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# Characterisation of the papillary structure of the nasolabial mirror of cats

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**Abstract.** The relevance of this study is due to the need for scientifically sound, accurate and non-invasive methods of identification of domestic animals, in particular cats, in veterinary and forensic veterinary practice. Existing methods of identification (chipping, tagging, ournics) have a number of disadvantages – possibility of loss, painful procedure or allergic reactions. This increases the importance of finding alternative solutions. The aim of the work was to morphologically analyse the papillary structure of the nasolabial mirror of cats (*Felis catus*) and to scientifically substantiate its use as a unique identification trait of an animal. The following methods were applied during the study: taking prints using Trodat 9052 stamp pad and paper, scanning images of prints, digital processing using CorelDraw 2017 and Adobe Photoshop programs, as well as comparative morphological analysis of the obtained data. The nasolabial mirrors of 157 cats were examined, including repeated imprinting in 14 individuals after a certain time interval. It was found that papillary patterns of the nasolabial mirror have three stable morphological properties: individuality (uniqueness of the pattern in each individual), invariability (they are preserved during life) and ability to regenerate (restoration of the pattern in the absence of destruction of the microbial layer of the skin). Additionally, it was found that the obtained prints can serve as objective material for identification of the animal during veterinary examination, registration, forensic examination or in conditions of loss. The results have shown the possibility of developing a biometric system of accounting of pets based on the analysis of papillary structures of the nose. The practical significance of the study lies in the application of the results in veterinary clinics, forensic examination, customs authorities and in the creation of a unified database of domestic animals

**Keywords:** animal dermatoglyphics; papillary patterns of *Felis catus*; individual identification; morphological analysis; biometric veterinary medicine; forensic veterinary expertise

## Introduction

Domestic cats have accompanied humans for thousands of years, fulfilling not only utilitarian but also emotional functions. They help control rodent populations, are used in zootherapy, and act as companions in both urban and rural settings. Modern realities – urbanisation, increasing numbers of stray animals, increased

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migration of pets between regions and countries – require an increased level of animal control and record keeping, especially in situations of loss, theft or epizootic risk. This in turn necessitates the development of accurate and ethically acceptable identification methods (Yatsenko *et al*., 2025).

A variety of animal identification methods are used in veterinary practice, including tattooing, tagging, microchipping and DNA passporting. However, each has its limitations. For example, microchips require scanning devices, can cause allergic reactions and sometimes migrate under the animal's skin. Therefore, there is a need to develop alternative approaches that are both accurate, safe, cost-effective and versatile (Singh *et al*., 2024). As noted by S. Spotkay & L. Lykhina (2019), one of the promising directions in animal identification is the use of dermatoglyphic traits, in particular papillary patterns on the nasolabial mirror. These patterns, like fingerprints in humans, are unique and virtually unchanging throughout the animal's life. Unlike invasive identification methods, this method does not require surgery, making it convenient and painless for pets and professionals alike (Meng *et al*., 2025).

Modern research confirms the biometric potential of papillary structures. In particular, G. Kimani *et al*. (2023) investigated the possibility of identifying dogs and cats by nose and paw prints, creating prototypes of biometric databases. The authors noted the high stability of nose prints in cats and suggested their use as a permanent identification marker. V. Immonen *et al*. (2023) proposed the application of computer vision and machine learning techniques to analyse nasolabial mirror images. Their results showed that such algorithms can achieve accuracy comparable to microchipping methods, provided that image acquisition techniques are standardised. In a study by W. Andrew *et al*. (2021), morphological features of facial structures of domestic animals were examined. The authors concluded that papillary structures in cats persist over time and do not change significantly even in adulthood, making them a particularly reliable identification feature.

