of dots does not form a specific pat-

tern. These points are distributed randomly and spread above or below the number 0 on the Y-axis, so there is no heteroscedasticity and the regression model can be used to predict. The coefficient of determination (R²) measures how far a model can explain the independent or dependent variables (Table 4).

Table 4. Test Results of Coefficient of Determination (R²)

| Model Summary | | | |
|---------------|--------|-----------|------------|
| S | R-sq | R-sq(adj) | R-sq(pred) |
| 0.485897 | 72.25% | 70.51% | 68.44% |

Source: compiled by authors using Minitab based on survey data results

The coefficient of determination test shows that the value of the coefficient of determination or R Squared is 72.25%, which shows that the variation of independent variables (seeds, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, pesticides, and labour) used in the model can explain 72.25% of the variation in the

dependent variable (cassava production). While 27.75% was influenced by other variables not included in the regression model. The F test is used to test whether the independent variable) together affect the dependent variable (cassava production). The results of the F test can be seen in Table 5.

Table 5. F-test Result

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|------------|-----|---------|--------|---------|---------|
| Regression | 7 | 68,8312 | 9.8330 | 41,65 | 0,000 |
| Error | 112 | 26,4427 | 0.2361 | | |
| Total | 119 | 95,2739 | | | |

Source: compiled by authors using Minitab based on survey data results

The probability value (P-Value) is 0.000, less than α ($\alpha = 0.05$). The independent variables; seeds, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, pesticides, and labour, significantly affect the dependent variable, namely cassava production in Wonogiri Regency. The statistical test t is used to determine how far the influence of the free variables of seedlings, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, pesticides, and individual labour can explain the variation of the dependent variable in the form of cassava production. The P-value of seed input was obtained at $0.052 < \alpha = 0.1$. Seed input

(X₁) individually affects cassava production in Wonogiri Regency (Y). Manure and Phonska fertilizer inputs affect cassava production, with a P-Value of $0.000 < \alpha = 0.01$ for manure and a P-Value of $0.028 < \alpha = 0.05$ for Phonska fertilizer. Pesticide input has a P-Value of $0.000 < \alpha = 0.01$, which shows that pesticides significantly affect cassava production in Wonogiri Regency. The labour variable has a P-value of $0.029 < \alpha = 0.05$, meaning that labour input significantly affects cassava production in the Wonogiri Regency. Based on Table 6, the cassava production function in Wonogiri Regency can be written:

$$\ln Y = 3.924 + 0.1533 \ln X_1 + 0.4305 \ln X_2 + 0.0496 \ln X_3 + 0.0527 \ln X_4 + 0.0273 \ln X_5 + 1.004 \ln X_6 + 0.1749 \ln X_7$$

Table 6. t-Test Results from Factors Affecting Cassava Production

| Term | Coef | SE Coef. | T-Value | P-Value |
|---------------------------|----------------------|----------|---------|---------|
| Constant | 3,924 | 0,439 | 8,95 | 0,000 |
| LnX1 (Seed) | 0,1533* | 0,0782 | 1,96 | 0,052 |
| LnX2 (Manure) | 0,4305*** | 0,0635 | 6,78 | 0,000 |
| LnX3 (SP36 Fertilizer) | 0,0496 ^{ns} | 0,0321 | 1,54 | 0,125 |
| LnX4 (Phonska Fertilizer) | 0,0527** | 0,0236 | 2,23 | 0,028 |

Table 6, Continued

| Term | Coef | SE Coef. | T-Value | P-Value |
|------------------------|----------------------|----------|---------|---------|
| LnX5 (Urea Fertilizer) | 0.0273 ^{ns} | 0.0251 | 1.09 | 0.279 |
| LnX6 (Pesticides) | 1.004 ^{***} | 0.227 | 4.42 | 0.000 |
| LnX7 (Labour) | 0.1749 ^{**} | 0.0792 | 2.21 | 0.029 |

Note: * Significant at the level of 10%; ** Significant at the level of 5%; *** Significant at the level of 1%; ns: non-significant

Source: compiled by authors using Minitab based on survey data results

Based on the cassava production function, the production factor that has the greatest influence on cassava production is pesticides (X6), with a regression coefficient of 1.004. The value of the regression coefficient of pesticide use shows that every addition of pesticides by 1% will increase cassava production by 1.004%. The production factor that has the least influence on cassava production is urea fertilizer (X5), with a regression coefficient of 0.0273. The value of the regression coefficient of urea fertilizer shows that every addition of 1% will increase cassava production, although it is not significant because it only increases by 0.0273%.

Cassava seeds (X1) have a production elasticity of 0.1533 and positively affect cassava production in Wonogiri Regency. Adding seed production factors by 1% will increase cassava production by 0.1533%, with other factors considered fixed (*ceteris paribus*). Manure (X2) has a production elasticity of 0.4305, indicating that increasing the use of manure production factors by 1% will increase cassava production by 0.4305%, with other factors considered fixed (*ceteris paribus*). SP36 fertilizer (X3) has an elasticity value of 0.0496, meaning that if there is an addition of SP36 fertilizer production factors by 1%, it will increase cassava production but not significantly because it only increases by 0.0496% with other factors considered fixed (*ceteris paribus*). Similarly, Phonska fertilizer (X4) has a positive regression coefficient value with a production elasticity of 0.0527. Increasing Phonska fertilizer production factors by 1% will increase cassava production by 0.0527%, with other factors considered fixed (*ceteris paribus*). The factor of labour production (X7) significantly affects the confidence level of 95%. The value of the elasticity of labour production factors is 0.1749, which means that every increase in labour use by 1% will increase cassava production by 0.1749%.

While the production factor, in the form of pesticides, has a production elasticity value of 1.004. Production elasticity in area I is greater than one ($E_p > 1$), meaning that adding pesticide production factors as much as 1% will cause an increase in cassava production, which is always greater than 1%. This area is said to be increasing returns to scale area because each addition of production factors will increase the amount of production, which increases more and more. In this area, maximum profit has not been achieved because production can still always be increased by adding inputs (factors of production). Thus, this area is irrational. According to D. Debertin (2012), the production function

is divided into three areas, distinguished based on the production elasticity of the production factors used. Area I is a production area with a production elasticity greater than one ($E_p > 1$), area II is a production area with an elasticity between zero and one ($0 < E_p < 1$), and area III is a production area with a production elasticity smaller than one ($E_p < 1$).

The elasticity value, except for pesticides, has an elasticity value greater than zero but smaller than 1 ($0 < E_p < 1$) (in production area II). The results of research by I. Ansah *et al.* (2023) also showed that labour, planting materials, and pesticides affect the level of cassava production, with the difference that planting materials and pesticides have a negative elasticity value, whereas, in this study, the value was positive. The research of S.E. Esheya (2022) showed positive elasticity results for cassava cutting and labour. Still, fertilizer input has a negative elasticity, indicating that the input allocation and utilization are at an irrational production stage (stage III) due to excessive use.

Every additional 1% of production factors can increase production by between zero and 1%. At a certain level, the use of input will provide maximum benefits. This shows that the production elasticity value for each input in the form of seeds, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, and labour is in the rational area, meaning that its use has provided benefits and advantages. The sum of the elasticity values for each input can be used to see the condition of the agricultural business scale. The results of this research show that the elasticity amount is 1.8923, which means that adding one percent of each production will increase production by 1.89%. The total production elasticity value is greater than one, this is in line with the research results of E. Widyastiara *et al.* (2023), so that cassava farming is in a condition of increasing returns to scale. Cassava farmers have not used inputs efficiently in conditions of increasing returns to scale because in these conditions maximum profits have not been achieved, so inputs are underutilized by cassava farmers. Cassava farmers can increase the optimal use of inputs as resources (Gbigbi, 2021; Mwebaze *et al.*, 2022).

Cassava is a commodity for rural development (FAO, 2018). Hence, the production process in cassava farming is the main activity of rural communities in meeting their and their families' living needs. Cassava farming provides a significant multiplier effect by developing employment and business opportunities from cassava production activities, resulting in changes in the dynamics

of the rural economy based on cassava production agribusiness. The production elasticities of inputs and labour were the greatest in the rural extension (Freitas *et al.*, 2021). Facilitating rural economic transformation can be focused on relative comparative advantage across diverse conditions. The utilization of local advantages owned by each region can be adjusted to the needs of each community. According to A. Kolapo & E. Abimbola (2020), increasing agricultural productivity through the use of inputs and utilizing local resources can reduce poverty through increasing farmer's income. According to E. Ikuemonisan *et al.* (2020), interventions to increase cassava production have resulted in increased output and stimulated the rural economy.

Cassava farming in Wonogiri Regency is not yet efficient technically, allocative, and economically. There is an opportunity to increase efficiency by optimizing input use and limiting minimum costs to reach an efficient level. Based on the overall level of input used in cassava farming, the elasticity of cassava production is in a condition of increasing returns to scale, which shows that the maximum level of profit can still be achieved by farmers by adding input in a fixed proportion. Utilizing local resources as input in farming is an effort to use input efficiently, where maintaining local advantages can be taken from existing natural attributes. Natural conditions following the growth of a plant, with the availability of agricultural production factors, can encourage the economic development of an area, especially rural areas. Rural dependence on natural conditions can be utilized by optimizing resources in efficiency to increase productivity, as factors needed in cassava farming.

CONCLUSIONS

This study analyses the efficiency and elasticity of cassava farming in Wonogiri Regency. The Data Envelopment Analysis (DEA) analysis results obtained an average technical efficiency level of 0.646 or 64.6%. The results of DEA with an input-oriented model show that farmers who are not yet efficient can increase the level of efficiency value by using cassava farming inputs. Cassava farmers in Wonogiri Regency have an allocative efficiency rate of 0.471 or 47.1%, which shows that farmers can reduce current average production costs by 52.9% to achieve potential minimum production costs. In terms of economic efficiency, cassava farmers have not yet reached an efficient level. Allocative efficiency relates to the price level of each input issued by farmers. This shows that the most important role in increasing

the efficiency is the optimal allocation of input use with consideration of the right price.

The results of production elasticity show that all production factors in the form of seeds, manure, SP36 fertilizer, Phonska fertilizer, urea fertilizer, and labour are of positive value. All factors of production except pesticides are in the rational area. The production elasticity value of each of these inputs is at the rational stage, meaning that its use has provided benefits and advantages in rural development efforts in post-covid 19 conditions. The capacity of a farm to achieve maximum production levels with a certain set of inputs refers to efficiency results. Evaluation of the level of agricultural efficiency allows decision-making for farmers. The use of inputs as a resource in farming plays an important role in the level of production and productivity of farming, so the farmer's decision in determining the level of input use is very important. The price factor for each input influences the level of allocative efficiency or cost efficiency, so farmers must try to use inputs as optimally as possible at the minimum cost level to produce the maximum possible output or level of cassava farming production.

The addition of production factors has a positive effect on cassava production. However, if farmers do not consider the right input decisions, it will result in additional input, reducing production. Increasing the production scale can be done by giving attention to using inputs as resources. From the results, there is an opportunity to improve the efficiency of cassava farming. Such conditions encourage increasing efficiency to accelerate rural development to increase the distribution of economic activities and farmers' income. This research can still be developed for future research using other methods, such as Stochastic Frontier Analysis (SFA), in analysing the efficiency of cassava farming. Other variables as input in farming can be included in the model to explore determinants of efficiency. Study development can be done by analysing off-farm cassava with a wider scope.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Аналіз ефективності вирощування маніоки як підтримки економічних змін у сільській місцевості після Covid-19 у князівстві Воногірі

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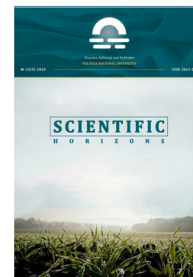
Анотація. Вирощування маніоки, як важливого товару в сільському господарстві графства Воногірі, є необхідним для структурних змін у сільській економіці графства Воногірі в умовах пост-COVID-19. Це дослідження має на меті визначити рівень ефективності та проаналізувати еластичність вирощування маніоки. Для аналізу ефективності вирощування маніоки було використано метод Data Envelopment Analysis, а для аналізу еластичності виробництва – множинний лінійний регресійний аналіз. Результати Data Envelopment Analysis з використанням моделі, орієнтованої на вхідні ресурси, показують, що фермери мають рівень технічної ефективності 64,6 %, ефективності розподілу 47,1 % та економічної ефективності 30 %. Фермери, які не є ефективними, можуть підвищити свою ефективність, використовуючи фактори виробництва маніоки. Еластичність виробництва розсади, гною, добрива SP36, добрива Фонська, карбаміду, пестицидів та робочої сили є позитивною. Масштаб бізнес-результатів показує, що фермерське господарство перебуває в стані зростаючої віддачі від масштабу. Додавання факторів виробництва має позитивний вплив на виробництво маніоки. Однак, якщо не враховувати фактори виробництва, це призведе до додаткових витрат, що знизить врожайність. Оптимальне використання факторів виробництва може збільшити масштаби виробництва маніоки та підвищити ефективність. Це дослідження може бути корисним для фермерів для підвищення рівня ефективності за рахунок ефективного використання факторів виробництва. Воно може бути корисним для уряду при розробці планів розвитку сільських територій, що включають розвиток фермерства та реалізацію політики підвищення ефективності

Ключові слова: фактори виробництва; еластичність; сільський розвиток; Кобб-Дуглас; аналіз оболонки даних

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Comparative study of organic farming systems in different geographical regions

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Abstract. Among the prerequisites for agricultural production efficiency, improved farming systems that include a cost-effective organic approach to all stages of the production process play an important role. The need for a gradual transition of agricultural land use to biological methods of soil cultivation is relevant given the high level of agricultural landscape destruction and the growing demand for organic products. The purpose of the article was to provide a comparative

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analysis of the current state of development of organic production systems in different geographical regions of Ukraine. The study was conducted using general scientific methods of cognition, the main ones being the method of system analysis and the dialectical method. In the course of the study, the situation in the field of organic farming in the regional context, reserves, and prospects of opportunities in this area were investigated. An analysis of changes in the characteristics of the area and the number of certified organic farming entities in the time period is formed. The expediency of developing organic agronomy in modern economic conditions, as well as the possibility of ensuring the environmental safety of sustainable land use by increasing the share of organic tillage in the overall farming system, is substantiated. The priority vectors of development are highlighted, the regulatory and legal support of the industry is analysed. The specifics of the process of managing enterprises with the use of modern monitoring and investment opportunities are studied, on the basis of which the main measures to optimize the situation are developed, including economic incentives for farmers, the formation of a land bank for organic farming, control of anthropogenic pressure on the environment, compliance with safety requirements and adaptation of quality standards, as well as the preservation of local ecosystems. The practical significance of the research results is manifested in the possibility of using them in the development of sectoral programmes aimed at optimizing the functioning of organic farming systems, increasing their economic efficiency, and forming the concept of transition from conventional to organic farming in Ukraine

Keywords: integrated protection; sustainable nature management; biological processing; agricultural sector; certification

INTRODUCTION

The unsatisfactory ecological condition of landscapes involved in agricultural activities, high rates of ploughed up farmland, and depleted soil fertility have a destructive impact on the quantitative and qualitative indicators of agricultural production. Given the current situation, there is a growing need to transition from traditional forms of land use to organic, ecologically sustainable and environmentally friendly ones. As of 2023, there is a global trend towards the development of organic agronomy and conservation tillage technologies. The situation in Ukraine, given the priority of sustainable development, is characterized by a gradual transition to organic farming, but the scale of the dynamics is not significant. It should be noted that the difference in the geographical location of the country's agricultural regions determines the respective peculiarities of organic land use development, and natural conditions are not always the determining factor in the process. In developed countries, there are numerous programmes and projects to optimize the condition of agricultural landscapes (Mudrak & Mudrak, 2019). Such projects aim to take a holistic approach to the problems of ecosystems affected by agricultural use and to increase the productivity and efficiency of the agricultural sector.

The issue of implementing organic farming systems has been studied in the publications of many researchers. An analysis of the results of scientific developments on the subject of the study allows concluding that most scientists pay maximum attention to comparing the traditional intensive farming system with the organic one. For example, Y.S. Sosnytska *et al.* (2019) study the algorithm of the principles of organic farming in Ukraine, and S. Amons (2022) focuses on the algorithm

of biological plant protection in the system of rational land use. Researchers A. Kharchenko & O. Onyshchenko (2020), at the same time, study the technologies and algorithms of organic land use in agriculture, and V.I. Pichura *et al.* (2022) thoroughly investigate the aspects of economic efficiency in the field.

A number of scientific publications by Ukrainian researchers study the criteria for the development and evaluation of preventive and regeneration measures of environmental, socio-economic and managerial nature aimed at improving existing strategies for the development of the organic farming system in different regions of Ukraine. S.I. Demianenko (2022) focuses on the difficulties of implementing biological land use systems in the transitional conditions of the transitional economic period, in particular, on the need for legislative regulation of activities in the field. L.I. Moklyachuk *et al.* (2020) focus on the peculiarities of the transition from traditional to ecologically oriented organic farming systems in the context of global climate change, the problems of such dynamics and ways to overcome them. A. Mudrak & H. Mudrak (2019) see environmental monitoring of Ukrainian agricultural landscapes as a basis for optimizing their condition and maximizing their efficient use.

Despite the considerable attention to the research issue by the scientific community, the issues of developing an algorithm for effectively stimulating the development of organic farming systems in Ukraine in the regional context, as well as their effective management using the capabilities of economic and legal instruments, remain insufficiently researched and require further scientific consideration. The purpose of the study was to make a comparative analysis of

organic farming systems in different geographical regions of Ukraine, with the identification of priority optimization areas for the development of the industry in the current conditions.

MATERIALS AND METHODS

In the course of the study, a number of general scientific methods of cognition were applied. The theoretical and methodological basis of the study is based on the dialectical method, the systematic approach, and the generally accepted principles of conducting comprehensive research. The systemic approach, in particular, made it possible to study the object and subject of study as a system in the entirety of interrelationships. The method of abstraction was used to identify the main categorical concepts. With its help, the concept of an integral process of the management system in the field of organic farming as a structural and consequential set of interrelations was formed. The abstract-logical and dialectical methods of scientific knowledge, as well as the method of scientific abstraction, were used in the study to clarify the conceptual apparatus, formulate theoretical generalizations and conclusions.

The general scientific methods of analysis and synthesis were used in the course of work on the article to identify the essence of the managerial and economic mechanism of the object under study, as well as to determine the strategic vectors of development of organic farming in Ukraine. In addition, with the help of analytical processing of information arrays, the peculiarities of the relationships between the elements of the phenomenon under study were recorded, the main factors of functioning and priority significant elements of the object under study were identified. The method of specification is used to record the effectiveness and feasibility of a set of management measures for regional land use systems, as well as to identify optimal conditions and solutions for the preservation of agricultural landscapes and mitigation of environmental risks in agricultural production complexes. The comparative method was used in the study to identify the specifics of the dynamics of organic farming systems based on indicators of quantitative and qualitative changes. The general scientific method of induction was used for prognostic analytics of development

features. Deduction is used in the process of formulating proposals for optimizing the management system in the field under study.

The formalization method was used to identify priority vectors for optimizing regional organic farming systems on the basis of green sustainable development, as well as to highlight the research findings that are intended for active practical use in the land use management system in the agricultural sector. In addition, the study used the method of ascending from the abstract to the concrete, in the form of a sequential transition from general abstract informative data on organic farming systems to the situation in different geographical regions of Ukraine and innovative opportunities of biological agriculture. To assess the dynamics of modern organic farming practices in different geographical regions of Ukraine, the article uses statistical data from the Ministry of Agrarian Policy and Food of Ukraine, namely, the structure of sown areas and the number of business entities. The data on quantitative indicators of organic farming were used through the Information and Analytical Portal of the Agro-Industrial Complex of Ukraine and the National Research Centre "Institute of Agrarian Economics" (Organic production in..., 2022; Ukraine ranks 20th..., 2022).

A systematic approach was used to identify the features, advantages, and effectiveness of certain solutions and approaches in the organic farming system. This approach is aimed at a comprehensive search for solutions in the modern agro-industrial complex with a focus on environmental safety, economic efficiency and ensuring the principles of sustainable development. Particular attention is paid to the need to take into account possible obstacles in the practical implementation of the organic farming strategy in the economic realities of developing countries.

RESULTS

According to the operational monitoring carried out by the Ministry of Agrarian Policy in cooperation with foreign certification bodies, as of 2023, the total area of agricultural land involved in organic farming systems was 263619 ha, which is less than 1% of the total area of agricultural land in Ukraine. The total number of business entities in the study area was 462 (Table 1).

Table 1. Organic map of Ukraine as of 2023

| Region | Total number of operators [*] | Total area of certified agricultural land, ha | Area of agricultural land with organic status, ha |
|-------------------------------|--|---|---|
| Autonomous Republic of Crimea | 0 | 0 | 0 |
| Vinnytsia | 52 | 2753 | 2618 |
| Volyn | 20 | 5182 | 5153 |
| Dnipro | 24 | 18451 | 18362 |
| Donetsk | 0 | 0 | 0 |

Table 1, Continued

| Region | Total number of operators ¹ | Total area of certified agricultural land, ha | Area of agricultural land with organic status, ha |
|-----------------|--|---|---|
| Zhytomyr | 24 | 36796 | 36077 |
| Zakarpattia | 10 | 1600 | 1566 |
| Zaporizhzhia | 12 | 32072 | 24747 |
| Ivano-Frankivsk | 14 | 351 | 341 |
| Kyiv | 24 | 36796 | 36077 |
| Kropyvnytskyi | 5 | 11831 | 11828 |
| Luhansk | 1 | 0 | 0 |
| Lviv | 21 | 2378 | 2320 |
| Mykolayiv | 23 | 1598 | 441 |
| Odesa | 40 | 40831 | 38729 |
| Poltava | 33 | 24261 | 24166 |
| Rivne | 18 | 18177 | 17772 |
| Sumy | 17 | 50 | 50 |
| Ternopil | 8 | 2080 | 2080 |
| Kharkiv | 16 | 3808 | 3790 |
| Kherson | 14 | 29413 | 29250 |
| Khmelnytskyi | 18 | 10668 | 10661 |
| Cherkasy | 12 | 2635 | 49 |
| Chernivtsi | 3 | 190 | 0 |
| Chernihiv | 9 | 9115 | 9091 |

Note: * – including 380 agricultural producers certified to a standard equivalent to EU and NOP organic legislation (USA)

Source: compiled by the authors

Organic farming is one of the most promising areas for the development of the agricultural sector in Ukraine. Over the past few years, the number of farming enterprises in Ukraine has grown significantly. This is due to the increased demand for organic food and the growing awareness of the benefits of organic products among the population. Organic farming uses natural resources and methods that are environmentally friendly and preserve biodiversity. Unlike conventional industrial farming, organic farming does not actually use chemical fertilizers and pesticides, and does not involve genetically modified plants. This makes it possible to produce high-quality and environmentally friendly food that does not pollute the environment and is of great importance for human health.

One of the advantages of organic farming in Ukraine is its economic efficiency. Organic food has a high price on the market, which allows farmers to earn high profits. In addition, organic farming allows for the export of production costs through the use of natural resources and research with pests and natural plants. However, despite the prospects of organic farming in Ukraine, there are certain problems that may slow down its development. One of them is the lack of qualified personnel. In addition, there is a lack of government support and low public awareness of the benefits of organic farming. Exports of organic products from Ukraine are characterized by a

focus on European countries, which accounted for about 80% of all Ukrainian organic exports in 2022 (Organic production in..., 2022). In 2022, 226.4 thousand tonnes of organic agricultural products from Ukraine were imported to European countries, and the trend in 2023 remains positive. In general, in 2022, Ukraine sold organic exports to more than 30 countries, including the USA, Germany, Austria, the Netherlands, Poland, the UK, Switzerland, Italy, Denmark, and Lithuania. At the same time, Ukraine's main organic exports are cereals, oilseeds and berries, as well as sunflower oil, vegetables, and fruits (Ukraine ranks 20th..., 2022). Overall, in 2022, Ukraine exported 13% more organic products to the European Union and Switzerland than in 2021, and the results of 2023 are expected to be no less impressive.

Official statistics show that as of 2002, 31 farms engaged in the cultivation of organic products were registered in Ukraine, and in 2021 there were already 528 organic producers, with the maximum increase in quantitative indicators in the study area observed in 2015-2019. At the same time, after this period, there was a slight slowdown in the positive dynamics, as shown in Figure 2. It should be noted that 2022 brought its own adjustments in the form of Russia's full-scale invasion of Ukraine, which inevitably affected all spheres of economic life. As of 2023, there are 462 certified organic farms in Ukraine (Fig. 1).

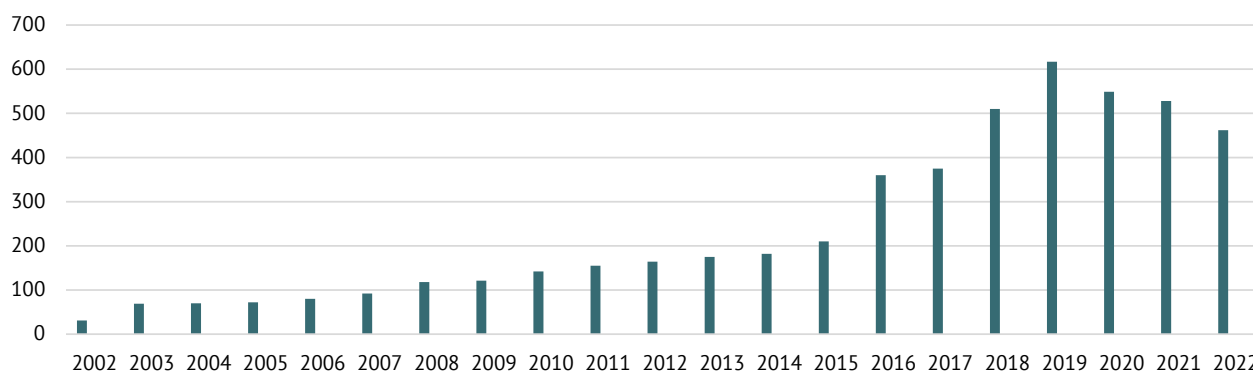


Figure 1. The number of organic farming enterprises in Ukraine in the period 2002-2023

Source: compiled by the authors

In order to ensure a systematic approach to the study of organic farming in Ukraine, it is necessary to take into account its sectoral features and benchmarks that form a model of effective biological land use. Thus, organic farming in Ukraine is a complex production complex, the effective management of which requires taking into account the specifics of the sectoral functioning in terms of resource potential, as well as ensuring its reproduction at the appropriate level. Compliance with the principles of sustainable development requires ensuring a closed production cycle at an agricultural enterprise. In other words, organic farming should be implemented under the influence of reproduction algorithms using the available production factors: organizational, economic, production, material and technical, environmental and social.

In order to minimize crop losses, it is advisable to introduce a stabilization period, which is the period of time required to carry out a set of agrochemical and reclamation measures aimed at eliminating the negative effects of previous land use and improving or stabilizing the quality of soils in order to reduce economic losses due to reduced crop yields during the transition period. This approach requires additional time and money, but it is a necessary step for growing organic agricultural products on land affected by uncontrolled anthropogenic activities and will minimize farm losses during the transition period. It was estimated that up to UAH 79 thousand per hectare of agricultural land would be required to carry out work during the stabilization period to improve the quality of soil. The amount of such costs is usually decisive when making a decision to switch to organic production.

The majority of organic farming businesses are located in Kyiv, Odesa, Kherson, Vinnytsia, Zakarpattia, Poltava, Lviv, and Zhytomyr regions. Certified farms are characterized by different sizes and scales of activity (Organic production in..., 2022). Given the tendency to increase the share of small organic farms, the priority of their specialization in terms of growing fruit and berry products, as well as the export orientation of producers, especially in terms of legumes and berries, is growing.

As of 2023, the largest area of land allocated for certified organic farming was recorded in Odesa (102 thousand ha), Kherson (76 thousand ha), Dnipro (38 thousand ha) and Zhytomyr (32 thousand ha) regions, and the largest number of enterprises in this area was in Odesa region.