In parallel to the technical aspects of biometrics, A. Shafiev *et al*. (2023) have drawn attention to the regulatory and ethical aspects of implementing biometric methods in animal records. Electronic registries incorporating biometric data are already being implemented in EU countries, including to combat uncontrolled breeding and animal cruelty. A. Hitelman *et al*. (2022) reviewed the potential use of dermatoglyphics in veterinary forensics. They emphasise that, similar to human fingerprinting, morphological features of the nasal surface can be adapted to the needs of forensic veterinary science, especially in cases involving the identification of animals in epizootics or ownership disputes. An experimental study by M. Stennett *et al*. (2022) confirmed that digital imaging of nasolabial mirror prints using scanners and their subsequent processing in graphic editors can achieve highly reproducible results. Particularly interesting is the fact that even with partial tissue damage in animals the possibility of identification is preserved due to the uniqueness of the preserved areas of the pattern. Also worth noting is the work of A. Kaur *et al*. (2022), which analyses identification methods in natural disasters. The authors suggest using visual biometric traits, including nasal prints, as a complement to microchips, especially in cases where electronic devices are non-functional.

Thus, a review of the current scientific literature indicates a high scientific and practical interest in the development of animal identification methods based on dermatoglyphic traits. Despite the many theoretical and empirical publications, most of the research has focused on dogs, cattle and wild animals, note S. Li *et al*. (2021). Studies focusing specifically on cats, especially in terms of papillary regeneration and resistance to trauma, are extremely limited. In addition, to date, there are no standardised protocols for taking and analysing prints from domestic cats. The need for reliable identification of animals is increasing not only in veterinary practice, but also in forensic veterinary examination, forensic science, customs control and databases. The development of a non-invasive method based on nasolabial morphology can significantly improve the accuracy and availability of identification procedures (Li *et al*., 2022).

An important feature of the approach proposed in this article is its accessibility and ease of implementation in both veterinary clinic and field settings. As noted by P. Cihan *et al*. (2024), nasolabial mirror prints can be obtained using inexpensive materials – stamp pad, paper and scanning device. In addition, the ability to digitally process images using standard graphic editors allows rapid and accurate comparison of prints between individuals. Taking into account the high degree of individuality of the papillary pattern, stability of its shape during the animal's life and ability to partial regeneration, this method can be recommended as a basis for the development of a national system of biometric registration of domestic cats. This is particularly relevant in the context of creating a unified electronic database containing visual identifiers to track the origin, affiliation and epidemiological status of animals. The aim of the present study was to perform morphological analysis of the papillary structure of the nasolabial mirror of cats and to evaluate the possibility of its application as a biometric identification trait.

## Materials and Methods

The study was conducted from May to December 2023 at the Department of Histology and Pathology, Faculty of Veterinary Medicine and Biotechnology, K.I. Skryabin Kyrgyz National Agrarian University (Bishkek), with the participation of private veterinary clinics and pet owners. Nasolabial mirror prints of 157 cats, including

both pedigreed and mongrel individuals of different ages and sexes, were used as material. To study pattern stability, repeat prints were obtained from 14 cats after 2 to 6 months. The material was collected with the voluntary consent of the animal owners. All procedures were performed without the use of anaesthesia and were painless. The animals did not experience discomfort, as the method of fingerprinting is completely non-invasive. The study was performed in compliance with the generally accepted ethical standards governing work with animals in veterinary morphology (Directive 2010/63/EU, 2010).

The methodology was based on a modified dermatoglyphic analysis technique adapted to the anatomo-physiological features of cats. A Trodat 9052 stamp pad with hypoallergenic, non-irritating ink was used for taking prints. The surface of the nasolabial mirror was pressed against a clean sheet of paper on a hard surface, after which the resulting prints were dried and scanned using a Canon 3010 multifunctional device. The digitised images were processed in CorelDraw 2017 graphics software where pattern tracing, contour extraction and contrast enhancement were performed. Additionally, the tools of scaling, overlay and mirror comparison were used, which allowed morphological assessment of three main properties: individuality – absence of repeating patterns even in close relatives; invariability – stability of the papillary pattern over time; ability to regenerate – partial restoration of the pattern after damage.

Each print was digitally archived and compared with the results of repeated surveys, which allowed us to draw conclusions about the stability and reproducibility of traits, as described in Yu. Malofeev & S. Ermakova (2006). Possible technical errors related to lighting, position of the animal's head and humidity of the nasal surface were taken into account in the analyses. The information base of the study included both original experimental data and comparative data from scientific publications on dermatoglyphics in domestic animals, including the works of S. Samishchenko (2003), J. Frewein & B. Vollmerhaus (2003) and others. The applied approach allowed us to objectively confirm the suitability of papillary structures of the nasolabial mirror of cats for reliable visual identification of animals in veterinary, forensic and forensic practice.

## Results and Discussion

In the course of the study it was found that the surface of the nasolabial mirror in cats is a unique anatomical zone in terms of microrelief, which can fulfil the identification function. The morphology of the papillary pattern of each individual had clear individual features, which is confirmed by visual analysis of the obtained images. Comparison of prints and photographs revealed pronounced differences in the shape, location and configuration of papillary pattern areas between different animals, indicating a high degree of individuality of this structure. Figure 1 demonstrates the visual differences between the two cats: the first image shows a grouped pattern with larger tubercles and asymmetrical areas, whereas the second image shows a more even distribution and finely dispersed structure. Both images were obtained under the same illumination and scale, emphasising the objectivity of the differences.

**Figure 1.** Nasolabial mirror surface of two different cats with a characteristic papillary pattern
**Source:** photo by the authors

The obtained images of the nasolabial mirror confirmed a high degree of individuality of the papillary pattern in each studied cat. As in human dactyloscopy, these patterns represent a unique morphological configuration that is not repeated in other individuals. This fact was confirmed by a comparative analysis of the prints of all 157 cats: no coincidences between the patterns were recorded, including animals of the same age and breed. The anatomical structure of the nasolabial mirror in cats includes rough skin devoid of hair covering, forming numerous areolae and micro tubercles, which remain in a relatively stable position during the animal's life. This structure is described in I. Tuminaite & R. Kröger (2020), where it is stated that the nasal planum is subdivided into polygonal areas with a clear boundary, forming an individual pattern.

According to the morphological analysis data, the nasal surface represents an identification area suitable for visual comparison and archiving in digital format. The obtained images were brought to a uniform scale, processed in a graphic editor, and then compared with control prints. Despite minor external differences in brightness and contrast, the pattern structure remained clear and reproducible. To improve the accuracy

of identification, an animal record card was introduced, including a photograph or nasolabial mirror print, as well as information about the animal: nickname, age, sex, breed, colour, date and place of image acquisition, and owner data (Fig. 2a). This approach allows not only instant identification, but also the use of this data in further – during passportisation, veterinary surveillance, registration or tracing of lost animals.

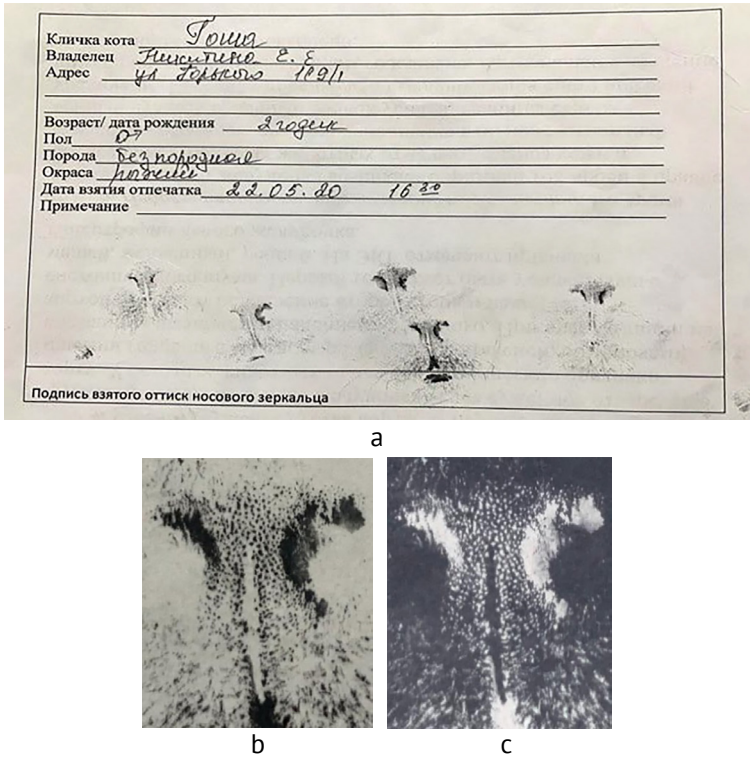


**Figure 2.** Example of an identification card and digital print of the nasolabial mirror of a cat named Gosha
**Note:** sex – male, age – 2 years, imprint date – 22.05.2020
**Source:** image prepared by the authors based on field survey data and computer processing CorelDraw 2017