Comparing the level of development of organic farming in different geographical regions of Ukraine, it is noted that the tendency of dependence of the efficiency of biological land use implementation on the optimality of natural prerequisites is very conditional. The factors of economic incentives for agricultural producers, availability of regional investment programmes, and the readiness of the agronomic sector to dynamic changes in the management system have a significant impact. Long-term intensive agriculture has led to significant environmental problems. Agroecosystems are inherently extremely energy-intensive, with poor adaptive capacity and potentially high levels of soil fertility depletion (Carter, 2020). The situation is particularly difficult in irrigated vegetable production. An alternative is organic land management, which involves covering the soil with vegetation for as long as possible (Beillouin *et al.*, 2022). Innovative technological techniques and algorithms that allow for a gradual transition from an overly intensive farming system to scientifically based biologisation will make it possible to implement European standards of sustainable development, which are understood by the international community as alternative or regenerative farming in the agricultural sector (Ramesh *et al.*, 2019).

Organic crop production, however, cannot yet fully become an alternative to conventional farming; both areas should be developed synergistically. Until recently, Ukraine has not paid attention to conducting comprehensive research on the cultivation of individual crops using organic farming methods. However, the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine has developed a system of organizational measures and technological techniques that can form the basis of a promising organic agricultural production system. The

main problem in biological farming is the proper reproduction of soil fertility. As of 2023, the ploughed-up rate of agricultural landscapes in Ukraine is 80%, and in some places it reaches 95%. Compared to similar indicators in developed countries, this figure is only 25% in the United States, 37% in Hungary, and 48% in France, Germany, and Canada (Organic production in..., 2022; Ukraine ranks 20th..., 2022). The optimal preventive way to minimize the level of ploughed up agricultural land is to create ecological buffer zones of 10%, which will allow for the preservation of natural biodiversity. Also, the use of special crop rotations is a necessary technological method of organic crop cultivation. In this case, on irrigated lands, crop rotations should be based on plant species that provide preventive protection of soil fertility and intensification of nutrients.

Organic agriculture in Ukraine is characterized by significant opportunities to increase production efficiency. It should be noted, however, that its effective implementation requires a number of managerial, financial and technological measures, including those at the national level. These include providing agricultural producers with access to up-to-date information on innovative tillage technologies and organic quality standards, ensuring certification of products of small agricultural land users, attracting investment opportunities, developing partnerships, developing a communication strategy to raise awareness of farmers, improving agricultural organic policy, stimulating innovation and research in the field of organic land use (Sosnytska *et al.*, 2019; Kharchenko & Onyshchenko, 2020). Organic agriculture has a positive impact on the balance between the economic efficiency of agricultural production and the environmental sustainability of agroecosystems. In addition, it contributes to the protection of biodiversity, the fight against genetically modified organisms, and the maintenance of soil fertility through biological means. The latter include minimizing mechanical tillage, applying organic fertilizers, and individualizing agricultural technologies and processes (Mudrak & Mudrak, 2019). Prospects for the development of organic farming include sustainable development of rural areas, high levels of crop productivity, increased interest in environmentally friendly products, growing opportunities for exporting organic products, simplification of certification and labelling procedures, and the growing role of government incentives for organic land use.

Increasing the share of organic farming will help to solve the problem of employment of the country's rural population, as well as quantitative and qualitative indicators of agricultural productivity. The introduction of a model of agricultural sector development based on organic farming provides for the implementation of the principles of sustainable landscape development and identifies priority vectors for rural development in the future. In view of the above, Ukraine's current agri-environmental policy should pay considerable attention

to the restoration of soil, preventive environmental protection and the provision of environmentally friendly products to the population. At the same time, the agro-landscape management system should be an integral part of organic land use standards. Priority areas for optimizing the industry include the development of new technological capabilities to minimize the destructive impact on soils (e.g., no-till systems) and ensure high economic efficiency of agricultural activities while preventively ensuring a sustainable environment.

It should be noted that Ukraine should take a comprehensive approach to solving these problems. First and foremost, it is about the further formation of ecologically balanced holistic terrestrial ecosystems on the basis of organic farms, which are able to ensure the harmonization of agricultural and natural lands. The NAAS institutions conduct research under the programme "Scientific basis for the development of organic agricultural production and mechanisms of its functioning in Ukraine", which defines the main directions of scientific support for the organic farming industry (Organic production in..., 2022; Ukraine ranks 20th..., 2022). Soil, agrochemical, and soil ecological research is aimed at effective assessment, zoning and regulation of the suitability of soil conditions for organic farming, as well as the development of methods for a comprehensive assessment of the environmental condition of agricultural land for their suitability for organic production and the development of alternative ways to improve and preserve soil fertility.

The development of organic production in Ukraine is hampered by the imperfection of the legislative and regulatory framework that would clearly define the state policy in this area. Other reasons include the predominance of exports, underdevelopment of the domestic market for certified organic products, limited product range (mainly grains and oilseeds), lack of consumer awareness of the benefits of organic products, lack of investment in organic production, and a poor consumer basket of these products. Despite the problems outlined in the research area, organic land use in Ukraine has significant potential that can be unlocked during the post-war recovery period with strong international support and investment opportunities.

DISCUSSION

Most modern scientists consider organic farming systems to be a priority for the sustainable development of the ecological network of agricultural areas, which provides the basis for the effective restoration and rational use of agricultural production resources in the context of reorientation of economic processes towards sustainable development. In particular, scientists T. Tschardtke *et al.* (2021) have proved that the environmental aspects of agricultural development should be based primarily on optimizing the state of the environment and focusing on the renewability of agricultural landscapes.

Scientists emphasize that the vectors of unlocking the ecological and economic potential of agricultural complexes are formed using the optimal design of organic land use development. Such results of research are in line with the findings of the current study.

Modern researcher M. Singh (2021) focuses on the need to ensure that the anthropogenic load is proportionate to the adaptive resources of agricultural ecosystems, without violating the morphological and functional parameters of the environment. It is difficult to disagree with the author, and the current study reveals a similar interdependence of the resource base and methods of its use for economic purposes. It has been established that the tasks of soil cultivation in biological farming are based not only on the economic aspect and ensuring the proper physical condition of the soil cover, but also include environmental and biological indicators, namely: preservation of soil fertility, protection against erosion, minimization of the impact of toxic substances, ensuring proper conditions for seed germination and root development, accumulation of nutrients, and reliable control of pests and diseases. The conclusions of the research by E. Durán-Lara *et al.* (2020), who consider management support for organic farming as the main prerequisite for increasing crop productivity, show that the biological land management system has significantly expanded its implementation functions, becoming a hub for the implementation of sustainable development opportunities in modern agriculture. Scientists emphasize that the processes of transition from intensive to organic farming, in the absence of appropriate preventive measures, are often accompanied by a significant destabilizing transformation of socio-economic processes. In this regard, comparing the authors' conclusions with the results of the current study, it can be argued that the main function of the land use management system is to minimize anthropogenic destructive pressure by regulating the balance between the production and natural environment, as well as appropriate preparatory measures by agricultural market participants.

Scientists F. Eyhorn *et al.* (2019) identify the main reasons for the need to maximize soil protection and conservation within agricultural landscapes, including the disruption of the ecological balance between natural and anthropogenic lands, erosion, agrophysical and agrochemical degradation of soil cover, and disruption of soil nutrient, water and air regimes. Analysing the experience of management systems in the field of organic farming, scientists have found that its functioning is usually implemented in accordance with local needs and preferences. It should be noted that in the case of Ukraine, it is important to formulate an individual strategy for the development of organic land use, which will contribute to the growth of sustainability and competitiveness of agroecosystems. M. Diacono *et al.* (2019) emphasize the fact that intensive land use

has an ecologically destabilizing and degrading effect with varying degrees of intensity in different soil and climatic zones. It is difficult to disagree with the author. In addition, scientists argue that the extremely unfavourable conditions of modern agriculture are not caused by overloading the agroecosystems with excessive doses of agrochemicals, but by violating the basic ecological principle of agrochemical processes, according to which the removal of nutrients from the soil must be compensated for in a timely, complete and high-quality manner. This trend is also evident in different geographical regions of Ukraine. As an alternative, it is worth considering a system of biological regenerative land management, which involves careful selection of crops and varieties, crop rotation design, environmentally friendly fertilization, soil-protective and resource-saving tillage, as well as agrotechnical and biological methods of plant protection. The researchers suggest the use of intermediate green manure crops, which not only enrich the soil with organic matter, but also optimize the phytosanitary situation in the soil environment and protect against erosion processes. In Ukraine, it is possible to recommend such green manure crops as oil radish, white mustard, and ryegrass.

The extensive root system of plants allows the soil to remain loose and aerated, which creates better conditions for growing agricultural products. This is confirmed in the research by M. Krauss *et al.* (2020). Degraded landscapes with minimal or no vegetation cover are vulnerable to precipitation and winds. In addition, the presence of the root system of plants significantly strengthens the soil cover, protecting it from landslides, flooding, and floods. Scientists insist that organic farming, which involves covering the soil with vegetation or its residues for a longer period of the year, is the best way out of the crisis in agricultural landscapes. These research findings are in line with the results of the current work, positioning restorative land use as a priority area for the modern agro-industrial complex. At the same time, the primary segment of the biological farming system is the ecological zoning of agricultural landscapes and soil certification.

In the studies of A. Le Campion *et al.* (2020), the authors note that the primary task of organic land use is the formation of sustainable agroecosystems that can mitigate negative climate change and help the landscape complex adapt to the dynamics of weather and climate conditions. Scientists analyse the algorithmic structure of a typical organic production scheme, arguing for the need to expand technological capabilities and the need to invest in organic farming. It should be added that renewability is a key element of sustainable landscapes, as it is thanks to them that soil and landscape ecosystems regenerate and can function effectively without requiring significant investment.

Researchers A. Gamage *et al.* (2023) actualize the synergy of organic principles of modern land use with

the principles of sustainable development. The scientists argue that organic production balances the socio-economic balance of business and society, while having a positive impact on the natural resource potential of land use. In addition, they emphasize the urgent problems of implementing the principles of sustainable agricultural management, including the difficulties of financing and investment, as well as the availability of qualified personnel. Comparing the conclusions of scientists with the results of the current study, it is worth adding that in the context of post-war recovery, Ukraine has the prospect of attracting international cooperation mechanisms and targeted investment opportunities, which expands the horizons of agro-environmental solutions. Effective incentives at the national, regional and local levels to increase the use of organic farming projects through sustainable development programmes are seen as a priority for optimizing the situation in the industry (Clunies-Ross & Cox, 2023). The expected long-term results of such a management strategy include an improved social and environmental microclimate, increased economic efficiency of projects, and a healthier environment (Parizad & Bera, 2023). Every business entity that aims to develop organic farming should evaluate it as a set of interconnections between processes (crop rotation, tillage system, plant protection, fertilization), as the productivity of the agroecosystem depends on the optimization of all parts of the farming process in terms of synchronization.

In order to preserve agricultural landscapes, it is important to make efforts to develop a sustainable system of land management and governance. Analysing and summarizing the above, the growth of the organic farming function as part of a successful management policy in the agricultural sector of modern Ukraine is becoming a prognostic prospect, which will allow significantly increasing its productivity and implementing relevant solutions in accordance with the principles of sustainable green development. In addition, the shortage of organic products on the world market opens up significant prospects for Ukrainian organic producers.

CONCLUSIONS

The study analysed the multifactorial nature of the effective functioning of agro-landscape complexes based on the principles of sustainable development. It was possible to study the current situation in the field of organic farming in Ukraine in the regional context, as well as the reserves and prospects for opportunities in this area. The changes in the area and number of certified organic farming entities in the time period were analysed. It is established that the development of biological regenerative land use systems is a significant factor in improving economic performance in the field of crop production, strengthening the priorities of agricultural greening, and optimizing the state of the agroecosystems in terms of restoration and recreation.

The expediency of developing organic agronomy in modern economic conditions, as well as the possibility of guaranteeing the environmental safety of sustainable land use by increasing the share of organic soil cultivation in the overall farming system, is substantiated. The specifics of the process of enterprise management with the use of modern monitoring and investment opportunities are investigated, and the main measures to optimize the situation are proposed, including economic incentives for farmers, formation of a land bank for organic farming, monitoring of anthropogenic impact on environmental parameters, introduction of agricultural product quality standards, and preservation of local ecosystems. The author identifies priority vectors of development, including stimulation of organic agricultural production, financial and preferential support from the state, provision of subsidies, creation of a fund of land for organic land use, and introduction of modern technological capabilities.

It is determined that the implementation of these goals should be carried out by optimizing the management policy in the field of research. It has been established that strategic planning, operational management and development of effective regeneration and preventive measures are the top priorities of agroecological landscape complexes management. Such an approach will allow for a prompt response to new challenges, including the transformation of management activities, the growing importance of safety standards, and destructive processes in natural landscape ecosystems. The study focuses on the most important aspects of the problems in the field of implementation of organic farming systems. As a result of the study, inter-sectoral gaps have been identified that require urgent elimination through regulatory and legal regulation, the establishment of strict measures of responsibility for violations, and the involvement of international levers to regulate the situation.

An effective approach to the management system of modern agroecosystems involves a synergy of efforts that can ensure an increase in their functionality, efficiency, and ability to regenerate. As a result of the study, the main directions of promising research on the topic are highlighted. The need to ensure optimization of information support on the possibilities of introducing an organic farming system in different geographical regions of Ukraine is actualized. The need to apply international practical experience in order to optimize the functioning of organic agriculture is substantiated. Such measures will provide the prerequisites for solving current problems in the field of agricultural sector functioning and identifying reserves to improve the efficiency of its activities.

The purpose of promising scientific work in this area is to formulate strategic directions for optimizing the organic farming system in different geographical regions of Ukraine, as well as to form and integrate innovative

monitoring capabilities as a basic resource for analysing and resolving the situation in the industry. At the same time, it is necessary to attract international experience, update existing and develop new methods of agricultural management based on the principles of regeneration and sustainable land use. In addition, the priority area for further research is the improvement of the institutional framework for the functioning of organic

land use within the framework of European integration and post-war regeneration of Ukraine.

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CONFLICT OF INTEREST

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Порівняльне дослідження систем органічного землеробства в різних географічних регіонах

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Анотація. Серед передумов ефективності сільськогосподарського виробництва важлива роль належить вдосконаленню систем землеробства, що передбачають ощадливий органічний підхід до всіх етапів виробничого процесу. Необхідність поетапного переходу сільськогосподарського землекористування на біологічні методи обробітку ґрунту є актуальною з огляду на високий рівень деструкції агроландшафтів та розвиток попиту на органічну продукцію. Метою статті є порівняльна аналітика сучасного стану розвитку систем органічного виробництва в різних географічних регіонах України. Дослідження проводилось за допомогою загальнонаукових методів пізнання, основні з яких – метод системного аналізу та діалектичний метод. У ході роботи досліджено ситуацію в сфері органічного землеробства в регіональному розрізі, резерви та перспективи можливостей у даній сфері. Сформовано аналітику зміни у характеристиках площ та кількості сертифікованих суб'єктів господарювання в галузі органічного землеробства у часовому розрізі. Обґрунтовано доцільність розвитку органічної агрономії в сучасних умовах господарювання, а також можливість гарантування екологічної безпеки сталого землекористування шляхом збільшення частки органічного обробітку ґрунту в загальній системі землеробства. Виділено пріоритетні вектори розвитку, проаналізовано

нормативно-правове забезпечення галузі. Досліджено специфіку процесу управління підприємствами з залученням сучасних можливостей моніторингу та інвестування, на основі чого розроблено основні заходи з оптимізації ситуації, серед яких – економічне стимулювання аграріїв, формування земельного банку для органічного землеробства, контроль антропогенного тиску на навколишнє середовище, дотримання вимог безпеки та адаптація стандартів якості, а також збереження місцевих екосистем. Практична значущість результатів дослідження проявляється в можливості використання в ході розробки галузевих програм, що мають на меті оптимізацію функціонування систем органічного землеробства, зростання показників їх економічної ефективності, а також формування концепції переходу від традиційного до органічного землеробства в Україні

Ключові слова: інтегрований захист; стійке природокористування; біологічний обробіток; аграрний сектор; сертифікація

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European Union on the way towards sustainability in the domain of food security, improved nutrition, and sustainable agriculture

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Abstract. Sustainable development was the global key issue and is in the interest of human beings. Among the 17 Sustainable Development Goals, goal 2 is significant in terms of eliminating hunger, achieving food security, and improving sustainable agriculture. The study aims to analyse the state, development, association, and convergence of indicators that are related to monitoring the European Union's countries' progress toward to Zero Hunger Goal. For analytical purposes, the univariate statistical approach was used, correlation analysis depicted the linear relationship between the variables, the sigma and Beta convergence coefficients were employed to detect the convergence progress, and the index numbers enabled to follow the changes of the indicators over time. The convergence of the agricultural factor income per annual efforts was discovered, which is a positive signal for the catching-up process of the EU countries. A positive and significant correlation between the government support for the research and development of agriculture and the agricultural factor income was determined, therefore an increase in the government support allocation for research and development for agriculture can lead to an increase of the agricultural income. The analysis highlighted a negative, significant correlation between the ammonia emissions from agriculture and the area under organic farming that supports the idea

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of increasing organic farming with benefits to the environment and population health. The study results can be used for further development of the EU's ambitions toward sustainable agriculture and nutrition

Keywords: sustainable development; zero hunger; Goal 2 indicators; organic farming; association

INTRODUCTION

The research relevance was determined by a systemic transformational change that is related to the demanding use of resources and environmental pollution in agriculture and the food industry. Therefore, it is necessary to study the efforts for sustainable economic development, and the elimination of poverty and hunger through relevant measures, which were largely unsuccessful within individual state policies.

A similar study on this topic was carried out by C.G. Gonzalez (2021), who analysed the mechanisms of minimizing the differences between the rich and the poor through development goals to minimize poverty. J. Blesh *et al.* (2019) state that agriculture is the main livelihood for 70% of the global low-income population. They identified that agriculture is closely linked to weather and climate, which is a dominant factor in the variability of food production and associated levels of hunger. In this context, B.W. Muriithi *et al.* (2018) emphasize the necessity of the restoration of a holistic focus with an emphasis on environmental, social, and economic aspects. As such, they considered the climate as an object of further research with the development of a synergistic effect involving innovations in climate research with an emphasis on food security. A. Baer-Nawrocka and A. Sadowski (2019) analysed similar approaches in their study, based on which they consider the economic and technical availability of food. Furthermore, D.C. Bezu (2018) confirms the previous results and extends his study with a household survey and identifies factors (e.g., low level of non-agricultural activities, weather influence, land degradation, population tension) that threaten food security. Most countries with high populations face food insecurity and at the same time have a high birth rate and rapid population growth, which increases the challenge of adequately meeting nutritional needs.

The need to provide timely and accurate information on climate change and climate risk management in connection with the use of innovative tools and methodological procedures is also supported in the study of H. Valin (2019). To effectively use these scientific procedures, it is necessary, according to S. Kumar *et al.* (2023) to include in climate concepts information related to different periods for managing the strategy of optimal sustainable development. In this context, J. Streimikis and T. Baležentis (2020) in their study highlight the strong partnerships between international, and national stakeholders and agricultural and research institutions, as well as community organizations that play a role in supporting the achievement of the Sustainable Development Goals (SDGs). All these researchers are

also supported by H. El Bilali *et al.* (2019) who emphasize the strong interconnection of concepts and paradigms of food sustainability. Their study results support the development of a sustainable food concept regarding the availability of food, its accessibility and use.

According to the World Health Organization (2021), all these efforts represent critical challenges that offer diverse opportunities to promote food security. Based on the knowledge gained, the study aimed to quantify the development of indicators such as poverty eradication, achieving food security and improving sustainable agriculture. At the same time, the authors of the contribution focus on a more complex view regarding global food optimality and related indicators in the social and economic field of Sustainable Development (SD).

LITERATURE REVIEW

The 2030 Agenda is underpinned by 17 Sustainable Development Goals, which were created to integrate various efforts and issues into the framework of sustainable development, including poverty reduction. The new agenda characterizes sustainable development as a holistic benefit of socioeconomic and environmental improvement while adding important aspects, such as economic inequality, justice, gender equality and climate change. Given this broader scope, the SD concept recognizes the need for a comprehensive approach to the transformation between separate goals and represents the essence of the entire 2030 Agenda, SDG 1, which should eliminate poverty. This goal is determined by other SDGs, especially SDG 2: Zero Hunger. The United Nations (UN) emphasizes that "the elimination of poverty and hunger is inextricably linked to increasing food production, agricultural productivity and incomes, especially in rural areas, as it mainly concerns small farmers and their families" (United Nations, 2023).

Food insecurity is defined by N.M. Lowe (2021) as a low level of food access. The author confirmed that moderate food insecurity is associated with irregular and inappropriate eating and obtaining sufficient nutrition, as well as insufficient food. At the same time, the study also indicated slow implementation in the effort to reduce poverty. Food insecurity fluctuations are also often related to a reduction in food intake and related malnutrition to starvation, according to M. Canfield *et al.* (2021). Although, according to the authors, the UN strives to reduce these negative impacts, monitoring the management of global food distribution is insufficient. However, as reported by X. Chen *et al.* (2023), they identified increased food stability mainly in the countries of Asia

and Africa, which was mainly caused by the increasing ratio of grain production. Despite increased food stability and productivity, M. Anderson and M. Rivera-Ferre (2021) state that the second SD goal has not been achieved, therefore this environmental-social topic needs to be addressed more deeply. F. Baquedano *et al.* (2021) stated that on a global scale, food security is considered a production and consumption problem by measuring basic economic indicators. As such, a demand-driven concept was used to assess food security in 76 countries around the world. The results showed that the low and middle-income population was not able to secure basic food. Analyses of food safety were enriched by F. Song *et al.* (2022) who identified a new indicator related to the use of arable land area for assessing the global nature of food security. F. Götmark *et al.* (2018) report that although most research analyses food security in terms of land availability and access, it is also affected by countries' population ageing. According to the authors, these dimensions represent a comprehensive approach to food availability. A study by A. Sarkar *et al.* (2021) also suggested that persistent hunger, which is an essential indicator of food security, can normally be attributed mainly to sensitive social arrangements, low salaries, environmental threats of a global nature, and unfavourable logistic networks of countries.

MATERIALS AND METHODS

For analytical purposes, five variables were used to determine the state and development of the EU countries regarding SDG 2. These metrics are part of the European Union's SDG plan and were downloaded from the Eurostat database (Eurostat, n.d.). EU plan variables, such as groundwater nitrates, were used to estimate soil erosion by water, common bird index by type of species was not included in the analysis (End hunger, achieve food security and improved nutrition and promote sustainable agriculture, 2023). The main reason for the omission of certain metrics is the lack of data availability at the state levels. The analysis was done in two periods to assess changes. The period selection depended on the data availability and characteristics. Based on the EU SDG indicator set (Eurostat, n.d.), the following indicators were included: x_1 – obesity rate by body mass index; x_2 – agricultural factor income per annual work unit (change linked volumes); x_3 – government support to agricultural research and development (Euro per inhabitant); x_4 – area under organic farming (% of total utilised agricultural area); x_5 – ammonia emissions from agriculture (kilograms per hectare).

For analytical purposes, metrics from various periods were employed to track both development vectors. The used data sets come from the statistics office of the European Union and Eurostat (Eurostat, n.d.). The exact assignment of periods depends on the data availability and analysis goal. The indicator x_1 is only available in two years, namely 2014 and 2019, for each of the EU countries. For the variable x_2 , the starting season

is 2010, i.e., representing period 1, while the second period for the agricultural factor income per annual operations unit was set to the year 2021 as the latest year with available data for each of the EU member states. The first period for the indicators x_3 , x_4 and x_5 is the average value of the mentioned variables for 2010-2016. The second period for variables x_4 and x_5 represents the average values for 2017 – 2021, while the average variable x_3 was calculated for 2017 to 2022. The calculated averages were used to eliminate certain random annual fluctuations of the observed metrics. The average variables in the second period were calculated from 2017 to 2021 or from 2017 to 2022 depending on the dataset availability. The two-period analysis was used to follow the most important relative and absolute changes of the SDG 2 indicators (Eurostat, 2023). Fixed-base metric indexes were used to discover the cumulative change of the variables over a broader period.

For the analysis of a metric, the univariate statistical approach was selected (Loveday, 2016), the metrics were characterized by their average level, minimum, maximum, range, standard deviation and/or coefficient of variation (CV). The relative measure of variability, in other words, the coefficient of variation, is suitable for comparing the variability in different time spans or different indicators. The CV is part of the so-called sigma convergence coefficients. M. Simionescu (2014) and R.C. Das (2016) discovered that the regions and countries converge if the CV is declining. Closely related to sigma convergence is the Beta convergence process, which can be explained as a process in which poorer regions and countries grow faster than the richer ones and so the poorer regions catch on them. As R. Witte and J. Witte (2017) stated, the linear correlation between a pair of variables can be defined using Pearson's correlation coefficient. The analysed metrics were downloaded from the Eurostat web page (Eurostat, n.d.).

RESULTS AND DISCUSSION

Obesity is a serious problem in developed countries and is associated with the risk of noncommunicable, chronic diseases like heart disease, certain cancers, hypertension, type-2 diabetes, and stroke. As the obesity rate is considered a destimulant indicator, a decline in its values is rated positively (European Commission, 2022). The analysis of relative and absolute changes in two different periods was conducted to detect the direction of obesity changes. The obesity rate (Fig. 1) for the EU-27 increased from 15.4% in 2014 to 16.5% in 2019, which is a negative tendency. In 2014 the obesity rate ranged from 9.4% to 26.0% while in 2019 it ranged from 10.9% to 28.7%. In 2014 the lowest values were typical for Romania (9.4%), Italy (10.8%) and the Netherlands (13.3%), while the highest rates were achieved in Hungary (21.2%), Latvia (21.3%) and Malta (26.0%). Before 2019, the position of the countries that belonged to the best group and the worst group did not change significantly.

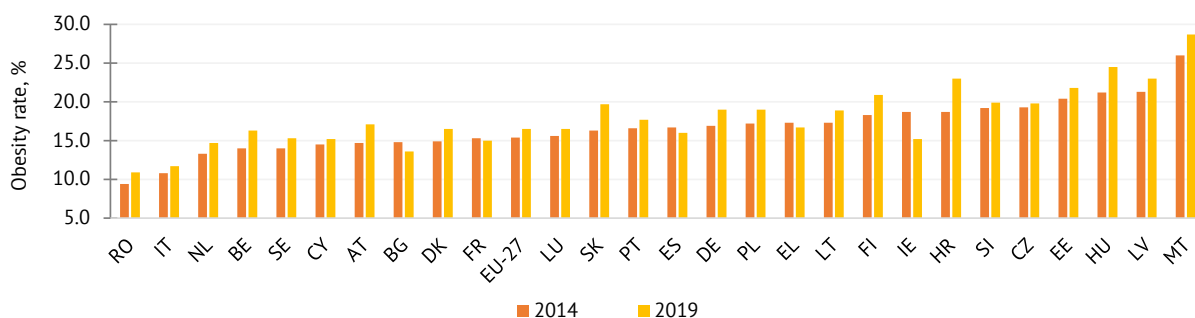


Figure 1. Obesity rate in 2014 and 2019 (%)

Source: based on presentation of the data downloaded from the Eurostat database (n.d.)

An increase in obesity rate was noted in most of the EU countries in the analysed period while a decline was noted only in five EU countries, namely in Ireland, Bulgaria, Spain, Greece, and France. From 2014 to 2019, the highest absolute decline of the obesity rate by 3.5 percentage points (p.p.) was noted in Ireland and the highest increase in Croatia by 4.3 percentage points. Alongside the average obesity rate for the EU-27 increase, the relative variability measured by the coefficient of variation also deteriorated (from 21.6% to 23.6%) and, therefore, no sign of obesity rate convergence was present.

The agricultural factor income per annual operations unit in Euro, 2010, was low in the “new” EU member states while high in the “older” member states (Fig. 2). These results were expected as the less developed

countries in the EU are the countries that joined the EU in 2004 or later. The most notable fact from the x_2 metric analysis is a strong convergence process, indicated by the real cumulative growth. The cumulative real growth between 2010-2021 was higher than 100% in Hungary, Slovakia, and Bulgaria (229.6%). The convergence of the less developed countries is possible since the countries with a low agricultural factor income per annual work in 2010 faced a strong real growth of this indicator and, therefore, these countries can be found in the upper left corner of the presented Figure 2. On the other hand, the countries with a high level of this indicator in 2010 reached a low real increase or a real decrease of the analysed variable. These countries can be found in the lower right corner of the presented Chart 4.

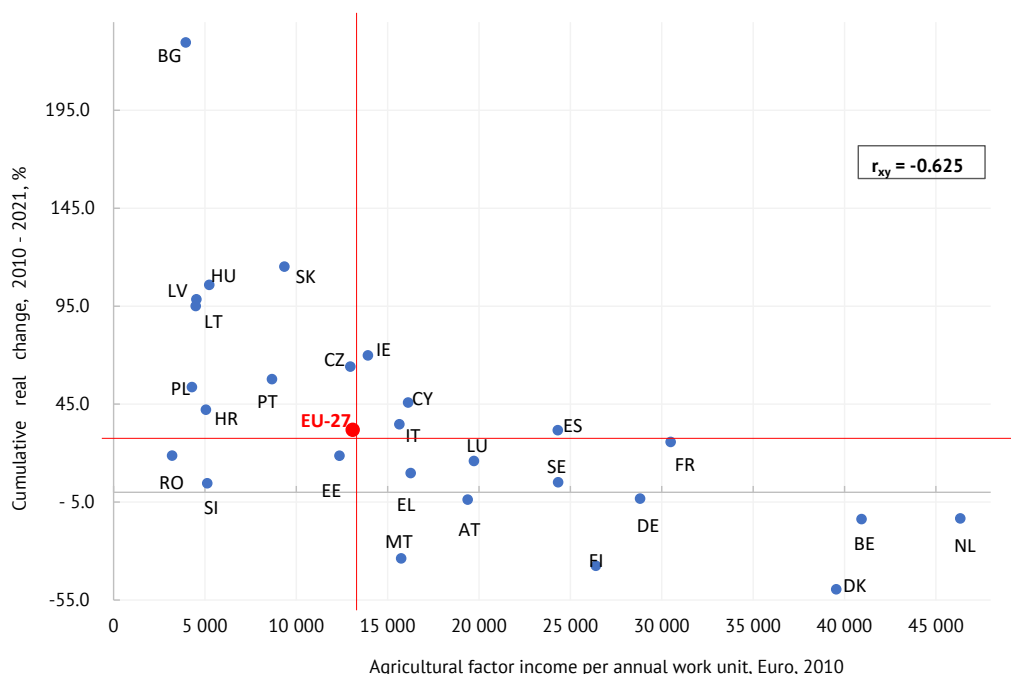


Figure 2. Agricultural factor income per annual work in the EU in 2010-2021

Note: EU countries country codes: BE-Belgium, BG-Bulgaria, CZ-Czech Republic, DK-Denmark, DE-Germany, EE-Estonia, IE-Ireland, EL-Greece, ES-Spain, FR-France, HR-Croatia, IT-Italy, CY-Cyprus, LV-Latvia, LT-Lithuania, LU-Luxembourg, HU-Hungary, MT-Malta, NL-the Netherlands, AT-Austria, PL-Poland, PT-Portugal, RO-Romania, SI-Slovenia, SK-Slovakia, FI-Finland, SE-Sweden

Source: based on presentation and calculations based on data downloaded from the Eurostat database (n.d.)

The high negative value of the correlation coefficient points out a strong β -convergence process, while the decline of the coefficient of variation from 92% in 2010 to 56.7% in 2021 depicts a strong Sigma convergence process. This development can be considered as a positive notion. The government budget allocation for Research and Development (R&D) for agriculture in most of the EU countries is lower than the EU-27 average (Fig. 3). To avoid a comparison of data that could be affected by certain annual fluctuations of the x_3 indicator, the average values for time spans 2010-2016 and 2017-2022 were calculated. The average value of the government support allocation for R&D for agriculture ranged from 0.7% to 19.7% from 2010 to 2016 and

from 0.6% to 20.1% from 2017-2022. The notably insufficient government backing for agricultural research and development in Luxembourg, Croatia, and Malta during 2010-2016, and in Luxembourg and Romania in the subsequent period, stands out, given that the indicator x_3 in these nations fell below 1.2%. Among the countries, with a higher than the EU-27 average governmental budget allocation for R&D for agriculture, the older and more developed EU member states can be found. The new and less developed EU countries offer lower support for R&D in general, which can also be reflected in their allocations for research and development for the agricultural sector of the economy, which was also low.

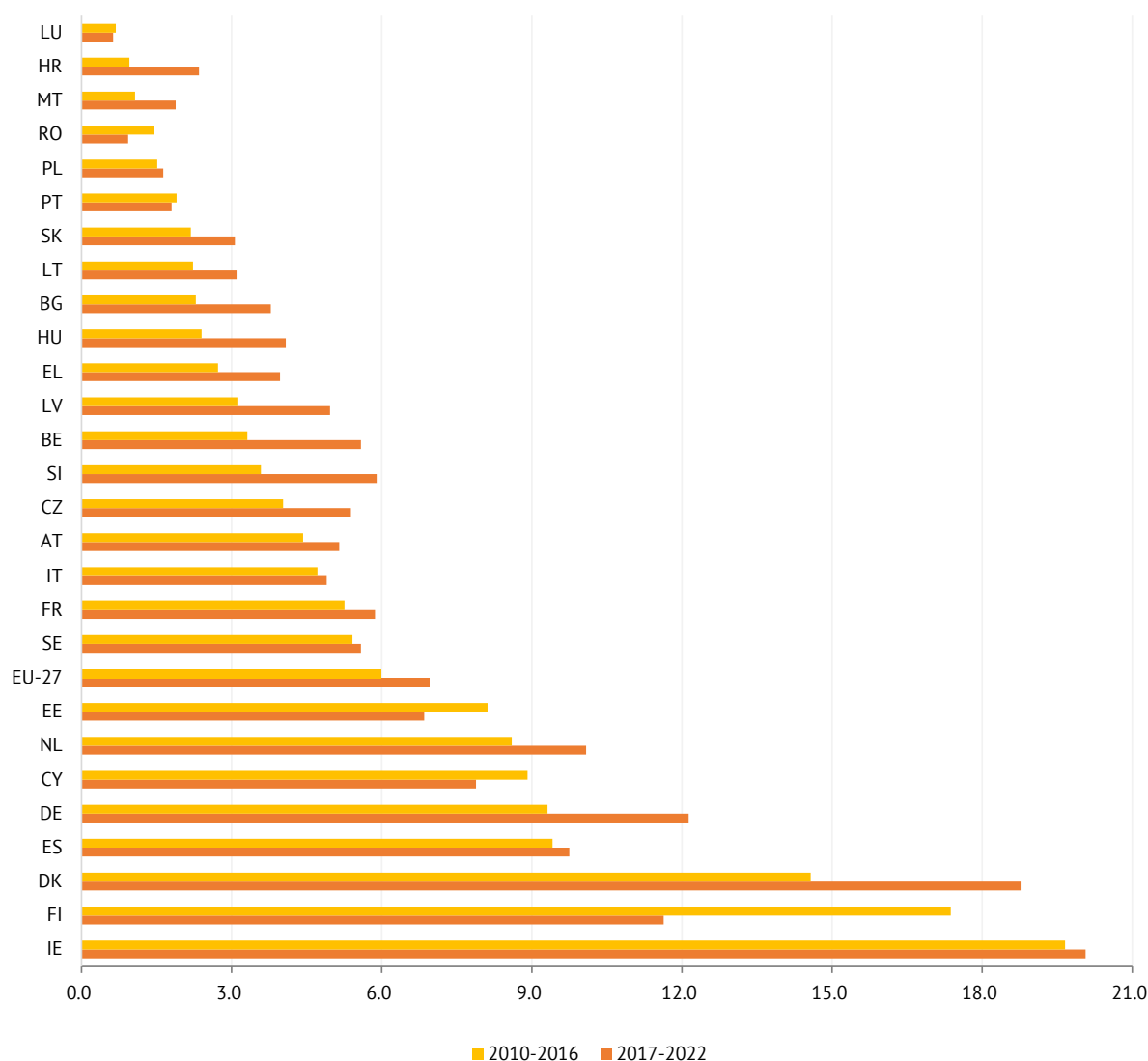


Figure 3. Government budget allocation for R&D for agriculture, Euro per inhabitant in 2010-2016 and 2017-2022
Source: based on presentation and calculations based on data downloaded from the Eurostat database (n.d.)

The only indicator among the EU SDG indicator set used to measure the progress toward SDG 2 with a targeted value for 2030 is the area under organic farming.

The percentage of total utilised agricultural area under organic farming should be as high as 25% in 2030. In 2021, only in one country, namely Austria, the indicator x_4 overpassed this threshold (Fig. 4).

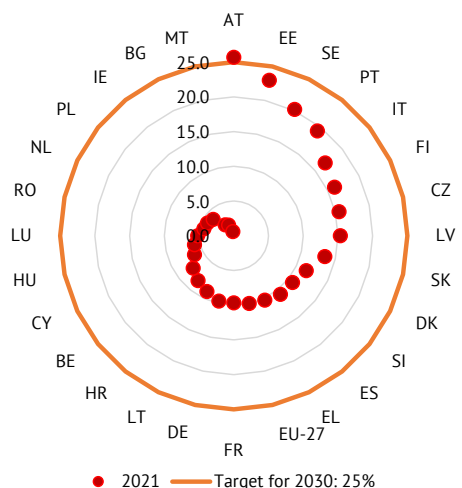


Figure 4. The area under organic farming in 2021 and the target for 2030 (percentage of total utilised agricultural area)

Source: based on presentation based on data downloaded from the Eurostat database (n.d.)

Organic production can help reduce public health risks to the population and, surprisingly, organic farming areas in some countries are only 0.6% (Malta) or 1.7% (Bulgaria). In 2021, the distance to the targeted value was lower than 10 p.p. in seven EU countries

while it was higher than 15 p.p. in 14 countries. The state of indicator x_4 presents a low interest of the countries to invest time and money to extend the area under organic farming to an acceptable level also in a situation when it is clear, that organic production has an important positive effect on the health and nutrition of the population. The leader among the EU countries in case of the indicator x_4 , Austria, should be a good example that it is possible to increase the area under organic farming to much higher percentages compared to other EU members and so to offer organic food with higher nutrition, to cut pollution due to organic farming or to combat climate change. The positives of organic farming are uncountable not only from the quality and nutrition benefits but also from the environmental aspects of the production. But still, most of the EU countries did not catch the positives of organic farming and so still the percentage of the total utilised agricultural area under organic farming is incomprehensibly low.

The average ammonia emissions from agriculture measured in kilogram per hectare ranged from 6.8 to 113.2 in the period 2010-2016 and from 7.0 to 112.0 in the period 2017-2021 (Fig. 5). Not only the range did not change significantly during the analysed period but also the coefficient of variation showed no significant change as it declined from 21.9% to only 21.4% in the analysed periods.

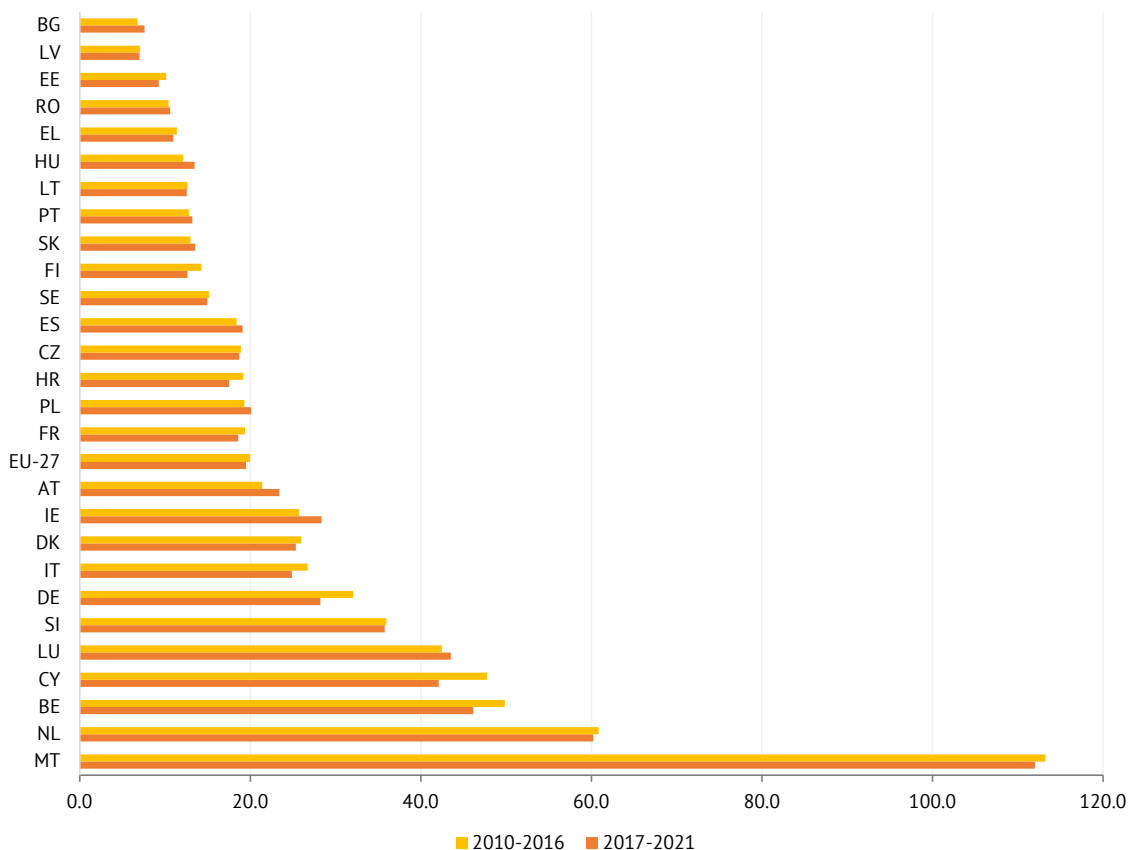


Figure 5. Ammonia emissions from agriculture, kilograms per hectare in 2010-2016 and 2017-2021

Source: based on presentation and calculations based on data downloaded from the Eurostat database (n.d.)

The highest ammonia emission from agriculture was typical for Malta, the Netherlands and Belgium with no change of their worst positions in 2010-2016 and 2017-2021. Conversely, the exceptionally low level of indicator x_5 in the more recent EU nations, particularly Bulgaria, Latvia, and Estonia, merits a positive rating, considering that agricultural ammonia emissions were below 10 kilograms per hectare. A most significant decline in relative terms was achieved in Germany, where the indicator x_5 shrunk by 12% (from 32.1 kg to 28.2 kg per hectare) in the analysis of two periods. A high relative decline was achieved in Cyprus (11.8%) and Finland (11.3%). The atmospheric ammonia negatively affects the air quality, it significantly contributes to $PM_{2.5}$ air pollution and, thus, the ammonia generates substantial health

damages, which can cause chronic respiratory illnesses, lung damage, irritation of the eyes and nose, and premature mortality.

The correlation analysis discovered an interesting linear relationship between the analysed indicators (Table 1). Moderate, positive, and statistically significant correlation between the agricultural factor income per annual yield unit and the government support for agricultural research and development in both analysed periods means, that in a country with a higher government support for agricultural research and development also a higher agricultural factor income is expected and vice versa. An increase in the agricultural factor income is therefore possible through an increase in government support for research and development in the agricultural sector of the economy.

Table 1. Pearson Correlation Coefficients

| Pearson Correlation Coefficients, N=27 Prob > r under H0: Rho=0 | | | | | |
|--|----------------|----------------|--------------------|--------------------|--------------------|
| Indicator | x_{1_2014} | x_{2_2010} | $x_{3_2010-2016}$ | $x_{4_2010-2016}$ | $x_{5_2010-2016}$ |
| x_{1_2014} | 1.000 | -0.294 0.14 | -0.023 0.91 | -0.039 0.85 | 0.259 0.19 |
| x_{2_2010} | -0.294 0.14 | 1.000 | 0.470 0.01 | 0.027 0.89 | 0.371 0.06 |
| $x_{3_2010-2016}$ | -0.023 0.91 | 0.470 0.01 | 1.000 | 0.046 0.82 | -0.029 0.89 |
| $x_{4_2010-2016}$ | -0.039 0.85 | 0.027 0.89 | 0.046 0.82 | 1.000 | -0.370 0.06 |
| $x_{5_2010-2016}$ | 0.259 0.19 | 0.371 0.06 | -0.029 0.89 | -0.370 0.06 | 1.000 |
| Indicator | x_{1_2019} | x_{2_2021} | $x_{3_2017-2022}$ | $x_{4_2017-2022}$ | $x_{5_2017-2022}$ |
| x_{1_2019} | 1.000 | -0.406 0.04 | -0.169 0.40 | 0.028 0.89 | 0.282 0.15 |
| x_{2_2021} | -0.406 0.04 | 1.000 | 0.414 0.03 | 0.034 0.87 | 0.204 0.31 |
| $x_{3_2017-2022}$ | -0.169 0.40 | 0.414 0.03 | 1.000 | 0.027 0.89 | 0.011 0.96 |
| $x_{4_2017-2022}$ | 0.028 0.89 | 0.034 0.87 | 0.027 0.89 | 1.000 | -0.402 0.04 |
| $x_{5_2017-2022}$ | 0.282 0.15 | 0.204 0.31 | 0.011 0.96 | -0.402 0.04 | 1.000 |

Notes: *p* values in italics, statistically significant ($p < 0.05$) linear correlation in bold

Source: based on calculations based on data downloaded from the Eurostat database (n.d.)

The discovery of a moderately negative and statistically significant linear connection between agricultural ammonia emissions and indicators of organic farming areas is particularly intriguing. This finding is a valuable notion, as in case of an increase in the area under organic farming a decline of the ammonia emissions from agriculture is expected. As such, with organic farming not only the consumption of food with higher quality is expected, but the next benefit for the population would be a decline in the ammonia emissions from

agriculture. The population will benefit from organic farming due to the shrinking of the negative emissions from agriculture which will help to reduce some non-communicable diseases.

Comparing the results and conclusion obtained in this study with the results obtained by other scientists, it is worth noting the convergence process of some macroeconomic characteristics in the EU over time (Simionescu, 2014; Das, 2016). The results are in line with other researchers regarding ammonia emissions,

pollution, and its negative impact on population health (Ma *et al.*, 2021; Wyer *et al.*, 2022) and the fact, that due to the increase of the area under organic farming the ammonia emissions from agriculture is declining. There is evidence that in upper-middle and high-income countries, overweight and obesity (FAO, 2019) is a huge social, economic and health challenge that should be monitored very closely. According to the publication of Eurostat (2023), non-systemic access to food, which reflects poverty and social exclusion, also occurs at the EU level. It was identified based on the increase in the number of inhabitants who had limited access to food, as well as the inappropriate geopolitical conditions of food chains, which increases the coefficient of relative as well as the absolute value of poverty. The study results highlight that, before the start of the COVID-19 pandemic, one in five European citizens was at risk of poverty, while less than 7% of the European population could not afford meat or fish products. As a result of the impact of the pandemic, this percentage has increased to almost 9% of the European population. The COVID-19 pandemic has also adversely affected food stability by disrupting long-term supply chains, further exacerbating poverty, resulting in reduced purchasing power and reduced demand for food waste (Clapp & Moseley, 2020). FAO (2019) also stated that the world is not on track to meet the SDGs. The rapid expansion of industrial agriculture after World War II caused a global decline in both wild and domesticated animal and plant species. J. von Braun *et al.* (2021) react to this situation in their study with critical claims that governments ignore those stakeholders who suffer most from the failure to meet the broad goals of SD. At the same time, they draw attention to low-quality and unreliable data in several countries of the world. D. Banik (2019) shared a similar opinion and also emphasized the importance of integration in the socio-economic and environmental fields. Yet, this approach demands more than just intersectoral coordination through information sharing; it necessitates interdisciplinary research as well. Even though the SDGs are not binding for countries, it is assumed that individual governments will take responsibility for the processing of national frameworks, which are supposed to help in achieving the "global goals".

The study brought an important and up-to-date analysis of the state and development of the indicators that are part of the EU SDG indicator set used by the EU for monitoring to progress toward sustainable development of the EU member states. The challenges require more innovative approaches and strategies to agricultural and food systems that address both the pandemic, such as coronavirus, and climate challenges (Rasul & Molden, 2020). Lessons from best practices suggest and provide an opportunity to accelerate the changes to even more sustainable and resilient food systems and redound to climate change mitigation (McNeill, 2019).

Measures to address the challenges of the COVID-19 pandemic can be linked to increased agricultural sustainability and improved resilience of food systems by investing in natural capital and embracing economic, ecological, and social considerations in the production, distribution, and consumption of food (HLPE, 2020). While pointing out that health issues are a priority in the short term, in the long term, government policies and actions are required to prioritize agricultural sustainability and constructing healthy food systems (Watts *et al.*, 2020). Policy decisions should focus on meeting urgent public health and food requirements, ensuring long-term resilience and sustainability in agriculture, as well as considering the impacts of climate change.

CONCLUSIONS

The development of the indicators that are used by the EU authorities to follow the successes or failures toward the SDG 2 was positive with only one exemption. The obesity rate, as a significant health determinant, increased in most of the EU countries, on average for the EU-27 it increased from 15.4% in 2014 to 16.5% in 2019. The indicator of annual agricultural factor income per worker exhibited a noteworthy positive shift, notably increasing in real terms within countries that initially had low productivity at the start of the analysed period. This shift notably contributed to the convergence of this indicator. In Bulgaria, the real agricultural factor income jumped by 229.6% between 2010 and 2021. The Government support for agricultural R&D is unfortunately low in the "new" less developed EU countries. The EU should increase the support of organic farming as this indicator has a target value for 2030 at 25%. In 2021 only Austria achieved this milestone, while the EU average achieved 10%. The ammonia emission from agriculture did not change significantly over the analysed period. The highest ammonia emissions from agriculture in 2021 were achieved in Malta (120.4 kilograms per hectare) while the lowest was in Latvia (6.8 kg per hectare). A noteworthy correlation was discovered between the ammonia emissions from agriculture and areas under organic farming. This correlation was negative and significant, which means that in a country with a higher proportion of area under organic farming, a lower ammonia emission is expected and vice versa. This is an important message for the EU countries that should more intensively support the formation of areas under organic farming. The benefit of such support will result in the decline of ammonia emissions from agriculture and the production of food with higher quality. Both positives will result in a better environment, better nutrition, and improvement of the public health of the population. Further research should concentrate on challenges of sustainability all over the world: countries face challenges on how to transform agriculture and food systems to be more resilient and climate-smart to severe global turns.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Європейський Союз на шляху до сталого розвитку у сфері продовольчої безпеки, поліпшення харчування та сталого сільського господарства

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Анотація. Сталий розвиток є ключовим глобальним питанням і відповідає інтересам людини. Серед 17 Цілей сталого розвитку, ціль 2 є важливою з точки зору подолання голоду, досягнення продовольчої безпеки та покращення сталого сільського господарства. Метою дослідження було аналіз стану, розвитку, зв'язку та конвергенції індикаторів, які стосуються моніторингу прогресу країн Європейського Союзу на шляху до досягнення Цілі «Нульовий голод». Для аналітичних цілей використовувався одновимірний статистичний підхід, кореляційний аналіз показав лінійний зв'язок між змінними, коефіцієнти сигма та бета конвергенції були використані для визначення прогресу конвергенції, а індексні показники дозволили простежити за змінами показників у часі. Було виявлено зближення показників доходу на фактор сільськогосподарського виробництва в розрахунку на річні зусилля, що є позитивним сигналом для процесу наздоганяючого розвитку країн ЄС. Визначено позитивну та значущу кореляцію між державною підтримкою досліджень і розробок у сільському господарстві та сільськогосподарським факторним доходом, тому збільшення державної підтримки на дослідження і розробки у сільському господарстві може призвести до зростання сільськогосподарського доходу. Аналіз виявив негативну, значущу кореляцію між викидами аміаку в сільському господарстві та площею органічного землеробства, що підтверджує ідею збільшення органічного землеробства з користю для довкілля та здоров'я населення. Результати дослідження можуть бути використані для подальшого розвитку амбіцій ЄС щодо сталого сільського господарства та харчування

Ключові слова: сталий розвиток; нульовий голод; індикатори Цілі 2; органічне сільське господарство; асоціація

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Ukrainian agricultural labour potential management modelling in the context of European integration

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Abstract. Research related to the labour potential in agriculture is relevant as the agricultural sector is one of the key sectors of the economy of Ukraine, and the integration of the country into the EU opens up new opportunities and requires the appropriate adaptation of management approaches to achieve competitiveness and sustainable development in the field of agricultural activity. The study aims to analyse, develop, and improve already existing strategic approaches to the management of the labour potential of Ukraine in agriculture, addressing the processes of integration

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into the European Union. Analytical, statistical, functional, system analysis, deduction, synthesis, and comparison methods were used in the study. The state of labour potential in agriculture was analysed, assessing the qualitative and quantitative composition of employees, their skills and education. The influence of European integration on the agricultural sector, in particular its requirements and opportunities for development, was studied, and a model of management and development of labour potential for the effective functioning of agrarian business was developed. The application of the strategy at the agricultural enterprise AgroGeneration was modelled. Working conditions and social protection of workers were studied, prioritizing the formation and development of personnel potential in the agricultural sector. The study determined that the management of labour potential in agriculture involves the use of a comprehensive strategy that would include industry specifics, European standards, innovative approaches, and best practices of other countries. The practical significance of the study lies in the development of specific practical recommendations and strategies for management bodies, agricultural enterprises, as well as agricultural workers to optimize the use of labour potential

Keywords: labour productivity; management optimization; competitiveness; working conditions; social protection

INTRODUCTION

Labour potential management is an important component of modern management and strategic development in various economic sectors. This issue is especially relevant in the context of agriculture, which is not only a key industry for many countries but also an important factor in ensuring food security and the sustainable development of the nation. Agriculture plays an integral role in the global economic landscape, providing not only food but also a significant number of jobs. However, effective management of labour potential in agriculture is a crucial task, as it allows to optimise the use of human resources, increase labour productivity, ensure decent working conditions, and contribute to the sustainable development of the agricultural sector. On the other hand, Ukraine's integration into the European Union opens up new horizons and requires the country to comply with European standards in all sectors of the economy, including agriculture. This makes the problem of effective management of labour potential in agriculture even more important and justified in terms of achieving successful integration and competitiveness in the international arena.

According to S.O. Dotsyuk (2021), a need to update the staffing and improve the skills of agricultural workers exists. This is necessary to meet European standards, increase productivity and maintain the competitiveness of the agricultural sector. This may include training programmes for farmers and farm workers, as well as the creation of favourable conditions for continuous learning and development of employees. According to V.I. Dudkevych (2021), Ukraine's integration into the European Union can be successful if labour conditions are improved, resources are used more efficiently, and the competitiveness of the agricultural sector is enhanced. For example, this could include the development of innovative agricultural methods that meet European standards, as well as measures to improve the quality and efficiency of farmers' work.

O.F. Yevsiukov *et al.* (2023) demonstrated the need to develop a system of training and professional

development of agricultural personnel. Optimising human resources through training and adaptation to new standards is a key element of a successful integration process. However, a need exists to develop programmes and initiatives to improve the skills of agricultural professionals, as well as to improve the quality of educational institutions that train personnel for the agricultural sector.