To assess the individuality and graphic stability of the papillary pattern in cats, several typical images were selected. The nasolabial print of a cat named Gosha, who was 2 years old at the time of imaging, is presented as an example. The analysis was carried out in two stages: first, the resulting print was captured with a camera, then converted into a digital graphic format and subjected to computer processing. The visual results are presented in Figure 2. Figure 2b shows the primary image of the print captured using the camera. The photograph was taken in daylight, focusing on the centre of the nasolabial mirror. Figure 2c is the same print processed in the CorelDraw 2017 graphic editor, converted to negative format, which allowed to enhance the visibility of microrelief and highlight key elements of the pattern. This approach is used to facilitate the comparison of prints during re-identification. Thus, the combination of imaging and digital processing methods ensures that the structure of the nasolabial mirror can be clearly reproduced and confirms the presence of a unique pattern in each animal. The use of the Trodat 9052 ink stamp and paper allows the prints to be obtained painlessly and without side effects, making the method applicable in practical veterinary medicine. This image can be used to identify animals and serve as a document for further use in forensic examinations. As can be seen in Figure 2, the authors obtained the image without any changes when they put the tracing into a computer programme.

To assess the stability of the papillary pattern over time, the prints of a 2-year-old male cat named Timofey were taken again. The primary print was taken on 11.09.2022 using a camera and then digitally processed. Figure 3 illustrates the visual differences between the original and negative images of the same print. This allowed the structure of the papillary elements to be observed in detail. Figure 3a shows the original print produced using Trodat 9052 ink pad and paper, without digital processing. The image shows the basic microrelief of the surface of the nasolabial mirror. Figure 3b shows the same print after digitisation and colour inversion in CorelDraw 2017 graphics software. This processing allows the visualisation of individual areolae and micro-bumps, making it possible to more accurately match areas when re-imaging. Both images confirm the stability and reproducibility of the pattern. Minor differences are only due to the nature of the illumination and the angle of acquisition, and not to changes in the structure itself.

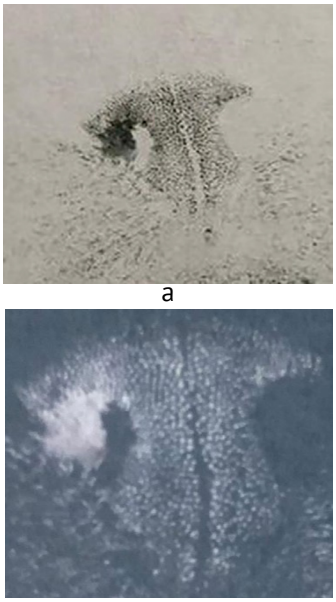

**Figure 3.** Nasolabial mirror of a cat named Timofey
**Note:** age – 2 years, male, nose print was obtained on 11.09.2022; a – original print; b – digital image in negative format
**Source:** photo by the authors

Figures 4a and 4b show a nose print of a cat named Musya, which was taken with a camera. The image was then loaded into the CorelDraw 2017 graphics programme on a computer and converted to negative format (Fig. 4b). In this way, using a Trodat 9052 stamp and paper, an image of the animal's nose and lip print can be produced.

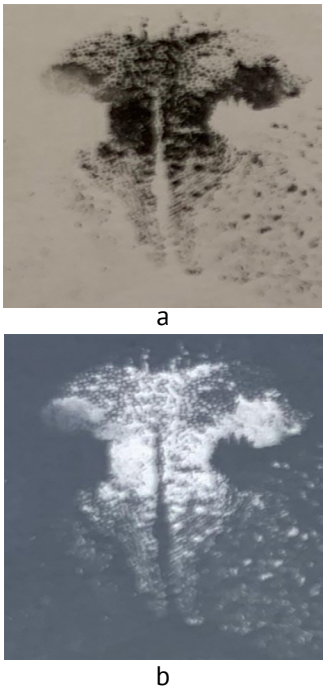

**Figure 4.** Nose print of a cat named Musya
**Note:** age – 7-8 months, female, nose print was obtained on 23.05.2022
**Source:** photo by the authors

Figures 5a and 5b show the nose print of a cat named Marquise, which was taken with a camera. The image was then loaded into the CorelDraw 2017 graphics programme on a computer and converted to negative format (Fig. 5b). Exposure of the nasal mirror of cats, in general, may have some similarity in characteristics that are determined by breed characteristics and a particular shape of the nasal mirror, but details or features of the pattern can vary considerably even among members of the same breed and between parents and their offspring.

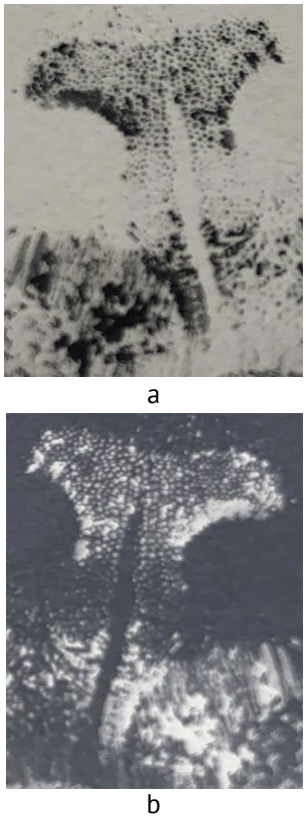

**Figure 5.** Nose print of a cat named Marquise
**Note:** age – 7-8 months, female, nose print was obtained on 23.05.2022
**Source:** photo by the authors

The comparative analysis of papillary patterns in related individuals demonstrated pronounced differences in the configuration of structures, even in the presence of common genetic features. Figure 6 shows digital images of the nasolabial mirrors of two animals: an adult male (father) and his offspring (son). The prints were taken using the same technique, allowing the images to be compared at an identical scale. Figure 6a shows the nasolabial mirror print of the parental individual. It is characterised by a high density of papillary elements in the central zone and symmetrically arranged lateral areolae. Figure 6b shows the imprint of the progeny. Despite the general similar contour of the external pattern, differences in microstructure are clearly visible in the details: a different shape of the areolae, their distribution and the expression of the central furrow.

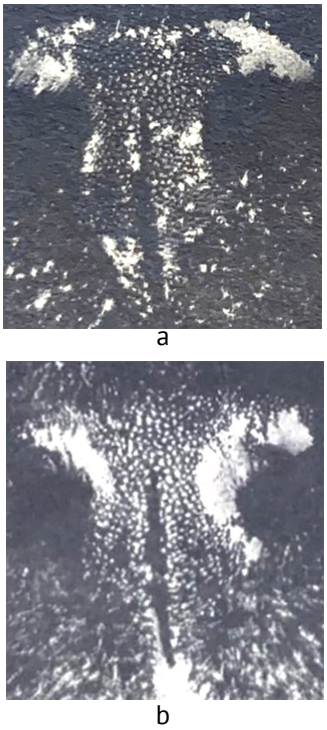

**Figure 6.** Nasolabial mirror of two cats
**Note:** a – father's picture; b – son's picture
**Source:** photo by the authors

Thus, the first property of papillary patterns is individuality: each pattern is unique, even among closely related animals. This property makes the method suitable for reliable identification in the practice of veterinary morphology. Additionally, based on observations of 14 individuals with repeated fingerprinting, it was found that the configuration of papillary elements remains stable. With the growth of the animal, a uniform increase in the area of the pattern is observed, but the structure and arrangement of the areolae do not change. This fact confirms the second key property – invariability of the papillary pattern over time.

The comparative analysis performed on the basis of nasolabial mirror prints obtained with a time interval allowed us to assess the stability and dynamics of the papillary pattern in cats. Figure 7 shows two images obtained from a cat named Fedot (date of birth – 02.02.2018). The first print was taken on 05.08.2020 and the second print was taken on 22.07.2021. Both images contain red markings indicating key structural elements comparable between the two time points. Figure 7a reflects the state of the pattern in 2020, Figure 7b almost a year later. Visual analysis shows that despite the natural age-related changes in the animal, the geometry and distribution of the papillary areolae remained stable, confirming the second fundamental property, the relative invariability of the pattern over time.