V. Voronina (2022) confirmed that optimisation of labour potential management will help to create favourable conditions for adaptation to European standards and increase the competitiveness of the agricultural sector of Ukraine. This requires reforming the human resource management system in agriculture. V. Onegina (2023) emphasises that systematisation and optimisation of working conditions contribute to the attraction and retention of highly skilled professionals, which is key to the competitiveness of the agricultural sector in the international context. The study results can be used to develop policies aimed at improving working conditions and creating an attractive environment for agricultural professionals.

In general, the need to upgrade and improve the skills of agricultural personnel to meet European standards and increase labour efficiency is needed. Integration into the EU requires effective management of labour potential and ensuring the competitiveness of the agricultural sector. The study aims to develop strategies for effective management of the labour potential in Ukrainian agriculture, considering the need to comply with European standards and ensure sustainable development of the agricultural sector.

MATERIALS AND METHODS

The study was based on official documents and reports of the State Statistics Service of Ukraine, as well as materials from the Official Website of the European Union, which describes such programmes as CAP Overview (2023), Horizon (2020) and European Green Deal (2020). The research on the situation with labour potential

in Ukraine was carried out using methods that reveal the content of the object. The analytical method was used to examine certain aspects of the labour potential management system to study their characteristics, interrelationships, and impact on the overall result. The staff composition and qualification level of agricultural workers were analysed to identify the need for further training and education.

The statistical method was used to study data on the level of employment in the agricultural sector and to analyse labour productivity and wages. The functional method was used to study the role of each element of the labour potential management system. By studying the functions of the HR department in the agricultural sector, it is possible to note how it contributes to the formation and optimisation of human resources. The system analysis helped to consider labour potential management as a complex system where each part is interconnected with the others. The impact of various factors (social, economic, political) on management and its results was considered.

The use of the deduction method allowed us to explore the general principles and concepts of labour potential management that are relevant in the European context. The synthesis method helped to combine or combine different elements, concepts, and aspects to create a new holistic view. In the context of workforce management, it helped to create an understanding of innovative strategies that combine the best aspects of existing approaches and other sources. The comparative approach was used to compare approaches to labour force management in agriculture in Ukraine and the EU. This allowed us to understand the strengths and weaknesses of each approach to identify the best strategies for achieving different strategic goals.

The study was conducted with the disclosure of several aspects, including theoretical and practical components. The theoretical aspect includes the analysis of various theories and models of human resources and labour potential management that can be applied in the context of agriculture. The study also examined global and European labour management standards related to ensuring labour quality in agriculture. Another aspect includes the use of modelling techniques to help create simulation models and conduct scenario analysis to identify optimal strategies for managing labour potential in Ukrainian agriculture in the context of European integration.

Based on the results obtained, specific recommendations will be developed to improve the efficiency of the sector and address the challenges that will contribute to the development of agriculture in Ukraine. In general, these actions are aimed at determining the feasibility of increasing the labour potential for the successful development of the agricultural sector and the country as a whole.

RESULTS

Human capital is an essential factor in the sustainable development of organisations and countries. This concept encompasses the set of capabilities and reserves of employees and organisations to achieve high levels of productivity and successful performance. The first aspect of labour potential that requires more detailed consideration is human resources. This component covers all working-age individuals who are part of a particular organisation or the population of the country as a whole. The impact of these resources on the productivity and performance of an organisation or industry is obvious. Having a competent and motivated workforce contributes significantly to an organisation's performance and productivity. It is necessary to research and understand how this aspect of the workforce can be optimised to achieve the best results (Sedyastuti *et al.*, 2021).

Health and performance are extremely important components of labour potential. The physical and psychological health of employees has a crucial impact on their productivity and ability to perform their duties effectively. Organisations should take a proactive interest in maintaining the health of their workforce, as this contributes to the stability and effectiveness of their employees. Measures aimed at maintaining and improving employee health can include medical programmes, fitness initiatives, psychological support, and the creation of a favourable working environment that contributes to the overall well-being of employees and, as a result, leads to increased productivity and the achievement of organisational goals (Kabeer, 2021).

Education and qualifications play a key role in shaping labour potential. The level of education and professional skills of employees directly affect their productivity and ability to adapt to new tasks and technologies. Motivation is also a significant factor, as it determines the extent to which employees are willing to devote attention and effort to achieving common goals. An effective system of incentives and motivation can significantly increase employee performance and improve job satisfaction. To achieve this effect, organisations should consider a variety of motivational methods, including financial incentives, professional development opportunities, recognition of achievements and social status. The incentive system should be transparent and fair so that employees feel that their efforts are valued and rewarded according to their contribution (Bawa, 2017).

Socio-economic conditions also affect labour potential by creating a favourable or unfavourable environment for work. Economic conditions, employment rates and social guarantees have a significant impact on labour potential. Professional development is another important component of labour potential. Training and skills development contribute to improving skills and adapting to modern requirements (Marginson, 2019). Understanding and optimally managing these components is crucial for the success and sustainable

development of organisations and countries. Managing human capital is an important element of a development strategy aimed at achieving high efficiency and competitiveness.

Labour potential management is a process of targeted influence on the human resources of a business structure, in which it is necessary to focus on establishing a match between the organisation's goals and the capabilities of employees. One of the elements of management activities is human resources management, which is based on a generalised view of the employee's

place in the organisation. The main goal of labour potential management is to ensure an optimal balance of processes of renewal and preservation of the quantitative and qualitative composition of personnel following the needs of the organisation itself, the requirements of the current legislation and the state of the labour market. The human resource management model is presented in the form of a diagram that demonstrates the relationship between the strategic directions of the enterprise's development and the methods of human resource management to achieve optimal business results (Fig. 1).



Figure 1. Human resource management model

Source: compiled by the authors

This model consists of several key elements. Firstly, it is based on the organisation's economic development strategy, which defines the company's goals and strategic directions. The next component is the human resource management strategy, which defines how the company plans to manage its workforce to achieve its strategic goals. The third aspect is the specific tools used to implement the HR strategy, such as incentive systems, staff development programmes. Next, there is the organisational structure of human resources management, which describes how HR management is organised. Finally, some indicators determine the effectiveness of human resource management through metrics that measure productivity, employee satisfaction and other aspects of human resource management. This model helps an organisation to optimise its human resources to achieve its strategic goals and improve its business.

Theoretical models of labour potential management highlight the main components of human resources management in institutions and companies. The purpose of these models is to optimise the use of

employees, increase their productivity and ensure the sustainable development of organisations. The competency-based management model pays attention to the development of employees' abilities and their adaptive potential to ensure that they are well-prepared to perform tasks and adapt quickly to changes. This model recognises that each employee has unique abilities and potential that can be developed. The organisation provides opportunities for education, training, and skill development to help employees become more competent and effective in their positions. Assessment of staff competencies helps to identify existing strengths and areas for further development. Based on the results of this assessment, strategic staff development plans are developed, which include learning and training plans and projects to develop new skills and abilities (Miranda *et al.*, 2017).

The transformational management model aims to change the organisational environment and corporate culture to create a stimulating environment for employees where they can develop their abilities and fulfil their potential. It aims to foster creativity, develop

leadership skills, and support employee initiatives. It emphasises the importance of education, training, and career development opportunities to help employees develop their skills and abilities. The transformational model also encourages employees to realise their potential and contribute to the organisation by giving them a sense of ownership in achieving common goals (Thomson III *et al.*, 2016). The systemic model of human resource management considers employees and the organisation as interconnected elements of a system. It involves studying and analysing the needs, goals, and internal processes both at the level of the individual employee and at the level of the organisation as a whole. The main idea is to ensure harmony between individual and organisational goals. This may include developing individual career plans and providing opportunities for professional development (Kim *et al.*, 2020).

The capability management model emphasises the importance of developing employees' skills and capabilities. Organisations that use this model provide employees with access to learning programmes, training, and resources so that they can improve their professional skills. The main goal is to ensure that employees are best prepared to perform their duties and

can quickly adapt to changes in the work environment (Hock-Doepgen *et al.*, 2021). The motivation management model focuses on creating a motivational atmosphere in an organisation. It involves using a variety of methods to encourage employees to achieve high performance. This may include bonus systems, rewards for achieving certain goals, and fostering creativity and leadership development. The goal is to make employees feel motivated and satisfied with their performance, which leads to higher levels of performance (Buchner, 2007). These theoretical models are the basis for the development of practical strategies and methods for managing labour potential in modern organisations. It is important to keep in mind that companies can use elements of different models depending on their characteristics and strategies to achieve success and sustainable development.

Agriculture in Ukraine is a key sector of the country's economy, providing food production, job creation and gross domestic product. The analysis of the labour potential of agriculture involves an assessment of important aspects related to the labour force and its efficiency in this sector of the economy. Table 1 analyses the main indicators of labour potential in agricultural activities.

Table 1. Indicators of Ukraine's labour potential in agriculture

| | 2018 | 2019 | 2020 | 2021 | 2022 | Deviation (-/+), 2022 Up to 2018 |
|--|--------|--------|--------|--------|--------|-------------------------------------|
| Labour productivity in enterprises engaged in agricultural activities | | | | | | |
| Agriculture, thousand UAH. Including: | 867.7 | 928.6 | 857.2 | 881.4 | 821.2 | -46.5 |
| Crop production | 900.1 | 954.4 | 853.7 | 908.8 | 789.2 | -110.8 |
| Husbandry | 730.4 | 815.2 | 872.8 | 940.1 | 880.2 | 149.8 |
| Labour productivity index at enterprises engaged in agricultural activities | | | | | | |
| Agriculture, %. Including: | 114.9 | 107.0 | 92.3 | 102.8 | 93.2 | -21.7 |
| Crop production | 115.8 | 106.0 | 89.4 | 106.5 | 86.8 | -29 |
| Husbandry | 109.9 | 111.6 | 107.1 | 107.7 | 93.6 | -16.3 |
| Number of employees at agricultural enterprises | 564874 | 553245 | 523782 | 525128 | 453111 | -111763 |
| Share of employed workers in agricultural enterprises in terms of total number, % | 7.97 | 7.67 | 7.10 | 7.12 | 7.21 | -0.76 |
| Average monthly nominal wages of full-time employees in agriculture | 7166 | 8738 | 9711 | 11680 | 11720 | 4554 |
| Share of the average monthly nominal salary of full-time employees to the average for the economy, % | 85.2 | 84.4 | 83.7 | 83.3 | 87.6 | 2.4 |
| Average monthly nominal salary at the US dollar exchange rate, USD | 258.9 | 373.9 | 346.8 | 427.8 | 321.1 | 62.2 |

Source: compiled by the authors

In 2022, the war had a serious impact on Ukraine's labour potential, upsetting the balance and causing instability in the labour sector and socio-economic development. The table shows that labour productivity and the number of employees in agriculture have fallen sharply. The war also caused changes in the education and training system. Education has become less

accessible for some people. The social and economic conditions in the country as a result of the war have affected the motivation of employees, and their readiness to face challenges and achieve goals. Security and the restoration of stability are key aspects of restoring labour potential and effective human resource management in Ukraine (Kotsur, 2022).

In line with the dollar exchange rate, the average monthly nominal wage of full-time employees in agriculture has significantly decreased compared to 2021, which hurts the operations of Ukrainian agricultural enterprises. Currently, there are motivationally weak aspects of the agricultural remuneration system, such as the uncertain role of the minimum wage and delays in the payment of wages to employees. It can be argued that in Ukraine, the level of remuneration is almost independent of the labour effort of employees, but is shaped by external factors (Dovgal, 2020). These external factors include inflation in the country, the economic situation, government regulation, and others.

European integration has a significant impact on Ukrainian agriculture, covering economic, technological, social, and infrastructural aspects of this strategically important sector. First, European integration opens the door to new markets for agricultural products. The European Union, as one of the largest consumers of agricultural products, is becoming a powerful market for farmers. This stimulates the development and modernisation of agricultural production, as well as adaptation to European quality and safety standards (Pe'er et al., 2020). Second, European integration contributes to the transformation of agriculture through the introduction of modern technologies and methods. Ukrainian farmers use European experience in implementing advanced agricultural technologies that improve product quality and increase yields. This contributes to the growth of agricultural efficiency and competitiveness in global markets. Third, engagement in the European integration process has an important social impact on the rural population, as it becomes more active in employment and sees improved working conditions. This opens up opportunities for more sustainable and secure working conditions in the agricultural sector. Further accession to the European space contributes to the strengthening of social and economic standards in agriculture (Melchior & Newig, 2021). Ukraine's integration into the EU is a complex but important process. Fully reaping the benefits of European integration in Ukraine's agriculture requires concerted efforts by the government, business, and civil society to jointly achieve sustainable and efficient development of this important sector.

The best practices of the European Union countries in the field of labour force management in the agricultural sector are important for increasing the efficiency and competitiveness of agriculture. The basic principles and methods they use can serve as a source of learning and inspiration for different countries. An important aspect is the training and development of workers. In many EU countries, there are special programmes that facilitate the training of farmers. For example, the Erasmus for Young Entrepreneurs programme allows young farmers to learn and gain experience working with experienced farmers in other EU countries. This allows

them not only to enrich their knowledge but also to implement new ideas and methods in their practice (Jurčić, 2020). The second aspect is the system of social guarantees and incentives for employees. EU countries provide adequate working conditions and some incentives for those who choose agriculture as a career. For example, France has a programme to support young farmers, which provides financial assistance and advice for beginners (Faysse et al., 2019). The third important aspect is the focus on sustainable development. EU countries are actively implementing practices aimed at reducing the environmental impact of agriculture. For example, the Netherlands uses innovative technologies to optimise the use of water and fertilisers, which contributes to environmental protection (Runhaar, 2017).

Several EU programmes have been highlighted to provide insights into best practices in the field of labour force management in the agricultural sector. The EU's Common Agricultural Policy (CAP) sets out the framework and instruments for agricultural development in the EU. One of the key components of the CAP is to support the development of rural areas and create employment opportunities in agriculture. This part of the programme includes various programmes, funds and initiatives aimed at creating sustainable labour management. One of the key objectives of these measures is to increase the efficiency of labour use in the agricultural sector, including skills development and support for employment in rural areas (CAP Overview, 2023). The Horizon 2020 programme is an EU initiative aimed at supporting research and innovation in agriculture and related sectors. Various projects are being developed under this programme to improve productivity and human resource management in the agricultural sector. The programme supports research and development of new technologies that help optimise the use of workers and resources in agriculture. European Green Deal (2020) is designed to achieve sustainable development and reduce the negative impact of agriculture on the environment. It includes measures to improve resource efficiency and introduce green technologies in the agricultural sector. One of the aspects is to improve labour management in agriculture, including optimising the use of workers and developing skills that meet the requirements of sustainable agriculture. Thus, the best practices of the European Union in managing the labour force in the agricultural sector reflect important aspects of training, social protection, and sustainable development. These practices can serve as good models for Ukraine as it seeks to increase the efficiency of its agriculture and manage its labour force optimally.

The strategy for optimising labour force management in Ukrainian agriculture should be comprehensive and focused on improving the productivity, efficiency, and competitiveness of the sector. Several key steps and strategic directions have been identified to achieve this goal (Fig. 2).

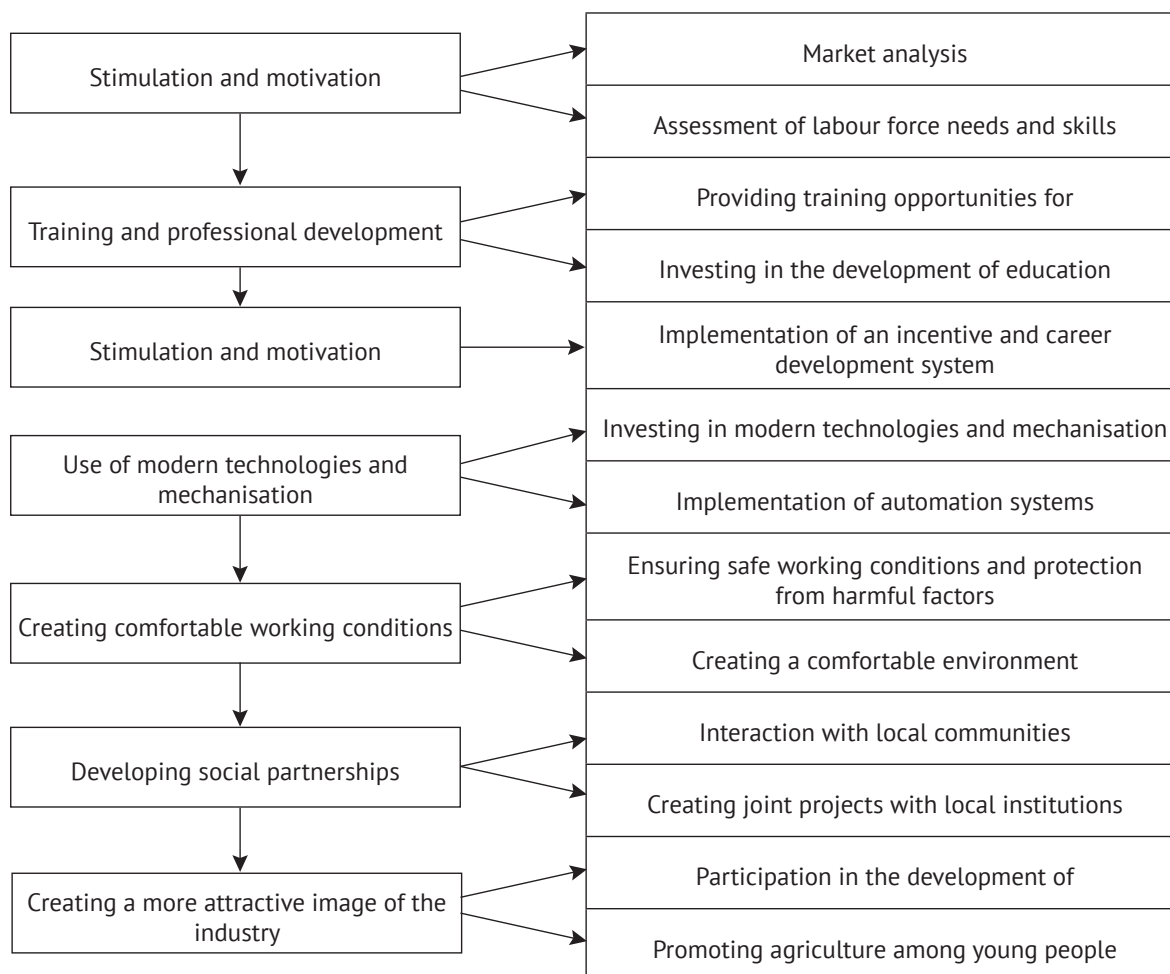


Figure 2. Strategy for optimising labour potential management in Ukrainian agriculture

Source: compiled by the authors

To simulate the application of the strategy to a real agricultural enterprise in Ukraine, the case of AgroGeneration, an agricultural firm specialising in the cultivation of vegetables, grains, and oilseeds should be considered. Needs analysis and assessment: AgroGeneration can analyse the labour market and internal needs of the company to identify vacancies and staffing requirements and consider the strategic goals of the business when planning staffing needs. Training and professional development: AgroGeneration employees can learn modern agricultural production methods through participation in training, seminars, and courses. For example, the company's agronomists can be trained in the use of modern pesticides and fertilisers to ensure high-quality crops. Incentives and motivation: AgroGeneration can use a bonus system for agronomists and employees who achieve high yields or high-quality products; provide incentives to achieve production improvement and cost optimisation targets. Use of modern technologies and mechanisation: The company can invest in new and comfortable tractors, combines and modern farm machinery to increase productivity. Em-

ployees can be provided with access to modern tools and software to perform tasks efficiently. Creating comfortable working conditions: Providing the necessary protection from pests and harmful environmental influences for agronomists and workers. Providing convenient working conditions for vegetable processing, including modern equipment for sorting and packaging. Developing social partnerships: Cooperation with local communities to ensure the sustainable development and growth of agricultural projects. Involvement of local people in production and processing processes, and job creation.

Creating a more attractive image of the industry: AgroGeneration can participate in local agricultural shows and exhibitions to present its products and attract new customers. It is actively involved in educational projects to teach young rural residents the basics of agriculture. This strategy model will help the company to achieve positive results in growing grain and vegetables, increase productivity and create favourable conditions for employees and the community. Figure 3 shows AgroGeneration's labour potential management model.

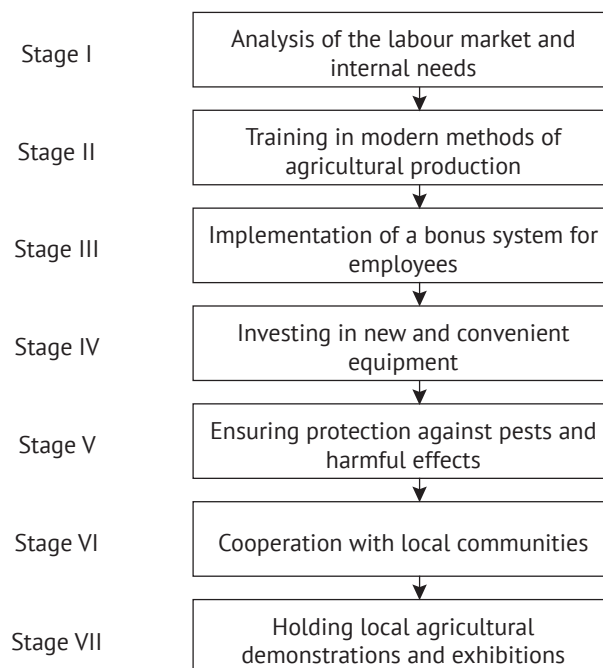


Figure 3. A model for managing the labour potential of AgroGeneration

Source: compiled by the authors

Considering the specific steps to optimise labour potential management in Ukrainian agriculture, it is possible to identify certain modern recommendations based on the example of successful practices in European countries for each point:

1. Needs analysis and assessment: development of an online platform for Ukrainian agriculture where farmers can regularly enter data on the number of employees, their qualifications and training needs; regional analysis to identify the specific needs of different regions of Ukraine; introduction of artificial intelligence to analyse this data and recommend an optimal learning plan.

2. Training and professional development: development of training programmes aimed at teaching modern agricultural technologies and the efficient use of machinery and equipment; creation of a virtual academy where farmers can learn online through interactive courses and simulations for practical skills; introduction of an instant feedback system for employees during training.

3. Stimulation and motivation: use of the “block-chain system” to automate and publicly record farmers’ production achievements; introduction of virtual bonuses as a reward for achieving certain results that can be exchanged for goods or services in agriculture.

4. Modern technologies and mechanisation: implementation of demonstration field stations where farmers can check and test new technologies before implementing them; employment of drones and sensors to monitor crops and land indicators in real-time.

5. Comfortable working conditions: introduction of a “supermarket” of workplace safety and security equipment at agricultural facilities; engagement of

ergonomics specialists to arrange workplaces and provide comfortable working conditions.

6. Social partnership development: creation of a council for social partnership, including representatives of agriculture, trade unions and government; launch of online forums and webinars to discuss topical agricultural issues and create a network of social partners.

7. More attractive image of the industry: development of interactive multimedia materials and videos showing the attractive aspects of working in agriculture and opportunities for career development; organisation of internships for young people on farms with the opportunity to gain practical experience and training in modern conditions.

These steps aim to optimise the management of labour potential in agriculture, increase productivity and attract new personnel to the sector. Optimisation of labour potential management in agriculture requires the development of a comprehensive strategy that considers sectoral specifics, European standards, innovative approaches, and best practices from other countries. It is important to remember that this process requires constant monitoring, analysis, and adaptation to changes in economic, social, and political conditions. The introduction of changes in labour potential management should help to increase agricultural productivity, improve the living standards of workers, and strengthen the competitiveness of the sector at the international level. European integration should be a step towards sustainable development and prosperity of Ukrainian agriculture. The process of optimising the management of labour potential requires joint efforts of the state, business, and the public, which will help

improve working conditions and the quality of life of the rural population.

DISCUSSION

The analysis shows a drop in productivity and a reduction in the number of employees, accompanied by a deterioration in working and living conditions. The military conflict has had a serious impact on the education and training system in Ukraine, as many educational institutions have been forced to switch to distance learning. This situation has resulted in limited access to education for a significant number of people, especially those living in conflict areas. Despite these challenges, there are opportunities to restore and improve Ukraine's labour potential. However, this requires systemic measures in areas such as education reform, reintegration of refugees into the labour force, and providing them with opportunities for professional development. Concerted action by the government, non-governmental organisations and international partners is needed to create the basis for restoring and developing Ukraine's labour potential in the context of European integration and post-conflict rehabilitation.

Authors E. Kurniawan *et al.* (2021) assessed the impact of economic and political aspects on labour potential in agriculture. One of the main findings of these authors was the significant impact of the external environment on labour productivity and workers' perceptions of working conditions. The authors deeply emphasised that changes in economic and political conditions have a significant impact on how employees perceive their work and its performance. At the same time, they argue that it is important to improve the level of social protection for workers in agriculture. They see this as an opportunity to improve working conditions and promote a motivating environment that would stimulate efficiency and productivity. Compared to the results described in this paper, there is a similarity in the approach to analysing the impact of the external environment on labour potential that is relevant for the agricultural sector in Ukraine. Indeed, the economic and political environment affects employees' perceptions of working conditions and their motivation, especially in the current Ukrainian context. However, unlike a few years ago, the current situation in Ukraine's agricultural sector requires not only improved social protection of employees but also active incentive programmes and favourable conditions for the development of employees' professional skills. This will ensure more efficient management of labour potential and increase the competitiveness of the agricultural sector in the current environment.

C. Bopp *et al.* (2019) focused on the remuneration system and the effectiveness of incentive programmes in agriculture. They found instability in these areas, which they attributed to external factors such as economic changes and political fluctuations. The authors suggest that systemic changes in the remuneration

system and incentive programmes are needed to improve the labour potential in agriculture. Their approach emphasises the importance of adapting to external changes and constantly updating the methods of motivating workers in agriculture. The authors' findings show a common trend in emphasising the importance of systemic changes in the remuneration system and incentive programmes. Effective remuneration and motivational measures are crucial for attracting and retaining highly skilled personnel in Ukrainian agriculture. They contribute to the competitiveness of the sector and ensure its stability and development in the current environment.

A.A. Davidescu *et al.* (2020) assessed the impact of training and development on labour potential in agriculture. They emphasised that the successful functioning of the industry is highly dependent on the level of education and skills of workers. A high level of qualifications contributes to higher labour productivity, improved production quality and the introduction of innovations in agriculture. The authors describe the importance of educational programmes and specialised training to improve the competence of workers. These programmes are aimed at developing specific skills and knowledge required to meet the challenges of the agricultural sector. They also help employees to adapt to the latest agricultural technologies and modern working methods, which gives them a competitive advantage in the market. Compared to the studies described in this paper, it is confirmed that investing in the training and development of personnel is an important step in improving the labour potential of modern Ukrainian agriculture. Professionally trained workers contribute to the efficiency and competitiveness of the sector, as well as to its sustainable development in the context of European integration.

Researchers S. Rotz *et al.* (2019) emphasise the importance of social partnership for increasing labour potential in agriculture. This is an important aspect that affects the efficiency and productivity of workers in this sector. The authors point out that cooperation between non-governmental organisations and enterprises is key in this context. Social partnerships between different parties – employees, employers, and authorities – aim to make joint efforts to address social, economic, and labour issues. It helps to balance interests, improve working conditions, provide social protection, and motivate employees. Creating a favourable working environment can include developing safety and health programmes, defining a fair remuneration system, and introducing incentive mechanisms for employees. It should be noted that partnerships should address key issues, such as improving working conditions, ensuring adequate remuneration, providing opportunities for professional growth and development, and ensuring social protection. For example, in Ukraine, cooperation between the government, agriculture and trade unions can help improve legislation and create a social protection system

that considers the specifics of agriculture and the interests of workers.