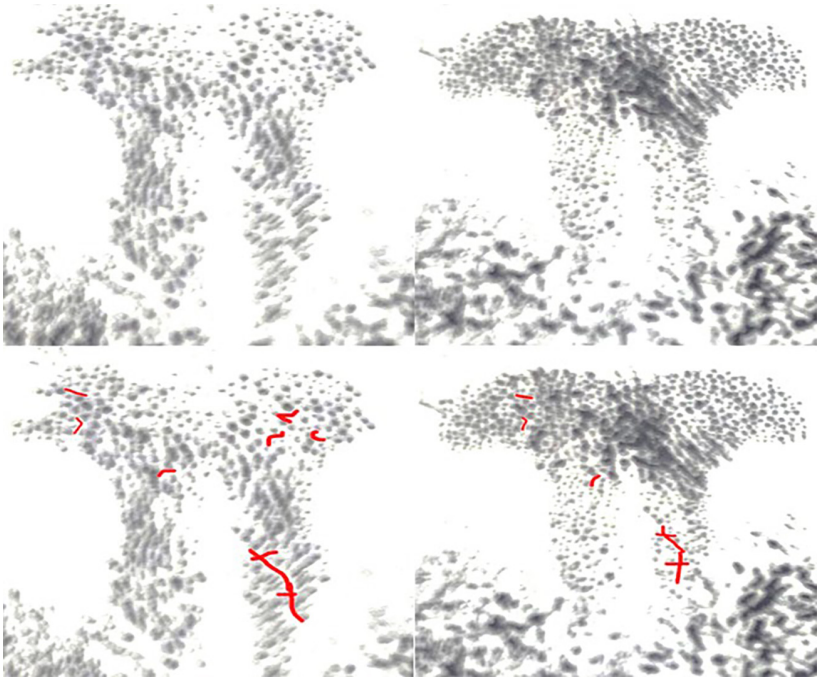

**Figure 7.** Nose print of a cat named Fedot
**Note:** date of birth – 02.02.2018; first print made on 05.08.2020, second print made on 22.07.2021
**Source:** photo by the authors

Figure 8 shows a pair of images taken from a cat named Boris (date of birth – 10.04.2019). The first print was taken on 05.03.2021 and the second on 07.07.2022. Similarly, the drawings were supplemented with visual markers (red lines) emphasising identical elements in the structure. Despite possible microtrauma or environmental exposure, the images show no signs of pattern degradation.

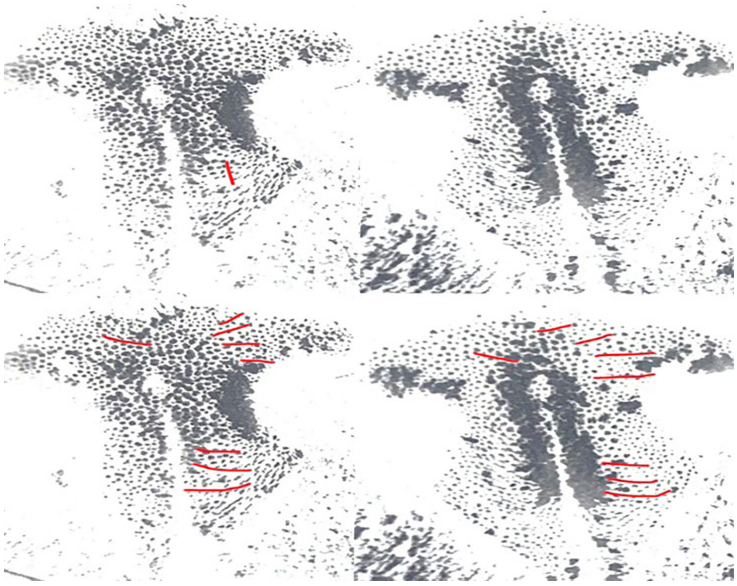

**Figure 8.** Nose print of a cat named Boris
**Note:** date of birth – 10.04.2019; first print made on 05.03.2021, second print made on 07.07.2022
**Source:** photo by the authors

The observation confirms that the papillary pattern retains its key characteristics throughout the animal's life. Cases of partial recovery of the pattern after superficial damage have also been recorded. This indicates the ability to regenerate, similar to that described in human fingerprinting studies: if the basal layer of the skin is preserved, regeneration is possible and identification features are reproducible (Samishchenko, 2003). The study found that papillary structures on the nasolabial mirror of cats have unique morphological characteristics suitable for use in biometric identification of animals. The dermatoglyphic patterns of the nasal surface in each individual have an individual character, similar to fingerprints in humans, as written by J. Frewein & B. Vollmerhaus (2003). Similar structures, previously studied mainly on the skin of limbs, have proven their suitability also on the nasal speculum of animals, including their possible application in sanitary-veterinary and forensic examination (Samishchenko, 2003). In the context of the development of animal visual biometrics, research shows the potential for automatic recognition of individuals based on unique natural patterns in wild animals (tigers, zebras, jaguars) using deep neural networks, which is consistent with the search for new non-invasive identification methods (Cheema & Anand, 2020). The results of this work also echo research on biometric identification of domestic animals, such as dogs, where deep neural networks are actively used to improve recognition accuracy and the possibility of combining "hard" (e.g., muzzle photos) and "soft" (breed, sex) biometric data in integrated systems is being explored (Lai *et al.*, 2020). Such an approach to non-invasive visual biometric identification is already showing high potential in the livestock industry, where, for example, highly accurate systems have been developed to recognise cattle from unique muzzle patterns, offering an effective replacement for traditional methods and contributing to improved welfare and herd management, as described in A. Shojaeipour *et al.* (2021).

In the present work, the analysis of 14 repeated prints obtained from different animals with a time interval confirmed that the configuration of papillary pattern elements remains stable. During the growth of the animal, there was only a proportional increase in the area of the pattern, without changes in the geometry of polyhedral areas. This allows us to speak about the invariability of the structural organisation of the pattern during the cat's life, like fingerprints in humans (Ponomarev, 2016; Spotkay, 2019). Additionally, the prints of two cats with traumatic damage to the nose were analysed. The results showed that in superficial lesions that do not affect the microbial (basal) layer of the skin, there is a partial restoration of the original pattern. In cases of deeper lesions, scarring changes are formed, accompanied by distortion of the pattern in the damaged area. However, in adjacent undamaged areas, the structure is preserved, which makes it possible to continue identification.

Thus, three key properties of the papillary structures of the nasolabial mirror of cats can be identified based on the analysis performed:

- Individuality: each animal has a unique papillary pattern that is not repeated even in closely related individuals. This property allows the nasolabial mirror to be used as a reliable biometric identifier;
- Immutability: the structure of the papillary pattern remains unchanged throughout the animal's life. With age, the areolae can only increase in size without

disturbing their shape and arrangement. This ensures the reliability of the method for long-term follow-up;

- Ability to regenerate: papillary skin structures have the ability to partially recover from damage if the basal layer is preserved. Even if scarring is present in one area, adjacent areas remain stable and identifiable.

The listed properties confirm the high suitability of using papillary patterns of the nasolabial mirror of cats in veterinary forensics, biometric registration and forensic veterinary identification. The results obtained can serve as a basis for the development of standard procedures for capturing, archiving and analysing prints within a unified pet registration system.

## Conclusions

In the course of the study, it was found that papillary patterns of the nasolabial mirror of cats have distinct morphological features that have not been previously subjected to systematic scientific study. The analysis allowed for identifying three key properties determining high identification value of these structures: individuality (each cat specimen has a unique papillary pattern that is not repeated even in related individuals, which makes accurate biometric identification possible); relative invariability (papillary structures remain unchanged throughout the animal's life – with age, only a harmonious increase in the size of areolae without loss of structural organisation is possible); ability to regenerate the papillary pattern of the nasolabial mirror of the cat; and the ability to be used as a tool for the identification of the nasolabial mirror of cats.