Authors T. Fonseca *et al.* (2019) analysed the problems that arise in the process of optimising labour capital. They identified several key aspects that are important for optimising labour potential. The high dependence of sectors on economic conditions, such as price conditions, availability of financing and market conditions, requires careful analysis and adaptation of labour management strategies. Social aspects, such as employee satisfaction, the creation of a favourable working environment and increasing motivation, are also important. It is proposed to introduce systemic changes and innovations in management to optimise the use of labour capital. Labour optimisation remains a critical issue in Ukraine's agricultural sector, which requires a comprehensive approach that encompasses economic, social and governance aspects. This integrated approach is important for ensuring efficient use of resources and achieving sustainable development of the sector. It is also noted that managerial aspects, including strategic planning and employee motivation, are recognised as key factors for optimising labour potential, according to the study results.

In general, various aspects such as economic and political conditions, remuneration, training and development, and social partnerships affect employee productivity and motivation. The authors identify the importance of adapting to external changes, such as economic changes and political fluctuations. Improving working conditions, providing social protection, and creating a motivating environment play a critical role in attracting and retaining qualified staff.

CONCLUSIONS

This study analyses labour potential as an important factor in the sustainable development of organisations and countries. Labour potential includes the capabilities and reserves of employees and organisations to achieve a high level of productivity and successful performance. The key components of labour potential, such as human resources, education and qualifications, motivation, and socio-economic conditions, are

considered. The theoretical models of labour potential management, which reflect important aspects of effective human resource management in organisations, are studied. Different models, such as competence, transformational, systemic, talent management and motivation, are outlined, which are the basis for developing practical strategies and methods of labour potential management in modern organisations. The labour potential of Ukrainian agriculture is analysed. The productivity of employees in agriculture in the period from 2018 to 2022 is determined and the consequences of the war on labour potential are identified. The important impact of European integration on Ukraine's agricultural sector, which includes economic, technological, social, and infrastructural aspects, is highlighted. Several EU best practices in the field of labour potential management in the agricultural sector are highlighted, namely the Common Agricultural Policy, the Horizon 2020 programme, and the European Green Deal. The possibility of increasing sales of Ukrainian agricultural products in the European market is analysed, as well as the impact of integration on agricultural development, including the use of modern technologies and the improvement of socio-economic standards for the rural population. A strategy for optimising labour potential management in the Ukrainian agricultural economy was developed to improve the sector's productivity, efficiency, and competitiveness.

Further research could include studying and analysing the best practices of the European Union in managing labour potential in agriculture and their possible implementation in the Ukrainian context. The training programs for farmers and agricultural professionals should be analysed to improve their skills and knowledge, as well as analysing the benefits and opportunities of using environmentally friendly technologies in agriculture.

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CONFLICT OF INTEREST

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Моделювання управління трудовим потенціалом України в сільському господарстві в умовах євроінтеграції

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Анотація. Дослідження, пов'язане з трудовим потенціалом в сільському господарстві, є досить актуальним, оскільки аграрний сектор є однією з ключових галузей економіки України, а інтеграція країни до ЄС відкриває нові можливості та вимагає відповідної адаптації управлінських підходів для досягнення конкурентоспроможності та сталого розвитку у сфері аграрної діяльності. Мета дослідження полягає в аналізі, розробці та вдосконаленні вже наявних стратегічних підходів до управління трудовим потенціалом України у сільському господарстві з урахуванням процесів інтеграції до Європейського Союзу. Серед використаних методів було застосовано аналітичний метод, статистичний метод, функціональний метод, метод системного аналізу, метод дедукції, метод синтезу та метод порівняння. В процесі дослідження було проаналізовано стан трудового потенціалу у сільському господарстві, оцінивши якісний та кількісний склад працівників, їх навички та освіти. Досліджено вплив євроінтеграції на аграрний сектор, зокрема її вимоги та можливості для розвитку, а також розроблено модель управління та розвитку трудового потенціалу для ефективного функціонування аграрного бізнесу. Було змодельовано застосування стратегії на сільськогосподарському підприємстві "AgroGeneration". Досліджено умови праці та соціальний захист працівників, а також зосереджена увага на формуванні та розвитку кадрового потенціалу в аграрному секторі. У ході дослідження було досягнуто такого результату, що управління трудовим потенціалом у сільському господарстві передбачає використання комплексної стратегії, яка б враховувала галузеві особливості, європейські стандарти, інноваційні підходи та кращі практики інших країн. Практичне значення дослідження полягає в розробці конкретних практичних рекомендацій та стратегій для органів управління, аграрних підприємств, а також працівників сільського господарства з метою оптимізації використання трудового потенціалу.

Ключові слова: продуктивність праці; оптимізація управління; конкурентоспроможність; умови праці; соціальний захист

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Innovative methods of organising the work of the AIC in market conditions (world experience and Kazakhstan)

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Abstract. The relevance of this issue lied in the need to explore new methods of organizing the agro-industrial complex, both in the global market and in the specific context of Kazakhstan. This exploration contained analysis of the benefits and challenges of the agricultural industry in Kazakhstan by drawing lessons from leading countries. The aim of this research was to identify the most effective approaches to enhance agricultural operations, unveil upcoming trends in the agro-industrial complex, establish the organizational and economic foundations for innovative development, and determine the socio-economic

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factors driving agricultural production. To achieve the goal, a systematic analysis of innovative processes in the agro-industrial complex was employed as the primary research method. Additionally, various analytical techniques such as synthesis, systematization, generalization, and comparison were utilized, including structural-functional and historical-legal approaches. The research presents innovative development pathways observed in advanced countries, including Kazakhstan, focusing on areas such as horticulture, animal husbandry, agricultural product processing, market development, agricultural cooperation, infrastructure development, scientific and personnel support, land resource management, digitalization of the agro-industrial complex, and government support. The study also addresses the shortcomings in the implementation of innovations within Kazakhstan's agro-industrial complex. Specifically, it provides detailed insights into methods for enhancing the efficiency of the agro-industrial sector, with particular emphasis on the digitalization of agricultural processes, precision farming systems, and smart farms. The research can be useful for professionals in various fields of the agro-industrial sector, policymakers involved in agricultural affairs, as well as businesspeople and investors interested in agricultural ventures

Keywords: agribusiness; agriculture; advanced countries; precision farming systems; smart farm; digitalisation

INTRODUCTION

The significance of employing innovative approaches in organizing the agro-industrial complex (AIC) cannot be overstated, as they contribute to enhancing labour productivity, production efficiency, and the overall effectiveness of the agricultural sector. These innovations encompass a wide range of advancements, including new technologies, equipment, crop varieties, animal breeds, fertilizers, and plant and animal protection products. They also involve novel methods of animal prevention and treatment, as well as innovative approaches to organizing, financing, and crediting agricultural production, and modern strategies for training, retraining, and developing skilled personnel.

The experience of Uzbekistan, as explored by I. Smanova and U. Sangirova (2018), proves particularly valuable due to the similarity in natural conditions between Uzbekistan and the subject country. Uzbekistan's successful implementation of reforms within a relatively short span of time resulted in significant progress in ensuring food security for its population and even establishing food exports. This highlights the importance of innovative infrastructure development, improved production and labour organization, and the establishment of robust institutional frameworks. The anticipated outcomes include advancements in scientific research, environmental preservation, information and communication capabilities, technological advancements, and the development of both industrial and social infrastructure. These efforts are essential for harnessing and preserving the natural resources of the agricultural sector (Myrzabek *et al.*, 2022).

In their paper S. Smagulova *et al.* (2022) analyses the management efficiency of the energy industry and the agro-industrial complex in Kazakhstan based on the introduction of digitalization to stimulate economic growth. The study highlights the energy-intensive and costly nature of Kazakhstan's economy, the deterioration of electrical equipment and agricultural machinery, and the seasonal shortage of fuel and lubricants. It also emphasizes the need for qualified engineering and

agro-technical personnel, the critical importance of the availability of investment in the agro-industrial complex, and the low degree of use of scientific, innovative, and digital approaches in the energy and agro-industrial sectors.

In a separate study conducted by O.V. Kruglyak *et al.* (2020), the focus is specifically on a narrow area of innovation related to genetic engineering, using dairy cattle breeding in Ukraine as an example. This research delves into innovations in breeding practices aimed at increasing dairy productivity. The study suggests that the foundation for the development of the dairy cattle industry in Ukraine should be the adoption of new specialized dairy breeds with genetic potential comparable to the best European counterparts. These breeds should surpass them in terms of reproduction and health, ultimately leading to economic profitability.

The research conducted by G. Madiyev *et al.* (2018) highlights the significance of providing financial support to small farms, which collectively contribute the majority of agricultural products to the market. To foster effective agricultural development and encourage the adoption of innovations, changes in macroeconomic regulations are necessary. This entails increasing government expenditure on agricultural development and revising the tax system in conjunction with its fiscal function.

In a separate study by Z. Sadykova & G. Rakhimzhanov (2020), the focus is on the need to reform the implementation of state functions, with strategic ones remaining under the purview of the state apparatus. This is due to the limited capacity of the state apparatus to independently make responsible decisions in an unstable institutional environment. Key qualitative indicators of this environment include bureaucratic hurdles, inadequate legal support for lending and risk insurance, low levels of business and professional qualifications, and a relatively stringent tax system. Additionally, this issue assumes importance in terms of attracting increased investments to the agricultural industry.

In light of these considerations, it is imperative that the government focuses on several key policy areas to drive innovative reforms (Organisation for Economic Co-operation and Development, 2013). Firstly, there should be a sustained commitment to improving the nation's road and railway infrastructure, ensuring efficient transportation networks. Streamlining procedures for construction permits is also crucial to promote business development and construction projects. Moreover, facilitating access to financing for enterprises in the food industry will bolster economic growth and job creation. Encouraging profit repatriation and providing enhanced incentives for investments in food processing cooperatives and technologies will further stimulate this vital sector. Lastly, the establishment of higher quality standards for food industry enterprises will enhance product safety and consumer confidence, ultimately contributing to economic progress.

Significant emphasis is placed on the digitalization of the agro-industrial complex, precision farming systems, smart farms, smart greenhouses, and other cutting-edge technologies. An illustrative example is the data laboratory that utilizes artificial intelligence to provide novel data sources, enabling timely assessments of food losses and land degradation levels. The Hand in Hand initiative has established a geospatial data platform containing a wealth of statistics from the Food and Agriculture Organization of the United Nations (FAO) (2020) and its partners. This platform offers numerous applications, including the acquisition of valuable information for monitoring agricultural systems at risk due to human impacts on land and water resources, as well as for analysing weather-related trends.

The analysis also considered Decree of the Government of the Republic of Kazakhstan No. 960 (2021). While this Concept offers a comprehensive examination of the innovative organization of the agro-industrial complex both globally and in Kazakhstan, it lacks detailed coverage of the pathways to digitalize agriculture. The study draws conclusions regarding the shortcomings within Kazakhstan's agricultural system. However, the agricultural industry in Kazakhstan harbours substantial unexplored potential and domestic competitive strengths in contrast to other nations. By implementing efficient agricultural policies, it can attain enduring growth and generate noteworthy economic benefits, ultimately enhancing the welfare of its population.

The study aimed to gather insights into the main trends in global agriculture, compare them with corresponding trends in Kazakhstan, and determine the strategies through which Kazakhstan can enhance the performance indicators of its agro-industrial complex.

MATERIALS AND METHODS

The primary approach employed in this study involved conducting a systematic analysis of innovative processes within the agro-industrial complex. Various methods

such as analysis, synthesis, systematization, generalization, and comparison were utilized, including structural-functional and historical-legal approaches. In order to underpin the analysis, statistical information sourced from the Ministry of Agriculture of Kazakhstan (n.d.), along with research studies investigating innovation dynamics and the integration of scientific and technological advancements, were assimilated.

System analysis formed the foundation of this study. It involved a series of actions aimed at establishing the structural relationships among variables or elements within the system under investigation. The analytical framework relied upon a combination of general scientific, experimental, natural, statistical, and mathematical methods. A diverse range of agribusiness domains were examined using system analysis, encompassing various innovative approaches, each associated with a distinct aspect of agro-industrial activity. The analysis encompassed both numerous advanced countries worldwide and Kazakhstan specifically.

The method of synthesis involves studying an object as a whole, considering its interconnected parts. In scientific research, synthesis works in conjunction with analysis, as it enables the integration of dissected components of a subject (object or phenomenon), establishing their connections, and understanding the subject in its entirety. Through synthesis, common trends were identified within each area under investigation. Systematization, on the other hand, is the process of consolidating diverse knowledge about objects (phenomena) into a unified scientific system, recognizing their interconnectedness. It reflects the unity of the world and is rooted in exploring the essential connections that bind these objects (phenomena) together. Generalization serves as a method of scientific cognition, allowing for the determination of shared features and properties among a specific category of objects. It involves moving from the particular to the general, from less comprehensive to more comprehensive perspectives.

Through the analysis of statistical data, the study revealed the quantifiable benefits associated with specific innovative methods. Various sources were examined to provide a comprehensive understanding of agricultural innovations from diverse perspectives. These sources encompassed a range of topics, including the compatibility protocol ISOBUS, which facilitates the use of attachments from different manufacturers, and the TRACES system, an online platform by the European Commission for sanitary and phytosanitary certification. The method of comparison, a scientific approach to investigating and comprehending reality, was employed to establish both commonalities and distinctions among processes, phenomena, and objects. By using the comparison method, the study juxtaposed the implementation of innovations in Kazakhstan with their utilization in advanced countries worldwide. This approach allowed for the identification of areas where

Kazakhstan should strive to align itself with global advancements in agriculture.

RESULTS

Examination of global practices in utilizing innovative approaches in the agricultural industry. Developed countries have embraced innovative approaches in crop production to mitigate the adverse effects of global climate change and promote sustainable agricultural development. These methods include resource-efficient practices and organic technologies aimed at enhancing ecological well-being and environmental preservation. Strategies such as diversification, precision farming, and the digitalization of technological processes have gained prominence. Molecular biology and genetic engineering are utilized to optimize the selection and production of new plant varieties. By leveraging these advanced techniques, breeders can accelerate the breeding process, leading to the regular development of high-yielding crop varieties that exhibit stress resistance and disease resilience. Swiss breeders, for instance, have successfully combined classical breeding methods with molecular approaches, enabling early identification of resistance genes in plants and shortening the selective breeding cycle (Roth *et al.*, 2023).

Another significant aspect is the improvement of weather forecasting accuracy, achieved through the establishment of an extensive network of weather stations and the creation of a comprehensive database of long-term meteorological observations. In many countries, phytosanitary controls and permit issuance are carried out through a fee-based system, which effectively mitigates the risks of corruption. The revenue generated from these fees contributes to the national budget and supports the remuneration of inspectors, as well as the enhancement of inspection facilities and equipment. To facilitate trade, the European Union (EU) has introduced the TRACES system, an online platform developed by the European Commission. This platform serves as a unified traceability system for obtaining sanitary and phytosanitary certifications required for the import and export of animals, animal-derived products, non-animal food and feed, and plants within the EU and for external trade.

The TRACES system, which is currently utilized in 90 countries with over 55,000 users, plays a crucial role in simplifying the issuance of sanitary and phytosanitary certificates and official documents for the import, export, and movement of live animals and animal products within the European Union (EU). In advanced countries, the inclusion of a significant portion of forage crops in crop rotation is key to the successful development of animal husbandry. For instance, in the United States of America (USA), forage crops occupy 65% of the cultivated area, and the production of feed grain surpasses that of food grain by a factor of four (Fuglie *et al.*, 2021). Innovative methods are also being

employed to enhance the genetic potential of livestock. Biotechnology, genomic and DNA analysis, and accelerated reproduction techniques are applied within animal breeding, leading to the consolidation of the entire livestock population. Extensive breeding efforts have resulted in dairy cows in developed cattle-breeding nations achieving milk productivity levels of 8.0-10.0 thousand kg or more over a lactation period exceeding 305 days (Lee *et al.*, 2020).

Since May 2021, the Eurasian Economic Union (EAEU) countries have been unifying their selection and breeding work through a relevant agreement. The European Union (EU) and the USA prioritize environmental sustainability and green growth principles in their livestock policy. Advanced nations emphasize the accelerated modernization of machinery and technologies in the processing sector, thereby ensuring high efficiency in meeting the population's food needs. Producers and processors in the EU benefit from low-interest loans and favourable repayment terms, while the USA encourages companies to invest in scientific advancements based on new technologies that enhance labour productivity.

Developed countries have implemented various strategies to boost agricultural product sales, such as the utilization of cooperatives, which account for 70% of agricultural product sales in Europe (Candemir *et al.*, 2021). In Canada and the USA, the figure stands at 60. Cooperatives are instrumental in enabling the efficient transportation of large quantities of products and ensuring their timely delivery by establishing robust trade and logistics infrastructure throughout the entire supply chain. Prominent instances of well-functioning distribution networks include the Rungis wholesale market in Paris, France, the Mercasa wholesale market network in Spain, and the Bronisze wholesale market in Warsaw, Poland. Developed countries have widely adopted international standards and regulations such as Sanitary and Phytosanitary Measures (SPS), Hazard Analysis Critical Control Point system (HACCP), and Good Laboratory Practice (GLP). These standards enhance consumer confidence in the safety and quality of agricultural products. In the face of globalization, climate change, and intensive agriculture, the resilience of agricultural production systems has diminished, making them more susceptible to harmful organisms, diseases, and hazardous substances. To address these threats and mitigate their adverse impact on agricultural and food product trade, SPS measures have been consistently emphasized by the FAO (2020). Cooperatives serve as a foundational component of agriculture in most countries worldwide. The European Union (EU) boasts a substantial network of around 22,000 cooperative enterprises (Roth *et al.*, 2023), while across the OECD (2013) nations, cooperatives have carved out distinctive niches encompassing sales, processing, and the provisioning of production facilities.

Wholesale purchasing cooperatives in the United States play a significant role in procuring seeds, chemicals, fuel, animal preparations, and facilitating various activities such as compound feed production, quality control of feed ingredients, logistics, equipment repairs, and spare parts delivery. In terms of fiscal incentives, US farmers who sell their products to cooperatives were granted tax breaks in 2017, with the possibility of tax exemption under specific conditions. The proportion of high-tech products and science expenditures in the gross domestic product (GDP) serves as a crucial indicator of a country's economy. On average, advanced countries allocate around 3% of their total GDP to knowledge-intensive products and science expenditures. It is noteworthy that in Kazakhstan, per capita expenditures amount to 10.27 US dollars, which is 87 times lower than in the USA (Amirbekova *et al.*, 2022).

In advanced countries, 70-85% of GDP is attributed to innovations, new technologies, upgraded products, and equipment that embody new knowledge and solutions. However, in Kazakhstan, this proportion is approximately 1% (Fuglie *et al.*, 2021). The management of innovation activity takes place at both territorial (regional) and industrial levels. Territorial priorities are associated with innovation clusters and the establishment of university-industry collaborations. Industry priorities

align with the goals set by government programs for the specific sector. The interconnectedness of territorial and sectoral management of innovation in the agro-industrial complex helps identify areas of concern and develop tools for modernizing agricultural enterprises (Galeano-Barrera *et al.*, 2022). The efficient functioning of the agro-industrial complex heavily relies on the effective governmental control and management of land resources. Many countries have legislation in place that prohibits the division of agricultural land into small plots, thus preventing fragmentation. Other countries aim to prevent excessive accumulation of agricultural land and impose requirements for landowners to reside near their land and possess the necessary expertise. Additionally, regulations exist to limit the maximum size of land plots. In Denmark, for instance, such a restriction applies to plots larger than 150 hectares (Hjalager *et al.*, 2022).

Digitalization in agriculture refers to the adoption and integration of digital technologies and data-driven solutions to enhance various aspects of agricultural practices, management, and decision-making. It encompasses a wide range of technologies and applications aimed at increasing productivity, efficiency, and sustainability in farming. Digitalization in agricultural holdings typically involves three stages (Table 1).

Table 1. Digitalization process and implementation of precision farming systems

| Stage | Precise farming systems | Description |
|---------------------|---|--|
| Stage 1: Initial | Accounting systems integration | This involves seamlessly incorporating financial and budgetary data into precision farming operations |
| | Electronic records management | Electronic records management in precision farming allows for the efficient storage, retrieval, and analysis of critical data related to crop yields, soil quality, equipment maintenance |
| | Dashboards | Dashboards provide a visual representation of KPIs and real-time data related to precision farming activities |
| | Key Performance Indicators (KPI) database | A KPI database in precision farming stores and organizes essential metrics and benchmarks related to crop productivity, resource utilization, and operational efficiency |
| Stage 2: Innovation | Global Positioning System (GPS)/GNSS | Enables precise tracking of machine operators and accurate field processing. Real-time data collection and accurate location information streamline farm tasks such as planning, mapping, soil sampling, tractor management |
| | Mobile devices | Utilized for microelement calculations, weather forecast tracking, field mapping, and GPS navigation, enhancing decision-making and on-field efficiency |
| | Robotics | Robotics technology is employed for tasks such as crop planting, crop monitoring, and weed control, automating labour-intensive processes and improving accuracy |
| | Irrigation systems | Facilitate remote monitoring and control of irrigation, leading to water conservation, time efficiency, fuel savings, and reduced vehicle wear and tear |
| | Internet of Things (IoT) | Involves connecting field sensors and satellite monitoring to transmit data to a centralized source, enabling data-driven insights and decision-making |
| Stage 3: Training | IT specialist training | It refers to the essential education and skill development programs aimed at equipping agricultural professionals with the knowledge and expertise required to effectively manage and leverage digital technologies and data-driven solutions in farming practices |

Source: compiled by the authors based on S. Rolandi *et al.* (2021), O. Ermetin *et al.* (2022), K. Bondal (2021)

Smart farming, also known as precision agriculture or digital farming, indeed involves the application of cutting-edge information and communication

technologies (ICT) in agricultural practices. It aims to optimize various aspects of farming operations by using data, sensors, automation, and connectivity (Fig. 1).

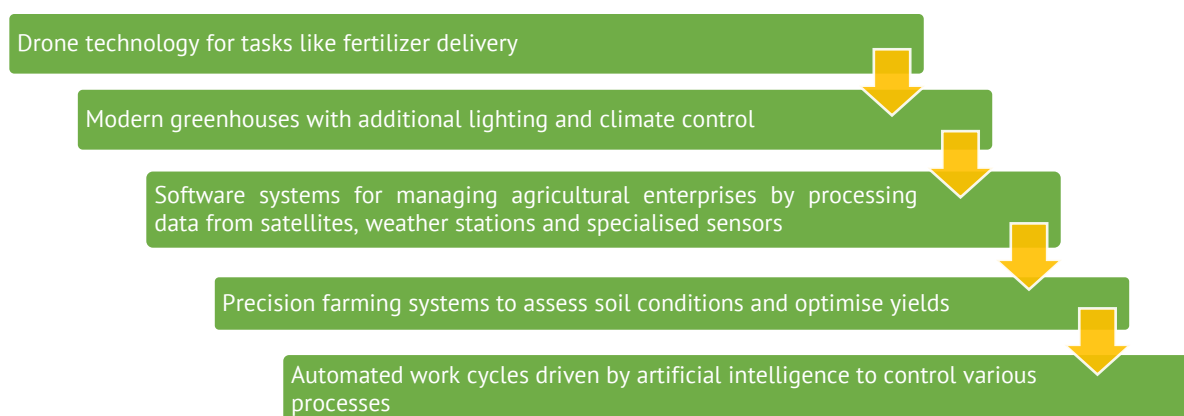


Figure 1. The key components of smart farming

Source: compiled by the authors based on M. Dhanaraju et al. (2022)

In New Zealand, drones have been multiply applied in agriculture, including field mapping, monitoring crop growth, and aiding shepherds in herding livestock. These drones utilize recorded dog barking and loudspeakers to facilitate the gathering of herds. JBM North America has developed a solution that enables the monitoring of animal conditions within herds, including their location, well-being, and nutritional levels, thereby enhancing herd management. Smart farming practices allow for more efficient utilization of pastures, forests, and fields, preventing soil depletion and the need for deforestation to create new grazing lands. Notably, the Integrated Crop Livestock Forestry Systems (ICLFS) program, implemented in Brazil, where approximately 23% of the world's cattle is raised, has proven effective in restoring degraded farmland (Glatzle *et al.*, 2021). Swiss researchers have highlighted the environmental benefits of smart farms, as they enable precise application of fertilizers and pesticides, mitigating the negative impact of agriculture.

Globally, state regulation plays a crucial role in the agro-industrial complex, particularly through economic measures aimed at supporting producers. These measures commonly involve price maintenance, cost compensation, subsidies for production structures, and the implementation of various programs. The specific application of these measures depends on each country's unique natural and climatic conditions. For instance, the United States subsidizes the profitability of agricultural production, while in Europe, subsidies are provided per hectare of agricultural land. In the Cairn countries, which are located in the subtropical zone, agricultural subsidies are non-existent (Hopewell & Margulis, 2023). The Cairn Group includes Argentina, Australia, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Guatemala, Indonesia, Malaysia, New Zealand,

Pakistan, Paraguay, Peru, Philippines, South Africa, Thailand, Uruguay, and Vietnam.

Analysis of the application of innovative methods in the agricultural sector of Kazakhstan. The adoption of agricultural innovations in Kazakhstan has been slow, particularly in crop production. Challenges include the dominance of monoculture, slow progress in expanding irrigated lands and implementing moisture-saving technologies, and limited use of mineral and organic fertilizers. The technological capabilities of the industry are lagging behind advanced countries, leading to yield fluctuations and inadequate processing and marketing of agricultural products. The budget constraints have resulted in insufficient support for veterinary organizations, shortage of veterinary specialists, and inadequate environmental monitoring. The renewal rate of agricultural machinery is below optimal levels, affecting medium and small farms' access to technical resources and energy. The government has implemented measures to support cooperatives, such as investment subsidies and simplified registration processes, along with improved oversight through the establishment of a state register and statistical service.

Cooperatives in Kazakhstan have limited effectiveness, with a significant number being inactive or fictitious for fraudulent subsidy purposes. However, there are still successful cooperatives that offer advantages such as bulk purchasing and streamlined crop sales. The adoption of digital technologies in the agricultural sector is relatively low, resulting in inefficient resource allocation. Pilot farms and livestock enterprises that have implemented digital technologies have experienced cost reductions, increased yields, and improved livestock outcomes. However, obstacles such as limited and unreliable rural connectivity, lack of digital literacy among employees, shortage of trained specialists, and

absence of a unified digital agricultural ecosystem hinder the widespread adoption of digital innovations in the industry. The Ministry of Agriculture of Kazakhstan (n.d.) has delineated a three-tiered approach to the integration of digital technologies within the agricultural sector. At the fundamental level, traditional farms leverage basic electronic field maps and soil analysis. Advancing to the next stage, farms embrace a higher degree of automation, incorporating technologies like fuel consumption sensors, GPS trackers, meteorological stations, electronic weed mapping, and business process management software. The pinnacle of this digital transformation is the Digital Farm, where an exceptionally automated agro-industrial system operates with minimal human intervention, making extensive use of advanced digital tools and technologies (Mukhammedov *et al.*, 2021).

In Kazakhstan, there are already more than 20 digital farms and approximately 170 advanced farms in operation. The Ministry of Agriculture (n.d.) has plans to establish at least 20 additional digital farms and four thousand advanced farms by 2023, completing the digitalization of the agricultural industry. The goal is to achieve 100% automation of processes and public services. Currently, the majority of farms in the country are still at the fundamental level, but the process of agricultural digitalization is underway. According to official data, almost all sown areas in Kazakhstan have been digitized, covering a total area of 24 million hectares. Pastures are also being analysed through digital means. New technologies in animal husbandry enable livestock monitoring and automated care. The use of GPS trackers allows for the tracking of herd movements and facilitates locating stray animals using smartphones. Saparkhan Omarov, the Minister of Agriculture of Kazakhstan, highlighted at the Astana Economic Forum that precision farming has led to a 2.5-fold increase in grain yield while reducing farmers' costs by over 20%.

A smart greenhouse represents an advanced indoor farming system that integrates information and communication technologies with agricultural practices. By utilizing ICT, smart farms are equipped to automatically monitor and analyse factors such as temperature, humidity, and sunlight, allowing farmers to cultivate crops without being reliant on unpredictable weather conditions (Kim, 2021). In Kazakhstan, where dry pastures and deserts are predominant, the implementation of smart greenhouses becomes particularly relevant. These greenhouses can be remotely controlled through smartphones, leading to reduced labour costs and increased production efficiency. Compared to conventional greenhouses, a smart greenhouse with a one-hectare area has the capacity to yield 400-450 tonnes of vegetables and berries annually, surpassing the 300-tonne production of a traditional greenhouse. This project not only contributes to the advancement of technology but also provides educational opportunities for students

and university staff to engage in research, seminars, and training sessions for rural entrepreneurs.

DISCUSSION

Drawing upon extensive research literature, various aspects of innovation within the agro-industrial sector have been examined. Many studies have concentrated on specific areas aimed at enhancing agricultural efficiency, such as genetic engineering, digitalization, and the development of cooperatives. This paper provides comprehensive coverage of these diverse areas. In their study G. Madiyev *et al.* (2018) highlight that while agribusiness represents a leading sector in Kazakhstan's economy, the industry currently faces challenges such as underutilization of resources, outdated equipment and technologies, limited competitiveness, and a prevalence of small-scale management and private subsidiary farms within the agricultural production structure. The study also identifies deficiencies in the agricultural market, infrastructure, and economic relationships among related enterprises. O.V. Kruglyak *et al.* (2020) emphasized the economic significance of cattle breeds and the importance of meticulous intensive selection work for achieving favourable economic outcomes in dairy cattle breeding.

Among Central Asian countries, Uzbekistan is a good example of the effective implementation of the principles of the digital transformation concept. Kh.Z. Rajamurodov *et al.* (2022) discusses the digitalization processes in Uzbekistan's agriculture, emphasizing the need for digital solutions and transformation due to economic improvements, resource-efficient technologies, and environmental compliance. The authors' highlights the role of digital platform ecosystems in this transformation, defining their significance. A study demonstrates a farm's implementation of a digital platform, resulting in increased profits and reduced costs. The study concludes that while digital platforms may not entirely eliminate intermediaries, they are effective in wholesale and retail food markets, projecting substantial additional profits for various agribusiness sectors. The creation of a national digital platform is proposed, with potential economic benefits and indirect advantages such as improved product quality and environmentally friendly practices.

V. Kvartiuk and M. Petrick (2021) examines the impact of Kazakhstan's 2003-2005 agricultural land reform on land rental and credit market participation, aiming to determine whether the reform facilitated efficient land allocation and access to credit for agricultural producers. However, the reform resulted in significant land concentration, failed to stimulate land sales, and reorganized the land-rental market in favor of the state as the primary landlord. It did not achieve the goal of providing access to land for skilled producers or improve land use as collateral. The reform had limited success in achieving its objectives, and further, more

substantial steps are needed to enhance Kazakhstan's agricultural land markets. According to the authors, Kazakhstan's current reliance on cheap rental land and inadequate progress in liberalizing land relations pose economic sustainability challenges, necessitating more comprehensive reforms to bridge the gap between productivity and land accumulation.

The issues of the organization of the electric power industry and the agro-industrial complex in Kazakhstan considered by S. Smagulova *et al.* (2023). The study employs econometric modeling to examine the impact of electricity production and digital farms on agricultural growth, presenting medium-term forecasts for the agricultural sector with digitalization. The work identifies challenges such as outdated equipment, lack of funding, and non-transparent tariffs in the energy sector, along with issues related to fuel supply and energy shortages. To address these challenges, the authors suggest modernizing existing power stations, promoting renewable energy, improving fuel distribution, enhancing digitalization, and reorienting the oil and gas industry toward high-value products. These measures are expected to contribute to economic growth, environmental preservation, and national security for sustainable development in Kazakhstan's digital energy and agro-industrial sectors.

In turn, M. Toguzova *et al.* (2023) studied the development and implementation of modern geoinformation technologies in agricultural production. This study conducted in the Eastern region of Kazakhstan analyzed the use of digital technologies in farms and identified key factors hindering their implementation and prospects for further development. The study found that larger farms have a higher degree of digitalization development compared to smaller enterprises, mainly due to financial opportunities and objective reasons related to the lack of need for digital technologies at a low level of production. The authors concluded that the level of identifying patterns for more accurate and effective forecasting will increase the yields and profitability of agriculture in the region, increasing productivity, reducing material costs, and more efficient allocation of funds and preservation of the environment.

In his study, A. Nurgozhayev (2021) discusses the digitalization of the agriculture sector in Kazakhstan and aims to determine the associated risks. The author found that five regions have low risk, while the Kostanay region has a high-risk rate in five risk categories, and the Almaty region has no plan for risk mitigation, monitoring, or management in case of digitalization-related risks. Risks were calculated for each region separately, and regions with low, moderate, and high risks were identified. The author also notes that farmers are more aware of other types of uncertainties than the risks associated with the digitalization of the agriculture sector, and regional designation authorities are knowledgeable and can assist in mitigating risks.

These studies emphasize the need for comprehensive reforms to address issues such as resource underutilization, outdated technologies, land reform inefficiencies, and energy sector challenges. Digitalization emerges as a promising avenue for increasing efficiency and sustainability, with success stories in Uzbekistan showcasing the potential of digital platforms to enhance profitability. Furthermore, geoinformation technologies offer pathways to boost agricultural productivity and reduce costs. However, it is crucial to recognize and manage the associated risks of digitalization. Overall, these findings offer valuable guidance for stakeholders and policymakers seeking to foster growth and resilience in the agro-industrial sector of Central Asian economies.

CONCLUSIONS

The agro-industrial sector in Kazakhstan requires systematic efforts towards innovation and improvement. This entails widespread adoption of precision farming systems, smart farms, and smart greenhouses, as well as land diversification and tax optimization. It is crucial to establish effective systems for land and water utilization. The consolidation of small farms into cooperatives would streamline the procurement of necessary goods and services, as well as the marketing of agricultural products. Government support, accessible financing, and comprehensive training programs are needed to enhance the digital skills and knowledge of agricultural workers, thereby strengthening the human capital in the sector. The integration of digital technologies helps minimize corruption by reducing the influence of human factors on decision-making processes.

Significant innovations in agribusiness would involve simplifying licensing procedures, transitioning them to electronic platforms, and fully automating business processes. Encouraging farms to embrace digitalization through state subsidies and establishing clear and transparent criteria would greatly enhance efficiency. This includes investment subsidies, expanded financing options, lending instruments, and loan insurance. Furthermore, comprehensive breeding work is necessary to improve the productivity of agricultural goods. Innovations in phytosanitary and veterinary control contribute to product quality and enhance their appeal in domestic and international markets. Adequate attention should be given to new scientific developments. As outlined in the Concept for the development of the agro-industrial complex of the Republic of Kazakhstan for 2021-2030, funding for agricultural science should reach a minimum of 1% of the GDP of the agro-industrial sector.

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CONFLICT OF INTEREST

The authors have no conflict of interest to disclose.

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Інноваційні методи організації роботи АПК в ринкових умовах (світовий досвід та Казахстан)

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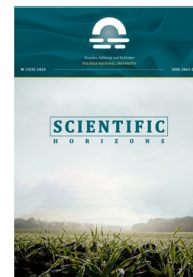
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Анотація. Актуальність даного питання полягало в необхідності вивчення нових методів організації агропромислового комплексу як в умовах глобального ринку, так і в специфічному контексті Казахстану. Це дослідження містить аналіз переваг та викликів сільськогосподарської галузі Казахстану на прикладі провідних країн світу. Метою дослідження було визначення найбільш ефективних підходів до підвищення ефективності сільськогосподарської діяльності, виявлення майбутніх тенденцій в агропромисловому комплексі, створення організаційно-економічних засад інноваційного розвитку, а також визначення соціально-економічних факторів, що стимулюють сільськогосподарське виробництво. Для досягнення поставленої мети основним методом дослідження був системний аналіз інноваційних процесів в агропромисловому комплексі. Крім того, використовувалися різні аналітичні прийоми, такі як синтез, систематизація, узагальнення та порівняння, а також структурно-функціональний та історико-правовий підходи. У дослідженні представлені інноваційні шляхи розвитку, що спостерігаються в передових країнах, включаючи Казахстан, з акцентом на таких сферах, як садівництво, тваринництво, переробка сільськогосподарської продукції, розвиток ринку, сільськогосподарська кооперація, розвиток інфраструктури, наукове та кадрове забезпечення, управління земельними ресурсами, діджиталізація агропромислового комплексу та державна підтримка. У дослідженні також розглядаються недоліки у впровадженні інновацій в агропромисловому комплексі Казахстану. Зокрема, в ньому детально розглядалися методи підвищення ефективності агропромислового сектору, з особливим акцентом на діджиталізацію сільськогосподарських процесів, системи точного землеробства та «розумні» ферми. Дослідження може бути корисним для фахівців різних галузей агропромислового сектору, політиків, які займаються питаннями сільського господарства, а також бізнесменів та інвесторів, які цікавляться аграрними підприємствами

Ключові слова: агробізнес; сільське господарство; розвинені країни; системи точного землеробства; смарт-ферми; діджиталізація

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State and prospects of fuel supply for agriculture in Ukraine

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Abstract. In the context of martial law in Ukraine, when the oil refining industry has stopped and most of the logistics chains have been destroyed, the issue of ensuring the availability of fuel and energy resources for agricultural production – the guarantor of food supply in Ukraine and the world – is of particular relevance. The purpose of the article was to study the consumption of petroleum products in the agricultural sector

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of Ukraine under martial law, to investigate the state and state regulation of the market and fuel from petroleum products, and to forecast their price in the future. The following methods were used in the article: dialectical, abstract and logical, statistical, correlation and regression, tabular and graphical, analysis of series of dynamics and structural changes, comparison, strategic planning and forecasting. Based on the results of the research carried out using statistical methods, the article analyses the consumption of petrol and diesel fuel by agricultural enterprises and calculates their cost per hectare of harvested area. It was found that the decrease in fuel consumption in 2022 was due to the fact that $\frac{1}{4}$ of the sown areas were not sown due to the war. The share of fuel used for the needs of the agricultural sector was also investigated. The correlation and regression analysis revealed a close relationship between the exchange rate and the price of diesel fuel in Ukraine, and a negative relationship between the world oil price and the price of diesel fuel. Due to the established dependence, a model for calculating the price of diesel fuel based on world oil prices and the exchange rate is developed, and the price is calculated. It is substantiated that the main economic method of state regulation of the fuel market is the establishment of an excise tax. It is concluded that the reduction in the consumption of fuel and energy resources in the agricultural sector of Ukraine has led to a decrease in the energy intensity of agricultural products. The results of the research are of practical importance, which will allow identifying destabilizing factors in the oil and oil products market, as well as formulating the State's policy that will promote the use of energy resources, in particular liquid fuel, in agriculture under martial law

Keywords: agricultural enterprises; energy intensity; energy security; martial law; oil products; import; logistics

INTRODUCTION

Since February 2022, the role of the Ukrainian agricultural sector in the food supply has been particularly significant in the world. The main factors behind its limitations were the reduction in crop areas due to the occupation and in the war zone, disruption of the logistics of both agricultural products and logistics of the industry, including energy supply. Given that agriculture mainly uses liquid fuels made from petroleum products and Ukraine's high dependence on imports of this type of energy, this issue requires special attention and control to ensure its immediate resolution. The presence of numerous participants in the Ukrainian fuel market and the integration of Ukraine's economy into the global economy have a decisive impact on changes in oil fuel prices. Fluctuations in oil prices, the exchange rate and Russia's military aggression against Ukraine contributed to the imbalance in the Ukrainian petroleum products market.

The price situation on the Ukrainian fuel market is complicated by the cooperative actions of traders. This is reflected in the asymmetry of prices, when a large jump in the value of an external factor causes a rapid rise in the price of petroleum products and a slow decline in the period of its weakening. All of this has a significant impact on the development of the national economy, given that oil prices are the main determinants of the overall price level, making the study relevant and timely.

The problem of using fuel and energy resources in the agricultural sector of Ukraine was studied by O. Zakharchuk *et al.* (2021). The vector of his research was aimed at providing agriculture with light oil products, their use in various technological processes, and

the possibility of saving energy resources in the process of applying innovative agricultural technologies. Consumption in agricultural enterprises was also studied by O. Zakharchuk and O. Vyshnevetska (2020). In addition to fuel consumption by the agricultural sector, they paid special attention to energy efficiency and energy security, price parity for agricultural products and oil products. They paid much attention to the study of the oil products market, the production infrastructure of the oil refining industry, and government regulation of these issues. S. Strapchuk studied the production and consumption of bioenergy resources. Strapchuk (2021). The author found that biodiesel production requires large land areas, so it is worth considering whether it is advisable to reduce the area under food crops in favour of energy crops. It has been found that biofuel production is not widespread enough, so most of the harvested rapeseed and soybeans are exported.

The efficiency of energy use in agriculture was substantiated by N.V. Pryshlyak (2021). External and internal economic and non-economic factors influencing the pricing of petroleum products in Ukraine were studied by V. Melnychuk & A. Melnychuk (2019). Aspects of legal regulation of trade in petroleum products in Ukraine were studied by V.S. Levchenko (2020). The state and prospects of development of the fuel market of Ukraine were studied by V. Kapustyan & I. Siretska (2018). They concluded that one of the main destabilizing factors in its development was significant import dependence with an unstable exchange rate. In their research, they argue that the Ukrainian oil refining industry is not able to fully respond to the changing socio-economic situation in Ukraine, and the

effectiveness of market reforms in the industry is low. In addition, they believe that the privatization of oil refineries has not given an impetus to the development of these enterprises, privatization agreements have not been fulfilled and, as a result, even minimal investment commitments for technical re-equipment of the industry, which is highly monopolized, have not been fulfilled.

The fuel and energy problems of agriculture under martial law have not been thoroughly studied. Firstly, this concerns the mechanisms for overcoming the fuel crisis that arose in the first year of the war, the loss of a significant percentage of imported fuel, the destruction of oil refineries and oil depots, and the enormous increase in fuel prices, all of which had a significant impact on Ukraine's food security and the development of the entire economy. That is why the purpose of the study was to assess the trends in quantitative and qualitative changes in fuel and energy resources used in agriculture, energy intensity and energy supply of agricultural production, the state, and state regulation of the oil fuel market, and the calculation of its price for 2023-2024.

MATERIALS AND METHODS

The research methodology is based on the dialectical method of scientific cognition (in the study of processes and phenomena that occur with the provision of energy resources to agriculture in Ukraine under martial law); abstract and logical (in substantiating theoretical provisions for reducing energy intensity in agriculture); statistical (to quantify the situation on the fuel market in absolute and relative terms); correlation and regression (to build a model for calculating the price of diesel fuel in Ukraine, taking into account the

The main economic method of state regulation of the fuel market is to set the excise tax rate. It was the method of structural shifts that was used to analyse the excise tax rates on fuel in Ukraine for the period 2011-2023. This period was not chosen by chance, as it was the time when Ukraine's energy import dependence was beginning to increase and the production of fuels and lubricants of Ukrainian origin was significantly reduced. At the same time, the Tax Code of Ukraine (n.d.), which is the main state price regulator of fuel in Ukraine, was introduced. To build a model for calculating the price of diesel fuel depending on the world oil price and the exchange rate, the correlation and regression analysis and forecasting methods were used. The initial information was an array of monthly data from the Ministry of Finance of Ukraine on world oil prices, diesel prices and the exchange rate from January 2014 to December 2022 (Prices and markets, n.d.).

The information base of the study included reference and information publications, the regulatory

framework of state economic regulation of the development of the agricultural sector of the economy (Official web portal of the Parliament of Ukraine), statistical and analytical data of the Ministry of Agrarian Policy and Food of Ukraine, the Ministry of Energy of Ukraine, the Ministry of Finance of Ukraine, the State Statistics Service of Ukraine, the State Customs Service of Ukraine, and scientific electronic sources.

RESULTS AND DISCUSSION

The importance of Ukraine's fuel and energy complex is determined by its role in the functioning of social and economic infrastructure. Its dependence on natural reserves of energy resources, imports, capital intensity and significant share in the cost of production of all sectors of the economy require special attention. By the early 2000s, there were oil refineries in seven regions of Ukraine. Their total capacity was 52 million tonnes per year. This was enough to cover the national economy's demand for domestically produced petrol and diesel fuel. The scale of the oil refining infrastructure is also evidenced by the 4,625 km long oil pipeline system with a capacity of 30-35 million tonnes per year. The design capacity of the Ukrainian oil transportation system is 100 million tonnes per year, and the capacity of the tank farm is 4 million m³ (Zakharchuk et al., 2021).

Ukraine's loss of subjectivity in the field of oil products supply is indicated by a 75% reduction in energy infrastructure by 23 February 2022. In 2022, new transport routes were developed and the fuel supply system was changed. Ukraine's fuel market has been completely rebuilt. An extensive fuel supply system has been created. Logistics has changed radically, which has led to an increase in costs. During the war period, the volume of fuel transported by petrol tankers increased from 0.5 to 50%. Fuel importers also changed. 95% of petrol and 75% of diesel are imported from Romania, Lithuania, Slovakia, Greece, Bulgaria, and Poland (State Customs Service of Ukraine, 2023).

In 2011-2023, the total consumption of petrol and diesel fuel by sectors of the national economy was 1.7-4.6 million tonnes and 4.7-6.3 million tonnes, respectively. The largest share of consumed fuel resources is accounted for by agriculture, the military sector, transport, and industry. The share of agricultural enterprises in the total consumption of diesel fuel is over 29%, and petrol – 7%. The corresponding figures for industry are 15-20% and 6%, and for transport, 2.5-4% and 19-20%. The relative stability in the consumption of fuel and energy resources by sectors of the national economy was disrupted after the full-scale invasion on 24 February 2022. The share of the military sector in total diesel fuel consumption in 2022 increased to 37.6%, which was more than half as much in pre-war 2021 (15.8%) (Fig. 1) (State Statistics Service of Ukraine, n.d.).

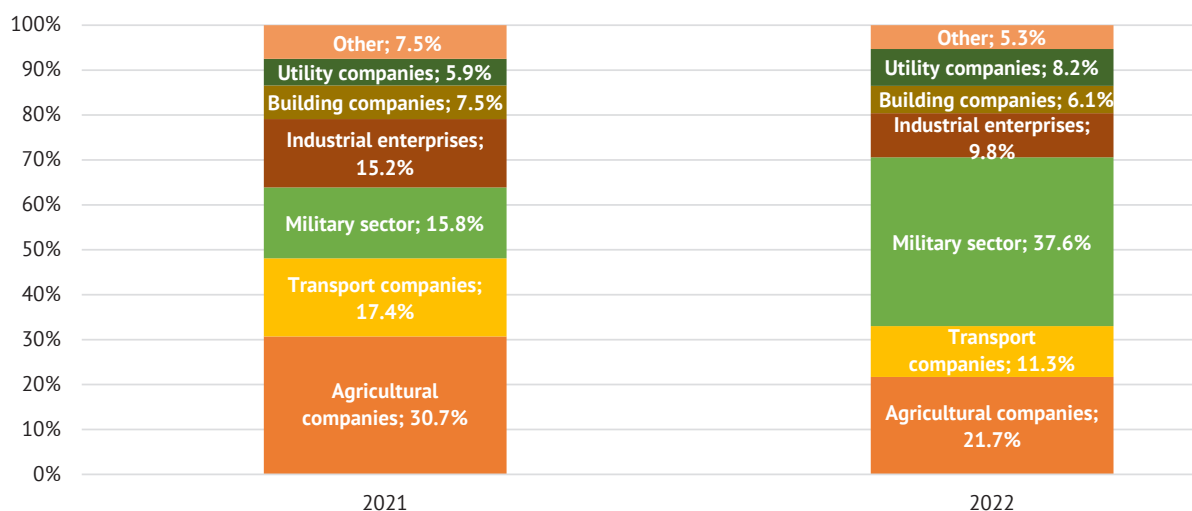


Figure 1. Share of major fuel consumers in 2021 and 2022

Source: (Market of oil products in Ukraine ..., 2023)

While agriculture and transport were the largest consumers of petroleum products before the beginning of 2022, the structure changed in favour of the military sector with the outbreak of war. In 2022, the share of fuel consumption by the military sector was 2.4 times higher than that of the agricultural sector. However, the agricultural sector

remains the main consumer of fuel in the national economy. The total consumption of diesel fuel in agriculture in 2023 was 972 thousand tonnes (calculated value), which is 33% less than in pre-war 2021. The situation is the same with petrol (Table 1).

Table 1. Fuel consumption by agricultural enterprises, thousand tons

| Type of fuel | Year | | | | | | | | | |
|-------------------------------------|--------|--------|--------|------|------|--------|--------|--------------------|--------------------|------------------|
| | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 (provisional) | 2022 (calculation) | 2023 (estimated) |
| Motor petrol | 149.3 | 132.8 | 130.3 | 125 | 106 | 111.3 | 84.4 | 96.0 | 93.1 (60.0) | 64.8 |
| Diesel | 1412.6 | 1255.6 | 1319.3 | 1345 | 1445 | 1604.3 | 1314.2 | 1459.4 | 1477.9 (900.0) | 972.0 |
| Petrol for 1 ha of sowing, kg | 7.9 | 7.1 | 6.9 | 6.5 | 5.5 | 5.7 | 4.3 | 4.8 | 6.6 (4.2) | 4.3 |
| Diesel fuels for 1 ha of sowing, kg | 75.0 | 67.1 | 70.2 | 69.8 | 74.6 | 81.8 | 66.6 | 72.3 | 100 (63.7) | 68.0 |

Note: *2022 in the numerator until February 24, 2022, in the denominator after February 24, 2022

Source: 2014-2020 – State Statistics Service of Ukraine. (n.d.). 2021-2023 authors' calculations. 2021-2022 – authors' calculations

The decrease in consumption of petroleum products in Ukrainian agriculture since independence was due to a 13% reduction in sown areas, a change in the structure of sown areas in favour of less energy-intensive crops, a fourfold reduction in the agricultural machinery fleet, the introduction of energy-saving technologies and a reduction in livestock. In 2022-2023, fuel consumption was affected by the war. Due to the large, occupied territories or those in the combat zone and the mining of the already liberated territories, not all agricultural land was cultivated. Since about a quarter of the sown areas were not sown in 2022, diesel consumption decreased to 900 thousand tonnes and petrol consumption to 60 thousand tonnes. In addition, in 2022, out of 764.3 thousand units, 109.6 thousand units of agricultural machinery (14.3%) were destroyed and 50.7 thousand units (6.6%) were damaged, with total losses of USD 4.7 bil-

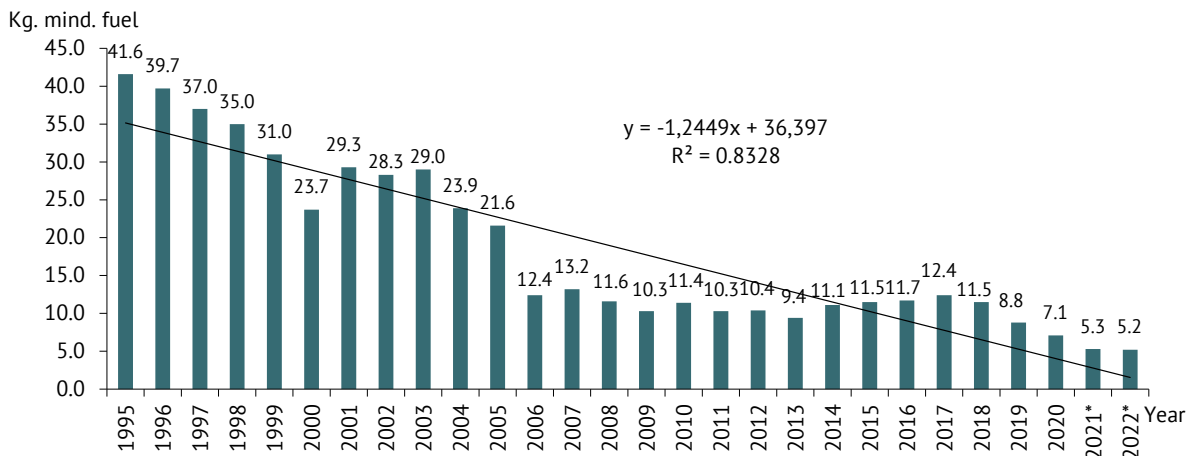
lion – USD 4.3 billion and USD 0.4 billion, respectively (Report on direct damage..., 2023). The liberation of territories and their partial demining in 2023 had consequences for agriculture. Crop areas were expanded, but they did not have a significant impact on the level of fuel and energy consumption. In 2023, compared to 2022, it increased (according to estimates) by only 8%.

At the same time, the company used combined tillage units that simultaneously perform several technological operations, alternative fuels, increased the share of low-energy crops in the structure of sown areas, and introduced advanced energy and resource-saving technologies. Agricultural and transport operations con-

sumed 85% and 15% of diesel fuel, respectively. Petrol was used mainly for transport (56%) and 44% for agricultural operations. Reduced energy consumption in agriculture has led to an 8-fold reduction in the energy intensity of agricultural products – 5.2 kg of standard fuel

in 2022 compared to 41.6 kg in 1995 (Fig. 2).

Figure 2. Energy intensity of gross agricultural products, i.e. of fuel per 1,000 hryvnias of gross production
Note: 2021*, 2022* is an estimated value
Source: Calculated from data of the State Statistics Service of Ukraine (n.d.)



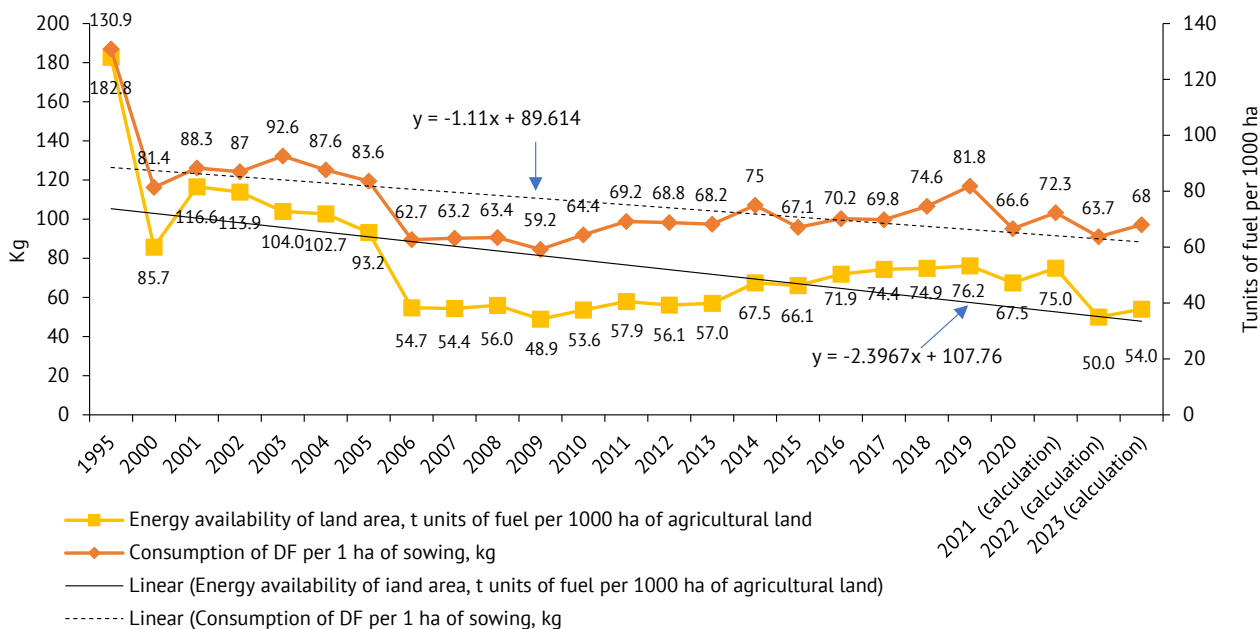
Ukraine. (n.d.)

Between 1995 and 2023, fuel consumption per 1,000 hectares of agricultural land decreased by 3.4 times and in 2022 amounted to 50 tonnes of equivalent fuel. At the same time, the cost of oil fuel per hectare of harvested

area increased. This was driven by rising fuel prices, the introduction of intensive technologies, which involve increasing the density of mechanized operations and increasing crop yields.

Figure 3. Energy security of the land area, i.e. of fuel per 1,000 hectares of agricultural land

Source: calculated from data of the State Statistics Service of Ukraine (n.d.)



The national economy is characterized by inter-sectoral price imbalances. Prices for oil products are growing faster than for agricultural products (State Statistics Service of Ukraine, n.d.). To purchase them, agricultur-

al enterprises need to sell more agricultural products annually (Table 2). In 1995, 1 tonne of diesel fuel cost 2.7 tonnes of grain, and in 2022 it cost 9.8 tonnes (>3.7 times). Compared to 2021, this figure has doubled. A similar trend is observed for all types of agricultural

products.

Table 2. Equivalence of the exchange of agricultural products and oil fuel, i.e.

| | Year | | | | | | | | | | | | |
|---------------------------------|------|------|------|------|------|------|------|------|-------|------|------|---------------------|---------------------|
| | 1995 | 2000 | 2005 | 2010 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2022 to 1995, times | 2022 to 2021, times |
| for 1 ton of petrol | | | | | | | | | | | | | |
| Grain | 2.7 | 3.1 | 6.3 | 5.9 | 5.4 | 6.6 | 5.8 | 7.7 | 4.8 | 4.5 | 9.8 | 3.7 | 2.2 |
| Sunflower | 0.9 | 2.6 | 2.7 | 2.2 | 2.2 | 2.7 | 2.7 | 3.72 | 2.1 | 1.7 | 3 | 3.3 | 1.8 |
| Sugar beets | 5.5 | 11.2 | 14.8 | 13.9 | 21.9 | 30.3 | 33.5 | 39.6 | 26.35 | 24.4 | 32.8 | 6.0 | 1.34 |
| Beef | 0.4 | 0.7 | 0.4 | 0.7 | 0.9 | 0.8 | 0.8 | 1 | 0.7 | 0.8 | 1.1 | 2.8 | 1.4 |
| Milk | 1.7 | 2.5 | 2.3 | 2.3 | 3.4 | 3.5 | 3.4 | 3.6 | 2.6 | 2.8 | 4 | 2.4 | 1.4 |
| for 1 ton of diesel fuel | | | | | | | | | | | | | |
| Grain | 2.3 | 3 | 6.7 | 5.9 | 4.4 | 7.7 | 7.4 | 7.4 | 4.9 | 4.5 | 9.8 | 4.3 | 2.4 |
| Sunflower | 0.8 | 2.6 | 2.8 | 2.2 | 1.8 | 3.2 | 3.4 | 3.6 | 2.1 | 1.7 | 3.3 | 4.1 | 1.9 |
| Sugar beets | 4.8 | 11 | 15.7 | 13.9 | 17.7 | 35.1 | 42.6 | 37.9 | 26.9 | 24.3 | 36.2 | 7.5 | 1.5 |
| Beef | 0.4 | 0.6 | 0.5 | 0.7 | 0.7 | 0.9 | 1 | 1 | 0.7 | 0.8 | 1.2 | 3 | 1.5 |
| Milk | 1.5 | 2.5 | 2.5 | 2.3 | 2.8 | 4 | 4.4 | 3.5 | 2.6 | 2.7 | 4.4 | 2.9 | 1.6 |

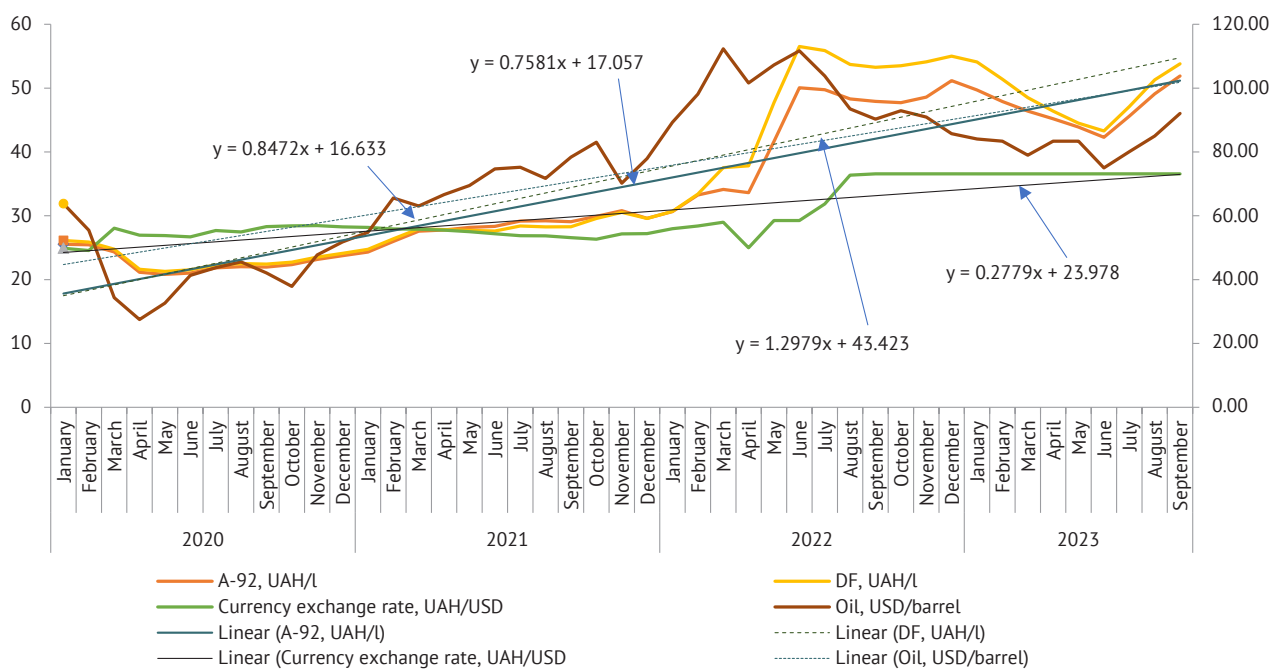
Source: calculated based on the data (State Statistics Service of Ukraine, n. d.)

According to the State Customs Service of Ukraine (n.d.), in 2022, imports of petroleum products to Ukraine

in monetary terms amounted to USD 8.8 billion. This is 56% higher than in 2021. In physical terms, imports amounted to 7.3 million tonnes, which is 17% less than in the previous year. According to the research, the retail price of diesel fuel depends on the global oil price and the exchange rate by 79.3%, while other factors account for 20.7%. However, in 2022, other factors also determined the dynamics of prices in the fuel market, especially the rise in the cost of transportation logistics. Starting in February 2022, the rise in fuel prices was driven by higher logistics costs and, consequently, higher dealer costs, in addition to the increase in oil

prices and changes in the national currency exchange rate. To slow down price growth and stabilize prices, the tax burden was reduced by cutting the value added tax from 20% to 7% and cancelling the excise duty. This has yielded results, and the dynamics of price growth has slowed down (Fig. 4). Improved logistics and sufficient imports in the second half of 2022 and early 2023 stabilized prices. And the refund of excise tax and VAT from 1 July 2023 led to an increase in prices.

Figure 4. Dynamics of world prices for oil, petrol, diesel fuel, and the exchange rate of the US dollar to UAH
Source: compiled according to information from the



Ministry of Finance of Ukraine, n. d.

Every year, in mid-February, before the start of spring field work, fuel prices begin to rise seasonally. During

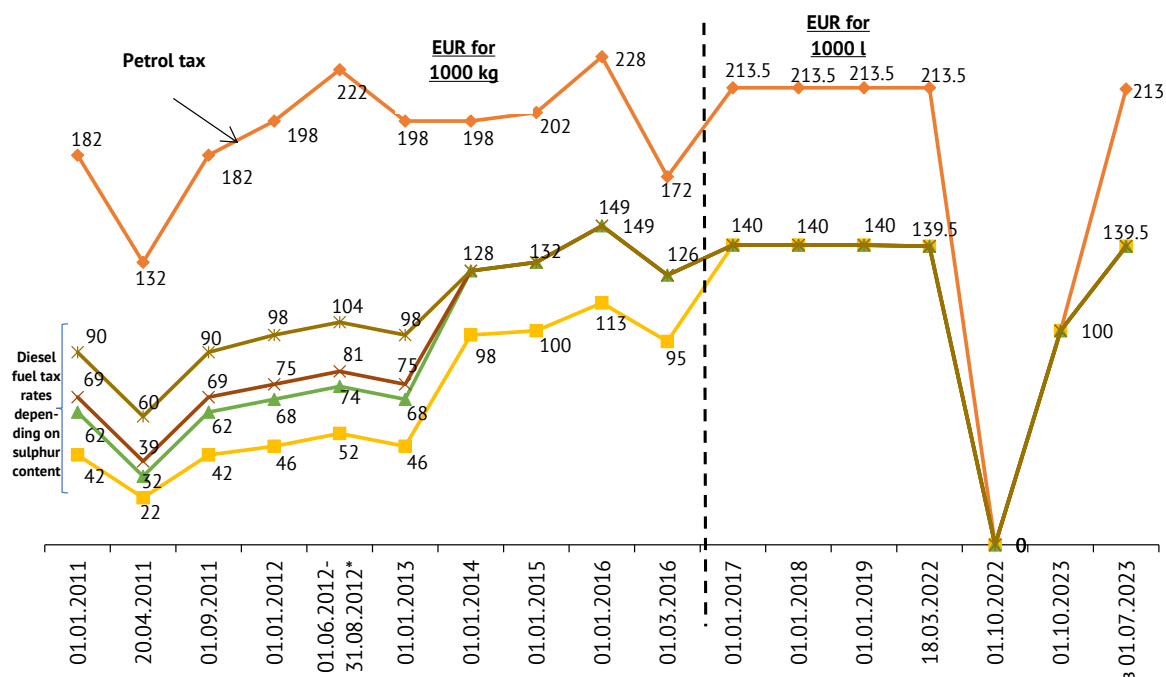
this period, retail prices for fuels and lubricants used in agriculture (low-octane petrol and diesel) will increase. Since February 2022, fuel prices have risen sharply, from 29.4 UAH/l in January to 49.5 UAH/l in June for petrol and 29.4 and 56.4 UAH/l for diesel, following the start of the Russian invasion and preparations for spring field work. On average, petrol prices increased by 70% and diesel prices by 92%. The rise in prices for petroleum products was also driven by the lack of diversity in supply routes, with only European supply remaining. For the first time since October 2014, the price of Brent Crude Oil on the global market reached USD 115 per barrel. USD per barrel (Ministry of Finance of Ukraine, n.d.).

Despite forecasts of further growth in the price of oil products, from mid-July 2022, the price began to decline and by the end of August it had fallen by 5% (Prices and markets, n.d.). For example, in the same period in Poland, the price of petrol was 5.8-6.4 zlotys

(45-49 UAH) per litre compared to 6.6-6.8 zlotys (48-50 UAH) per litre in May of the same year (Ceny Paliw w calej Polsce..., 2022). In other words, the price dynamics on the Ukrainian petroleum products market were changing in sync with the European one.

The main economic method of regulating the fuel market is the excise tax. Until 2014, excise rates on diesel fuel were determined by the sulphur content. Starting from 2014, the number of excise rates was reduced to two, and a single rate was introduced from 2017 to 2023. In 2016, the excise tax rates on petroleum fuel were transferred from EUR per 1000 kg to EUR per 1000 litres without increasing taxation, i.e. the excise tax rate was adjusted by the conversion factor of kilograms to litres (Tax Code of Ukraine, n.d.). In 2017-2022, the excise tax rates on petroleum products remained unchanged (Fig. 5).

Figure 5. Size excise tax on petroleum products in Ukraine, 2011-2023



* From 01.06.2012 to 31.08.2012, the average rate with a ten-day adjustment, depending on the average price of 1

Source: formed according to changes in the legislation of Ukraine in 2011-2023 (Tax Code of Ukraine, n. d.)

On 15 March 2022, the Law on Additional Tax Incentives to Support Businesses in Time of War (Draft Law

on Amendments to Section ..., 2022) was adopted and came into force on 17 March, aimed at, among other things, curbing prices for petroleum products. The law abolished the excise tax on fuel and reduced the VAT rate from 20 per cent to 7 per cent. In August 2022, the Cabinet of Ministers approved draft amendments to the Tax Code of Ukraine (Draft Law on Amendments to Section..., 2022) to partially refund the excise tax on petroleum products that was in effect before the war. The excise tax on fuel was set at EUR 100/1,000 litres, which is almost double the pre-war excise tax rate for

petrol and one and a half times higher for diesel fuel. This is significantly lower than the minimum level in the European Union – 359 euros/1000 litres, as stipulated by Directive 2003/96/EC (Tax Code of Ukraine, n.d.).

For example, tax rates in EU countries are as follows: for diesel fuel, the UK – 647 euros/1000 litres, Italy – 617, Belgium – 600, Ireland – 515, the Netherlands – 512, Malta – 472, Germany – 470, Slovenia – 430, the Czech Republic – 418, Slovakia – 398; for Euro-Super 95 petrol: the Netherlands – 808 euros/1000 litres, Italy – 728, France – 691, Finland – 684, Germany – 655,

the United Kingdom – 647, Sweden – 639, Estonia – 563, Latvia – 520, Spain – 473 (Fuel taxes in the EU, 2023). Since May 2021, average retail prices for petroleum products have been regulated by the Ministry of Economy of Ukraine and reviewed every ten days. These measures somewhat restrained fuel price increases. The Resolution of the Cabinet of Ministers of Ukraine No. 594 (2022) suspended the quarantine regulation that set the maximum trade markups to the average price of petroleum products sold at petrol stations. The decision to suspend was made with the expectation that prices would not exceed UAH 52 per litre of petrol and UAH 58 per litre of diesel fuel. With the outbreak of hostilities on the territory of Ukraine on 24 February 2022, the country's supply of petroleum products became a matter of national importance. The situation was most challenging for agriculture, which is in constant need of diesel fuel to run agricultural machinery. Therefore, traders' competition for the right to supply fuel to agricultural producers became another factor in strengthening competitiveness. This restrained the increase in retail prices (Draft Law on Amendments to Section..., 2022; Resolution of the Cabinet of Ministers of Ukraine No. 594, 2022, Tax Code of Ukraine, n.d.).

From 1 July 2023, VAT was refunded in Ukraine (from 7 to 20%), while the excise tax was increased from EUR 100 per 1000 litres to EUR 213 for petrol and EUR 139.4 for diesel fuel (Law of Ukraine No. 9174, 2023). This decision was made due to: the volume of petroleum products consumption, which will bring additional monthly revenues to the state budget of about UAH 8 billion; a decline in oil prices: from \$140/barrel in March 2022 to \$75/barrel in early 2023 (Ministry of Finance of Ukraine, n.d.); and the foreign exchange costs of petroleum products during martial law are the highest after weapons. This will reduce the outflow of foreign currency, while an increase in the tax burden and, consequently, higher prices will cause a decline in oil fuel consumption.

The need to increase the efficiency of agricultural production in the face of a permanent rise in the price

of oil products makes the issue of the energy intensity of agricultural products a pressing one. The low solvency of farmers, insufficient technical and technological support, and uneven fuel price increases are the reasons for negative processes in agriculture. Therefore, the problem of sufficient energy supply to meet their needs remains acute. During 2014-2023, the dynamics of prices for petroleum products and global oil prices changed synchronously in certain periods. While the global trend of declining oil prices was the opposite, the dynamics of prices for petroleum products in Ukraine had the opposite trend. This is primarily due to the upward trend in the exchange rate. Given the results of the analysis, it can be argued that the macroeconomic stability of the country is an objective condition for the effective functioning and development of the national fuel market.

The article uses multiple correlation and regression analysis to identify the impact of individual factors and their combination on the price of petroleum products and to establish price trends for the future. Based on the results of the regression analysis, a model for calculating the price of diesel fuel depending on world oil prices (X1) and the exchange rate (X2) is built:

$$Y = -9.9018 + 0.1192X_1 + 1.0989X_2. \quad (1)$$

The calculated regression coefficients show the level of influence of individual factors independent of each other on the resultant indicator. In particular, the value of $b_1 = 0.1192$ shows that an increase in the world oil price by USD 1 per 1 barrel. USD per 1 barrel leads to a 12 kopecks increase in the price of 1 litre of diesel fuel at a constant dollar exchange rate (the second factor). The value of $b_2 = 1.10989$ shows that an increase in the exchange rate of 1 USD by 1 UAH will lead to an increase in the price of diesel fuel by 1.1 UAH per 1 litre, with the world oil price unchanged (the first factor). Substituting the projected values of oil prices and the exchange rate into the equation, the projected prices for diesel fuel in Ukraine in 2023-2024 were obtained (Table 3).

Table 3. Forecasted prices for diesel fuel in Ukraine in 2023-2024

| Price of 1 barrel of Brent oil, USD | The price is 1 USD, hryvnias | | |
|-------------------------------------|------------------------------|-------|-------|
| | 36.56 | 38.50 | 40.00 |
| 78.0 | 49.57 | 51.70 | 53.35 |
| 90.0 | 51.00 | 53.13 | 54.78 |
| 105.0 | 52.79 | 54.92 | 56.57 |

Source: own calculations

According to the model, in 2023-2024 the price of diesel fuel in Ukraine will increase due to the main factors.

The built regression model for calculating the price of diesel fuel in Ukraine depending on the price of oil and the currency is the basis for identifying the directions of development of the oil products market and forecasting their prices in the short term.

Overall, the fuel and energy market is quite dynamic. The situation on it changes under the influence of internal and external factors. The growth in fuel prices is influenced by the war in Ukraine, which resulted in the suspension of fuel production by oil refineries, the in-

stability of the national currency and price fluctuations in the global crude oil market. The increase in the cost of petroleum products, in turn, affected the agricultural sector. Limited fuel supplies in the first half of 2022 due to constant shelling and, against the backdrop of this situation, a rapid rise in fuel prices, led to a reduction in the number of technological operations carried out in the production of agricultural products. Improved logistics and sufficient imports in the second half of 2022 and early 2023 stabilized prices and brought agricultural production back to normal.

The issue of the agricultural sector's supply of petroleum products, given the industry's great social significance, is of interest to both Ukrainian and foreign scholars. For example, W. Zhang *et al.* (2023) investigate the dependence of prices in retail petroleum product markets on world oil prices. In their study, they used a nonlinear time series analysis approach that takes into account the unique features of petroleum product markets and found asymmetric price adjustments depending on price shocks in the global oil market. This approach confirms the understanding of long-term price relations, short-term dynamic adjustments and mechanisms of price reaction to sharp changes in crude oil prices in the context of fuel markets.

The same conclusion was reached in their research by another group of scientists who studied the impact of market regulation on price fluctuations in the oil products market in the long term (He & Lin, 2023). They also studied the dependence of petrol and diesel prices on the price of oil. Their findings show that the asymmetric response of petrol and diesel prices to crude oil prices is basically the same. Only the long-run asymmetry was confirmed, while the short-run asymmetry was not tested. The long-run equilibrium price is slowly rising against the backdrop of oil price fluctuations, most likely due to the increasing market power of oil companies. This means that market power is approaching monopoly.

The relationship between fuel consumption and agricultural productivity has been studied by J. Hu *et al.* (2023). The researchers also study the impact of other factors such as the state of industries, population structure, and energy structure. The relationship between agricultural economics and energy management has also been studied from the perspective of impact-based policy. X. Wen *et al.* (2018) used univariate modelling to determine the impact of the petroleum product pricing reform on industry development. Their research indicates that upward price adjustments have a greater impact on market volatility than downward adjustments.

The dependence of taxation on fuel consumption in the national economy and by the population was studied by A.L. Proque *et al.* (2022). The results of their research indicate that tax policy directly affects production costs in industries that use vehicles more intensively or consume fuel directly in the production process, making changes in household income and con-

sumption more significant. This leads to a change in the budgetary constraints of the poorer segments of the population through the income and substitution effect – a reduction in other consumption items. Meeting the growing demand for fuel and energy resources in the context of their shortage was studied by B. Lin & M. Raza (2021). Using a translogarithmic production function, they determined the elasticity of substitution of energy inputs (petroleum products, electricity) with non-energy inputs (labour and capital). They determined the limit to which energy inputs can be interchangeable without losing economic efficiency.

The fuel consumption of technical means used in agriculture and its savings at different stages of the production process were also studied by P. He *et al.* (2019). They proposed a mathematical model that can describe a model for scheduling agricultural machinery with a minimum fuel consumption to optimize fuel consumption in non-working activities (travelling between fields and within fields). And they proved the possibility of saving up to 19.5% of fuel on internal logistics. Their research provides a general framework for reducing fuel consumption of heterogeneous agricultural machinery by taking into account non-working distances in intra- and inter-field logistics and making these agricultural vehicles more economical and environmentally friendly.

The long- and short-run relationships between fossil fuel prices, including oil and petroleum products, and agricultural commodity prices were investigated by S-M. Yoon (2022). The results of his research show a significant short-term bidirectional causality between oil, bioethanol, and grain prices. There is an asymmetric and non-linear relationship between these variables. There are also policy implications in this regard, such as energy price stability, reducing energy dependence on fossil fuels, promoting agricultural development, environmental sustainability, energy conversion and reducing greenhouse gas emissions.

Energy consumption is a matter of global concern, namely due to the limited availability of energy sources and the consequences in the form of gas emissions. In the agricultural sector, this issue is of additional concern, given that it is an economic activity that is sensitive to the cost of inputs. The aim of the study by V.J.P.D. Martinho (2016) is to analyse the energy use efficiency of European Union countries at the farm level in terms of agricultural output and agricultural area used. The researcher argues that increasing labour productivity in agriculture can reduce the need for energy and other inputs.

Given the high price of crude oil, the biofuel market is growing. In such circumstances, it is also important to introduce energy-saving technologies when using agricultural machinery. M. Mattetti *et al.* (2022) studied the issues of saving fuel resources in the operation of agricultural machinery, in particular tractors. They investigated technical innovations that can save fuel and,

as a result, reduce emissions of pollutant gases such as carbon monoxide (CO), nitrogen oxide (NOX), particulate matter (PM) and hydrocarbons (HC), gases emitted with the greenhouse effect, such as CO₂.

Studying the prospects for increasing the energy autonomy of the agro-industrial complex of Ukraine, G. Kaletnik (2019), using the experience of highly developed countries in alternative energy sources, proved that diversification of energy sources helps to reduce the level of energy dependence of the agro-industrial complex and is one of the factors of increasing the competitiveness of agricultural products in the market by reducing production costs.

Studying the scientific works of scientists from different countries who have studied fuel consumption and its market, it is impossible not to agree with their main ideas and conclusions: prices for petroleum products directly depend on the world oil price and government regulation of the petroleum products market, and the number of technological operations performed in the production of agricultural products affects the efficiency of agricultural production and is a key factor in increasing its competitiveness. Therefore, given the limited availability of petroleum-based fuels, it is important for Ukraine to develop biofuel production and diversify its supply of foreign oil fuels.

CONCLUSIONS

The study showed that over the past decade, the consumption of fuel and energy resources by the agricultural sector of Ukraine has significantly decreased. The consumption of diesel fuel decreased by 40% and petrol by 2.5 times. Since petrol is mainly used in agricultural production for transporting products, the significant reduction in consumption is explained by the involvement of third-party organizations in transportation. The decrease in diesel consumption had a number of positive and negative reasons. The negative factors include the rise in the price of fuel and energy resources, which entails a reduction in the number of technological operations performed and, accordingly, a decrease in the efficiency of agricultural production. On the positive side, the introduction of innovative technologies that allow saving fuel by using combined tillage machines, energy-saving tillage technologies

and precision farming. This, in turn, helped to reduce the energy intensity of agricultural land and increase the energy efficiency of agricultural production.

The structure of fuel consumption by industry has also changed. Prior to Russia's full-scale invasion of Ukraine in February 2022, the agricultural sector had been the main consumer of petroleum products for a long time. Its share in total consumption was about 30%. The war changed the structure in favour of the military sector. Its share increased to 37% of total consumption in the country, more than double the pre-war period.

The war and the resulting crisis in Ukraine's economy led to an increase in fuel and energy prices in the first half of 2022 by 70% for petrol and over 90% for diesel. At the same time, disruptions in the logistics of agricultural products due to constant shelling led to a decline in their value and further exacerbated the problem of price disparity. Even the government's policy of restraining fuel prices by reducing taxation and cancelling the excise duty in 2022 had only a temporary effect. Over the past year, the increase was 1.5-2 times, depending on the type of agricultural product.

Calculations showed a very close relationship between the price of fuel, the global oil price, and the exchange rate of the national currency against the US dollar. The established dependence made it possible to forecast changes in fuel prices in the short term for 2023-2024, depending on changes in these indicators. An increase in each of them will inevitably lead to an increase in the cost of petroleum products on the Ukrainian market. Therefore, in the current environment, it is important to restore and develop Ukraine's own production of both oil products and biofuels to reduce the overdependence of the national economy and the agricultural sector in particular on external factors that affect the fuel market, which will require further research on this topic.

ACKNOWLEDGEMENTS

There is none.

CONFLICT OF INTEREST

There is none.

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Стан та перспективи забезпеченості сільського господарства паливом в Україні

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Анотація. В умовах воєнного стану в Україні, коли нафтопереробна промисловість зупинилася, а більшість логістичних ланцюгів зруйновано, питання забезпеченості сільськогосподарського виробництва – гарант продовольчого забезпечення України і світу, паливно-енергетичними ресурсами набуває особливої актуальності. Мета статті – дослідити споживання нафтопродуктів в аграрному секторі України в умовах воєнного стану, дослідити стан та державне регулювання ринку та пального з нафтопродуктів зпрогнозувати їх ціну на перспективу. У статті було використано наступні методи: діалектичний, абстрактно-логічний, статистичний, кореляційно-регресійний, табличний і графічний, аналізу рядів динаміки та структурних зрушень, порівняння, стратегічного планування та прогнозування. За результатами досліджень, здійснених з використанням статистичних методів, проаналізовано споживання сільськогосподарськими підприємствами бензину та дизельного палива, а також розраховано їх вартість на гектар зібраної площі. Встановлено, що зменшення обсягів використання пального у 2022 р. пов'язане з тим, що ¼ посівних площ не було засіяно у зв'язку з війною. Було також досліджено, яка частка пального використовується для потреб аграрного сектору економіки. За результатами кореляційно-регресійного аналізу виявлено тісний зв'язок між валютним курсом і ціною на дизпалива в Україні та негативний – між світовою на нафту і ціною на дизельне пальне. Завдяки встановленій залежності розроблено модель розрахунку ціни на дизпаливо, виходячи з світових нафтових цін на валютного курсу та проведено розрахунок ціни. Обґрунтовано, що основним економічним методом державного регулювання ринку пального є встановлення акцизного податку. Зроблено висновок, що скорочення споживання паливно-енергетичних ресурсів у аграрному секторі України призвело до зменшення енергомісткості аграрної продукції. Результати досліджень мають практичне значення, яке дозволить виявити дестабілізуючі чинники на ринку нафти і нафтопродуктів, а також сформулювати політику держави, яка сприятиме використанню енергетичних ресурсів, зокрема рідкого палива, у сільському господарстві в умовах воєнного стану

Ключові слова: сільськогосподарські підприємства; енергомісткість; енергозабезпеченість; воєнний стан; нафтопродукти; імпорт; логістика



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A clinical case of a mixed testicular tumour with cryptorchidism in a dog of the Yorkshire Terrier breed

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Abstract. Histological examination of testicular tumours in cryptorchid males allows determining the nature of neoplasia, prognosis of long-term consequences in the form of metastases, and defining the optimal method of treatment of the animal, which determines the relevance of research in this area. The aim of the

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work is to determine the pathohistological structure of neoplasia of the left, cryptorchid, and morphology of the contralateral testes in a Yorkshire Terrier male with unilateral cryptorchidism. General clinical, ultrasonographic, radiological and histological methods were used in the examination of the animal. The article presents data on a mixed tumour of the intraperitoneal left testis of a 6-year-old Yorkshire Terrier, which is an atypical clinical case. It was found that the characteristic ultrasonographic features of the cryptorchid left testis tumour were numerous isoechoic foci of different diameters (from 4 to 26 mm), hyperechoic septa, and tuberos contours with a hyperechoic capsule. At laparotomy, the altered testis had an uneven surface saturated with blood vessels. The section showed milky-white neoplastic areas separated by fibrous bands that did not correspond to the normal structure of the organ. Histological examination of the parenchyma revealed areas of similar rounded cells in the form of a group of shapeless masses separated by a fibrous barrier. Neoplastic tubules had a developed fibrovascular stroma with an eosinophilic necrotic area. The protein membrane also had numerous fibrous formations. The layers of multifaceted cells were located perpendicular to the basal lamina, often with central necrosis, and the testicular mass contained multifocal haemorrhages. Such signs are characteristic of the lesion of Sertoli cells and interstitial Leydig cells, which indicated a mixed type of tumour of the left extraperitoneal testis of the Yorkshire Terrier. The contralateral right testis was unchanged and corresponded to the natural morphological and histological structure. The prostate was normal on macroscopic and histological examination, which has not been previously reported. Six-month follow-up of the dog showed no signs of metastatic process. The practical significance of the work is to obtain new scientific knowledge about the development of mixed tumours of the testis in cryptorchid males and the prospects for the treatment of diseased animals

Keywords: neoplasia of the testis; extraperitoneal testis; Sertoli cell tumour; interstitial Leydig cells; fibrovascular stroma

INTRODUCTION

Neoplasms of the canine gonads are playing an increasingly important role in small animal veterinary medicine due to the improvement of clinical diagnosis and treatment regimens. Cryptorchidism is a common abnormality of male reproductive development. With an increase in temperature (namely, body temperature), the germ cells of the testis are depleted, inflammatory reactions develop that negatively affect somatic cells (Sertoli, Leydig), and can provoke neoplasia. The strategy for treating males with cryptorchidism should be based on an understanding of the characteristics of neoplastic processes in the testes. Depending on the histological characteristics of the altered cryptorchid testis, the feasibility of using either surgical treatment alone or supplementing surgical intervention with chemotherapy is determined. The morphological characteristics of the tumour determine the choice of chemotherapeutic drugs, the scheme of their use, the list of methods for diagnosing distant metastatic processes in the body, as well as the prognosis for life, so the topic of research is relevant.

H. Aupperle-Lellbach *et al.* (2022) note that an important part of diagnosing patients with neoplasia is the histopathological examination of neoplasia, taking into account changes in the behaviour of the sick animal. According to the World Health Organization (n.d.), testicular tumours are quite common and are classified into interstitial cell tumours (Leydig cell tumours), seminomas and sustentacular cell tumours

(Sertoli tumours). Other neoplastic tumours are less common and are divided into mixed germ cell, stromal, and spermatocytic cord tumours. In dogs, testicular tumours are the most commonly reported genital tumours (16.8%), of which 56.3% are cryptorchid and 44.7% are scrotal (WHO, n.d.). Based on the results of studies of the prevalence, clinical manifestation, macroscopic and histological aspects of testicular neoplasms in males, Nascimento *et al.* (2020) noted the development of gonadal neoplasia in animals over 8 years of age.

The Fédération Internationale Cynologique Internationale has officially recognized about 350 dog breeds as being prone to diseases, including neoplasms. A group of researchers (Baioni *et al.*, 2017) noted that in the development of tumours in dogs of the German Shepherd, English Setter, Italian Hound, Maremma Shepherd breeds, the proportion of affected animals depends on the popularity of the breed in different time periods of human life. The work of C. Gradil & R. McCarthy (2023) shows that one of the risk factors for testicular neoplasia in males is cryptorchidism, which causes a 26-fold increase in the risk of Sertoli cell tumours and a 15-fold increase in seminoma. Dog breeds with more frequent occurrence of cryptorchidism than others include Chihuahua, Zwergschnauzer, Pomeranian Spitz, German Shepherd, Siberian Husky, Poodle, and Yorkshire Terrier. It has not been possible to establish the exact cause of cryptorchidism in

animals, but it is believed that this pathology is associated with a defect in the auto-recessive sex trait, which is often recorded in these breeds of dogs. The diagnosis of cryptorchidism (intra-abdominal or inguinal) is difficult, as such testes cannot be palpated, so it is advisable to use radiographic and ultrasonographic studies, which also help in the diagnosis of testicular neoplasia (Othman *et al.*, 2022).

N.I. Mykhalenko & D.V. Voitsekhovych (2017) found that interstitial cell tumours (Leydig cell tumour), seminomas and Sertoli cells are the most commonly reported tumours in dogs. Most of the publications on these testicular neoplasms are case reports of dogs of different breeds. There are only a few cohort studies that report on a population-based tumour registry in dogs (Kudo *et al.*, 2019; Manuali *et al.*, 2020), but they do not describe the clinical characteristics of testicular neoplasia. E. Chiti *et al.* (2022) report the need for curative orchiectomy for bilateral mixed testicular tumour, which has a positive result.

The analysis of the literature shows that cryptorchidism is a risk factor for testicular neoplasms in males; testicular tumours in males are common; histological examination of testicular tumours in cryptorchid males is important for establishing the diagnosis; orchiectomy gives positive treatment results; clinical and histological characteristics of cryptorchid testes with neoplasia are described sporadically and are not described in the national scientific literature. Thus, the study of a case of a mixed testicular tumour with cryptorchidism in a dog is useful for establishing the prevalence of testicular neoplasia in animals, characterizing the factors associated with the occurrence of this tumour, and describing original histological features that may be diagnostic in understanding their pathogenesis. This study aimed to histologically investigate and describe a clinical case of a testicular neoplasm removed from the abdominal cavity of a left-sided Yorkshire Terrier, which was first documented in the literature.

MATERIALS AND METHODS

The study was conducted at the Veterinary Medicine Clinic in Poltava in 2022-2023. The owners of a 6-year-old male Cryptorchid Yorkshire Terrier complained of decreased appetite and anxiety, especially at night. The dog is vaccinated against plague, parvovirus, leptospirosis, infectious hepatitis, parainfluenza, rabies. The dog is treated twice a year (in early spring and autumn) for ectoparasites. The animal consumed high quality food in accordance with all feeding standards. Water was freely available.

The dog was examined according to the following scheme: collection of anamnestic data, examination of

habitus, palpation, auscultation, thermometry, ultrasonographic examination of the abdominal cavity. Ultrasonographic examinations were performed with an ultrasound machine Sono Scape A6 (China), sectoral transducer (frequency 6.0 MHz). After the ultrasonographic detection of the neoplasm, an examination radiography of the animal was performed to exclude metastatic tumours. After that, a decision was made to surgically remove the tumour. The laparotomy was performed along the white line of the abdominal wall, according to the generally accepted method. The right testicle was removed in an open way, with ligation of the spermatic cord.

After extirpation of the testicular neoplasm, histological examinations were performed on the selected organs, which were numbered and fixed with a 10% aqueous solution of neutral formalin. The organ tissue pieces were washed under running water, dehydrated with aqueous solutions of ethyl alcohol in increasing concentration, and then embedded in paraffin. The paraffin blocks were cut on a sled microtome (type MPS-2, China) to obtain a histological section (7-10 µm thick), stained with Karatzi's iron haematoxylin and eosin. The obtained histological sections were examined under a light microscope MICROmed XS-5520 (objective ×4, ×10, ×40; eyepiece ×10, ×20). A 3 Mpix MICROmed digital camera (China) was used to take digital photos of the histological material.

The histological characteristics were assessed according to the World Health Organization (WHO) histological classification of genital tract tumours in domestic animals. All studies were conducted in accordance with modern requirements, standards, and methods (requirements of DSTU ISO/IEC 17025:2006 (2006)), Law of Ukraine No. 27 (2006), Order of the Ministry of Education and Science, Youth and Sports of Ukraine No. 249 (2012), European convention for the protection of vertebrate animals used for research and other scientific purposes (1986).

RESULTS AND DISCUSSION

After evaluating the results of the anamnestic data, the animal was diagnosed with sleep disorders. Abdominal wall palpation revealed a dense mass in the abdominal cavity. Ultrasonographic examination revealed an 11×13 cm mass of heterogeneous echogenic structure. The structure of the neoplasm was represented by numerous isoechoic foci, ranging in diameter from 4 to 26 mm, with hyperechoic septa of various thicknesses, uneven contours (Fig. 1). The lesion was well vascularized and corresponded to a degenerated parenchymal organ, its contours were tuberos and had a hyperechoic capsule. In general, it is impossible to determine the type of neoplasm by ultrasonography.

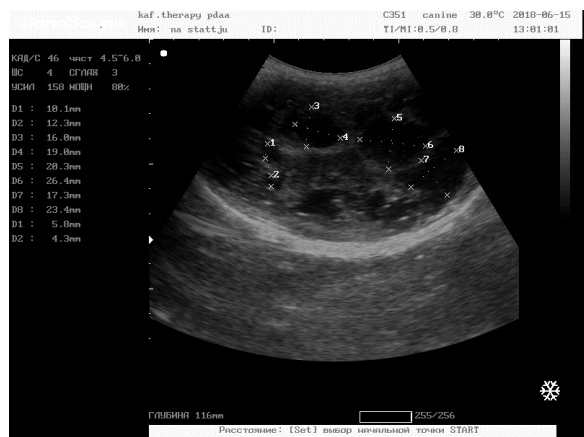


Figure 1. Ultrasound examination of a dense mass in the abdominal cavity

Based on anamnestic data, a diagnostic and therapeutic laparotomy was performed. An abdominal examination showed that the neoplasm was a modified left testis, which was removed. The right testis was unchanged and corresponded to the anatomical characteristics of clinically healthy dogs, with its own vaginal membrane formed by serous tissue, extending to the epididymis and mesentery. The connective tissue capsule of the testis was dense, closely fused with the

serous membrane, and from the head end of the organ it was immersed in its thickness and formed the mediastinum of the testis. Numerous partitions extended from the mediastinum, dividing the testis into separate chambers. The right testis was small, 22×16 mm in size, round-ellipsoidal in shape.

Histological examination of the contralateral testis showed that the protein membrane was a dense collagenous tissue with elastic fibres and formed partitions that divided the testis into lobes. The basis of the lobules was loose connective tissue permeated with tortuous seminiferous tubules, which represented the parenchyma. The wall of the seminiferous tubules was formed by its own membrane, which had basal, myoid and fibrous layers. Thus, the histological structure of the contralateral testis was normal.

Macroscopically, the retroperitoneal cryptorchid testis was characterized by the presence of an uneven, hyperaemic surface with dilated vessels (Fig. 2A). Loss of normal architecture was observed on the surface of the testis section. Multifocal cavitation haemorrhages were recorded over the entire area of the incision and on the surface of the testis (Fig. 2B). The prostate gland and mediastinal lymph nodes were severely enlarged. Homogeneous white parenchymal masses separated by dense connective tissue septa were found on the section.

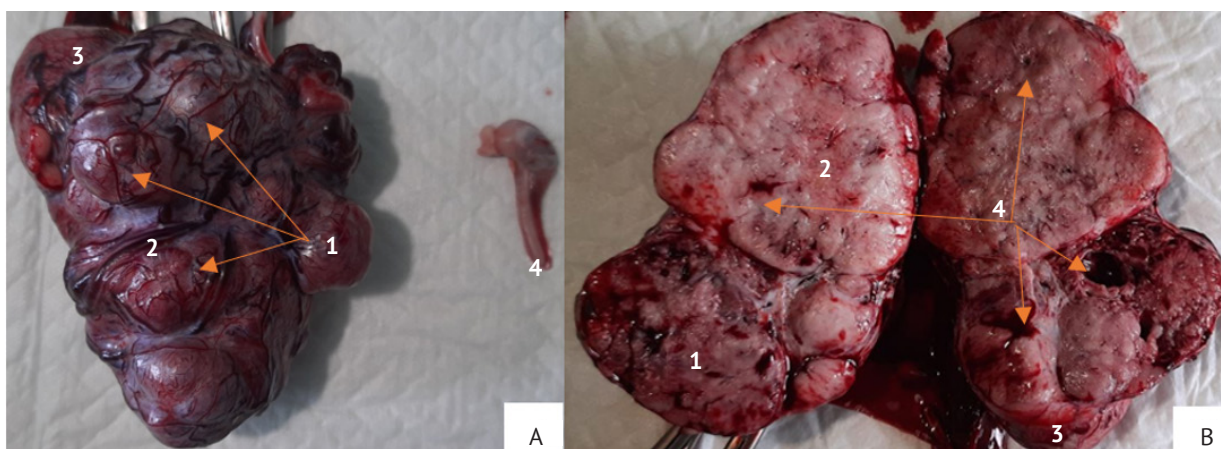


Figure 2. Macroscopic changes of the testis during unilateral cryptorchidism

Note: A – Semin (cryptorch) with the development of a seminoma: 1 – neoplasm; 2 – venous stasis; 3 – epididymal appendage; 4 – right testicle, without pathology (removed by castration). B – macroscopic changes in the testicle (sagittal section) with unilateral cryptorchidism: 1 – neoplasm; 2 – testicle parenchyma; 3 – accessory edge of the testicle; 4 – multifocal cavitation haemorrhages

Pathologically, the retroperitoneal cryptorchid testis was diagnosed as a mixed sertolioma (a tumour of Sertoli and Leydig cells of non-germ cell aetiology). Histological examination of the neoplasms revealed areas of parenchyma with similar rounded cells (Fig. 3A) with clear contours, light cytoplasm and large nuclei that formed conglomerates of shapeless masses (Fig. 3G). Such groups of cells were separated by fibrous partitions (Fig. 3B). In some areas, the growth

of germ cell epithelium was observed, which filled the cavity with the convoluted seminiferous tubules (Fig. 3B, 3C), which led to the damage to Sertoli cells, and thus made further gametogenesis impossible. Similar research results have been reported by other researchers, in particular, the authors pointed to the coexistence of a Sertoli cell tumour and proliferation of interstitial Leydig cells in a male that was not a cryptorchid (Chiti *et al.*, 2022).

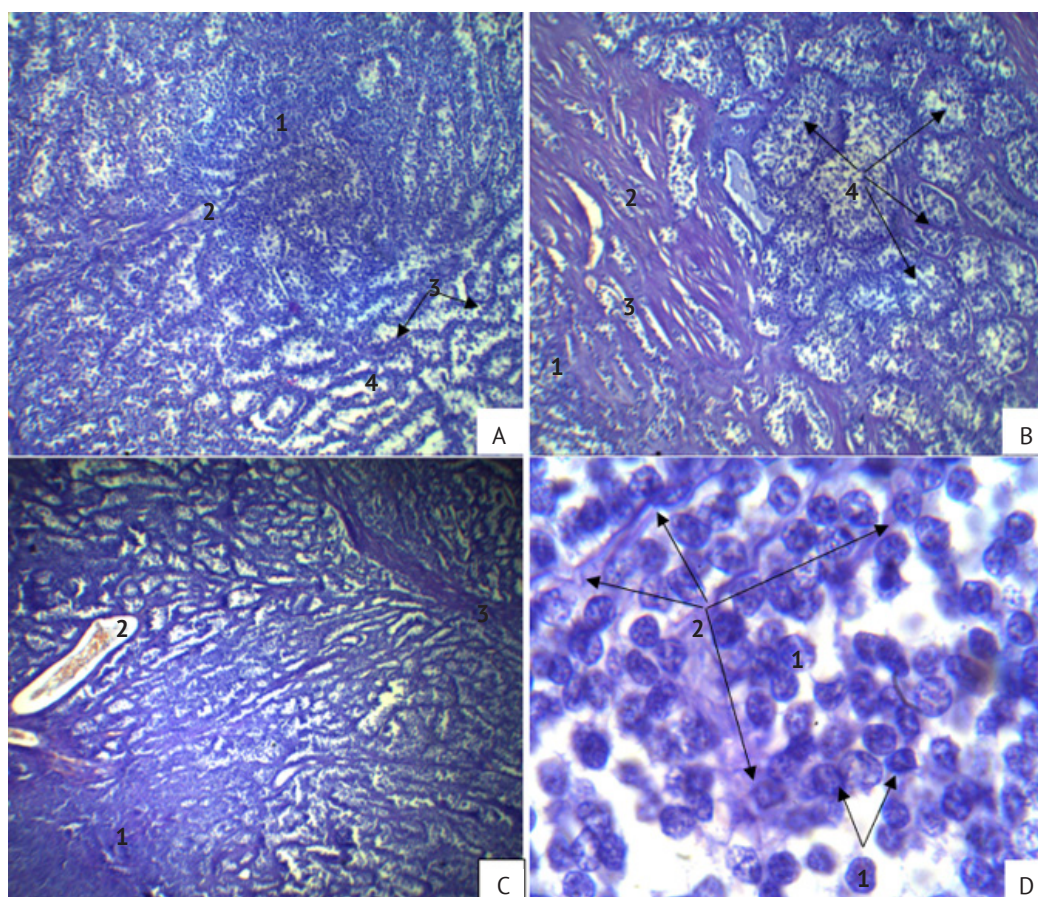


Figure 3. Histological changes of the testis in male seminoma

Notes: Haematoxylin and eosin staining. Magnification Ax64, Bx64, Cx160, Dx640. A: 1 – growth of germinogenic epithelium; 2 – capillary blood filling; 3 – walls of tortuous seminiferous tubules; 4 – lumen of tortuous seminiferous tubules; B: 1 – growth of germinogenic epithelium; 2 – connective tissue elements forming testicular septa; 3 – leukocyte infiltration; 4 – tortuous seminiferous tubules; C: 1 – growth of germinogenic epithelium; 2 – capillary blood filling; 3 – connective tissue elements forming testicular septa; D: 1 – germinogenic epithelium in the lumen of the seminiferous tubule behind seminomas; 2 – fibrous partitions;

It was found that the protein membrane of the retroperitoneal cryptic testis was thickened, with numerous fibrous formations. Densely packed neoplastic tubules of irregular size were separated, with a well-developed fibrovascular stroma. The convoluted seminiferous tubules consisted of many layers of moderately pleomorphic spindle-shaped cells or multifaceted cells arranged perpendicular to the basement membrane, with or without central necrosis. These tumour cells had a rounded or elongated nucleus and/or dense eosinophilic or vacuolated cytoplasmic lesions with an indistinct cell border and pattern. Some large neoplastic tubules contained an eosinophilic central necrotic area. Many small immature tubules penetrated the thickened protein membrane. Severe multifocal haemorrhages and necrotic foci were also observed in the testicular mass. Morphologically, the tumour cells resembled Sertoli cells in the testis.

Unilateral cryptorchidism provokes the development of testicular parenchymal atrophy, causing dystrophy, necrosis, and neoplasia, which subsequently

grows into metastatic tumours (Crescio *et al.*, 2022). According to the study of the clinical condition of the dog, after removal of the neoplastic cryptorchid testis, no metastases were detected within six months of development. The data obtained on the clinical signs of this pathology only partially correspond to similar cases of cryptorchidism, in particular, in bilateral cryptorchidism in an 11-year-old poodle, clinical signs were characterized by bilateral symmetrical alopecia swelling of the prepuce, gynaecomastia, seborrhoeic dermatitis with scales (DeForge, 2020), in a 4-year-old Lhasa Apso Cryptorchid – hyporexia and tremors (tremors), blood tests in case of cryptorchid neoplasia in dogs were characterized by anaemia and thrombocytopenia. There have also been reports of lameness and tenderness on scrotal palpation (Padaliya *et al.*, 2023). Considering the results of studies by other authors, it can be noted that the dog reported in this article had only sleep disturbance as clinical symptoms. Palpation revealed the presence of a tumour in the hypogastrium,

but the animal did not demonstrate pain. The appetite was slightly reduced.

Most veterinarians are of the opinion that the clinical signs of cryptorchid testicular neoplasia are not specific, so a combination of imaging methods is used for the final diagnosis – abdominal ultrasound, colour Doppler, and plain radiography (Tannouz *et al.*, 2019). To confirm the diagnosis, an ultrasound examination of the abdominal cavity was used, which revealed the formation of a heterogeneous echogenic structure with a hyperechoic capsule of uneven contours. Similar changes in the studies of dogs with testicular tumours, including cryptorchid tumours, were noted by Italian researchers R. Orlandi *et al.* (2022), including complex structural formations surrounded by a hyperechoic capsule. Along with testicular neoplasia, an enlargement of the prostate gland is reported, its parenchyma becomes heterogeneous and alternates with polycystic formations (Sun *et al.*, 2017), which was not observed in the case described in this article. The prostate gland ultrasonographically, macroscopically and histologically did not differ from that of clinically healthy animals. Probably, the condition of the prostate was maintained by the endocrine function of the non-cryptic testis. Obviously, in bilateral cryptorchidism, the hormonal status changes more clearly than in unilateral cryptorchidism.

One of the imaging methods for neoplasia is radiography, which can detect metastases to bone tissue, parenchymal and other organs. Radiological diagnostics in separate studies by M. Russo *et al.* (2021) demonstrated bone proliferation and lysis of the humerus, lesions of the left tenth rib and lumen of both proximal humerus metaphysis. At the same time, the described cases of radiography do not indicate a clear localization of the testis into the hypogastrium, which is associated with a variety of breed characteristics and pathophysiological conditions. According to other researchers, in particular E. Park *et al.* (2017), in the case of a combined tumour (Sertoli cells and interstitial Leydig cells), no metastasis was detected on plain radiography. This indicates the feasibility of surgical treatment. In order to assess the degree of the pathological process, it is proposed to determine the concentration of testosterone and estradiol in the blood, the level of which increases in the case of cryptorchidism.

Intraperitoneal testes (cryptorchid) have a high risk of developing neoplasia compared to intrascrotal testes. Changes in the cryptorchid testis are macroscopically characterized by dense parenchyma and the presence of rounded lesions in the periphery. Leydig cell hyperplasia is more common in older dogs, while Sertoli cell tumours, seminomas and leydigomas are reported in the testes with approximately equal frequency, but a significant percentage of neoplasia in retroperitoneal cryptic testes is diagnosed as seminoma. Histopathologically, there is abundant eosinophilic cytoplasm with round (oval) nuclei and punctate nucleoli (Pecile *et al.*, 2021).

In the case of malignant seminoma, metastases penetrate the lymph nodes and bones, with possible foci in the scrotum, vaginal membrane, and, after a while, the skin and perioesophageal structures.

In order to treat metastatic seminoma in dogs, multimodal therapy consisting of surgery and chemotherapy is used (Kisani *et al.*, 2017). In the case described in this article, both the retroperitoneal cryptorchid testis and the contralateral unaltered testis were surgically removed from the dog. Since the tests performed on the animal did not reveal a metastatic process, chemotherapy was not used. Further monitoring of the dog's condition, as already reported, showed the appropriateness of this decision. According to V.G.S. Tannouz *et al.* (2019), unilateral cryptorchidism has a right-sided localization, which is due to the fact that the right testis is formed more cranially than the left, and therefore the path to the scrotum is longer. An unusual case of unilateral cryptorchidism of the left testis with neoplasia was recorded in the dog under study, which has not been reported in the literature.

CONCLUSIONS

Clinical examination of a 6-year-old male Yorkshire Terrier revealed a dense 11×13 cm mass in the abdomen. Ultrasound examination of the mass was characterized as a neoplasia with numerous isoechoic foci with hyperechoic trabeculae of various shapes and contours, with advanced vascularization. Given the history of unilateral cryptorchidism, the tumour was considered as a neoplasia of the extraperitoneal testis. Given the potential malignancy of the neoplastic process described in the literature, an additional plain radiography was performed, which did not reveal metastases in the thoracic cavity and skeleton. The extraperitoneal testis was surgically removed, as well as the contralateral testis.

Histological examinations showed that the parenchyma consisted of conglomerates of shapeless masses formed mainly by uniform round cells, light cytoplasm and large nuclei. In addition, there was an overgrowth of germ cell epithelium, filling the cavity with the seminiferous tubules. Thus, structurally, the tumour is a combination of Sertoli cells and interstitial Leydig cells. At the same time, the contralateral testis had a natural histological structure. The prostate gland looked normal macroscopically and histologically, which was not previously described. Postoperative six-month follow-up showed no evidence of metastatic disease. This study emphasizes the importance of early diagnosis and treatment of neoplastic tumours in animals, especially those with certain risk factors such as cryptorchidism, and shows that histological analysis is an important tool in determining the structure of the tumour and choosing further treatment tactics. Additional monitoring and statistical data may help to develop a better understanding of the frequency and nature of neoplastic processes in cryptorchid males, as

well as their impact on the health of these animals in the future. The results of the study also highlight the importance of an interdisciplinary approach to medical diagnosis and treatment of animals, including the use of ultrasound, histology and other methods to obtain a complete clinical image of the tumour. The data also indicate the possibility of developing more individualized treatment methods, taking into account the histological characteristics of each specific case of neoplasia in an animal. This approach can improve treatment outcomes and increase the chances of recovery.

The prospect of further research is the accumulation of our own statistical data on the frequency of neoplasia in cryptorchid males, their histological structure and the impact on metabolic processes in the body of these animals.

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CONFLICT OF INTEREST

None.

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Клінічний випадок змішаної пухлини сім'яника з крипторхізмом у собаки породи йоркширський тер'єр

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Анотація. Гістологічне дослідження пухлин тестикул у кобелів-крипторхів дозволяє визначити характер неоплазії, прогноз розвитку віддалених наслідків у вигляді метастаз, визначити оптимальний метод лікування тварини, що визначає актуальність досліджень у цій сфері. Метою роботи є визначення патогістологічної будови неоплазії лівого, крипторхічного, та морфології контрлатерального сім'яників у кобеля породи йоркширський тер'єр за одностороннього крипторхізму. У обстеженні тварини використано загальноклінічні,

ультрасонографічні, рентгенологічні та гістологічні методи дослідження. У статті наведено дані щодо змішаної пухлини внутрішньоочеревинного лівого сім'яника йоркширського тер'єра віком 6 років, що є нетиповим клінічним випадком. Встановлено, що характерними ультрасонографічними ознаками новоутворення крипторхового лівого сім'яника були численні ізоехогенні осередки різного діаметру (від 4 до 26 мм), гіперехогенні перегородки, горбисті контури з гіперехогенною капсулою. За лапаротомії змінений сім'яник мав нерівну просочену кровонаповненими судинами поверхню. На розрізі реєстрували молочно-білі неопластичні ділянки, розділені волокнистими смугами, які не відповідали нормальній будові органу. За гістологічного дослідження в паренхімі реєстрували ділянки однотипних округлих клітин у вигляді групи безформної маси, що були розділені фіброзним бар'єром. Неопластичні каналці мали розвинену фіброваскулярну строму, з еозинофільною некротичною ділянкою. Білкова оболонка також мала численні фіброзні утворення. Шари багатогранних клітин розташовувались перпендикулярно до базальної пластинки, часто з центральним некрозом, тестикулярна маса містила мультифокальні крововиливи. Такі ознаки характерні для ураження клітин Сертолі та інтерстиціальних клітин Лейдіга, що вказувало на змішаний тип пухлини лівого позаочеревинного сім'яника йоркширського тер'єра. Контрлатеральний правий сім'яник був без змін і відповідав природній морфогістологічній будові. Простата за макроскопічного та гістологічного дослідження відповідала нормі, що раніше не повідомлялось. Шестимісячне спостереження за собакою наявність ознак метастатичного процесу не виявило. Практичне значення роботи полягає у отриманні нових наукових знань щодо розвитку змішаних пухлин сім'яника у кобелів-крипторхів та перспектив лікування хворих тварин

Ключові слова: неоплазія сім'яника; позаочеревинний сім'яник; пухлина клітин Сертолі; інтерстиціальні клітини Лейдіга; фіброваскулярна строма

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