The data obtained indicate the high suitability of papillary structures of the nasolabial mirror for application in forensic veterinary medicine, customs examination, forensics and in the creation of biometric animal registration systems. The technique of capturing and analysing prints can be used for reliable identification of animals in case of their loss, movement or the need to document their ownership. Prospects for further research include improvement of methods for digital fingerprint processing and development of automatic recognition systems, as well as extension of the technique to other animal species within the framework of biological defence and veterinary registration.

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## Conflict of Interest

The authors declare that there is no conflict of interest.

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# Мышыктардын насолабиалдык күзгүсүнүн папиллярдык түзүлүшүнүн мүнөздөмөсү

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**Аннотация.** Бул изилдөөнүн актуалдуулугу ветеринардык жана соттук ветеринардык практикада үй жаныбарларын, атап айтканда мышыктарды идентификациялоонун илимий жактан негизделген, так жана инвазивдүү эмес методдоруна муктаждык менен шартталган. Идентификациялоонун учурдагы ыкмалары (чиптөө, биркалоо, нашейниктер) бир катар кемчиликтерге ээ – процедуранын жоголушу, оорушу же аллергиялык реакциялар. Бул альтернативдүү чечимдерди табуунун маанилүүлүгүн жогорулатат. Иштин максаты мышыктардын назолабиалдык күзгүсүнүн папиллярдык түзүлүшүн морфологиялык талдоодо жана аны жаныбардын кайталангыс идентификациялык белгиси катары пайдаланууунун илимий негиздемесинде турат. Изилдөө процессинде төмөнкүдөй методдор колдонулган: Тстк 9052 штемпелдик жаздыктын жана кагаздын жардамы менен издерди алуу, издердин сүрөттөрүн сканерлөө, Сток 2017 жана Ттп программаларын колдонуу менен санариптик иштетүү, ошондой эле алынган маалыматтарды салыштырмалуу морфологиялык талдоо. 157 мышыктын насолабиалдык күзгүлөрү изилденген, анын ичинде белгилүү бир убакыт аралыгында 14 адамда кайра басылган. Мурун-Эрин күзгүсүнүн папиллярдык оймо-чиймелери үч туруктуу морфологиялык касиетке ээ экендиги аныкталды: индивидуалдуулук (ар бир индивиддеги үлгүнүн уникалдуулугу), өзгөрүлбөстүк (өмүр бою сакталат) жана регенерация жөндөмдүүлүгү (теринин микробдук катмары бузулбаган учурда үлгүнү калыбына келтирүү). Алынган издер ветеринардык кароодо, каттоодо, соттук экспертизада же дайынсыз жоголгон шартта жаныбарды идентификациялоо үчүн объективдүү материал катары кызмат кыла алары кошумча аныкталган. Натыйжалар мурундун папиллярдык структураларын талдоонун негизинде үй жаныбарларын эсепке алуунун биометрикалык системасын иштеп чыгуу мүмкүнчүлүгүн көрсөтөт. Изилдөөнүн практикалык мааниси ветеринардык клиникаларда, соттук экспертизада, бажы органдарында жана үй жаныбарларынын бирдиктүү маалымат базасын түзүүдө жыйынтыктарды колдонууда турат

**Негизги сөздөр:** жаныбарлардын дерматоглификасы; папиллярдык оймо-чиймелер; Жеке идентификация; морфологиялык анализ; биометрикалык ветеринария; соттук-ветеринардык экспертиза

# Характеристика папиллярного строения носогубного зеркала кошек

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**Аннотация.** Актуальность настоящего исследования обусловлена потребностью в научно обоснованных, точных и неинвазивных методах идентификации домашних животных, в частности кошек, в ветеринарной и судебно-ветеринарной практике. Существующие методы идентификации (чипирование, биркование, нашейники) имеют ряд недостатков – возможность утери, болезненность процедуры или аллергические реакции. Это повышает значимость поиска альтернативных решений. Цель работы заключалась в морфологическом анализе папиллярного строения носогубного зеркала кошек (*Felis catus*) и в научном обосновании его использования как уникального идентификационного признака животного. В процессе исследования были применены следующие методы: снятие отпечатков с помощью штемпельной подушки Trodat 9052 и бумаги, сканирование изображений отпечатков, цифровая обработка с применением программ CorelDraw 2017 и Adobe Photoshop, а также сравнительный морфологический анализ полученных данных. Были исследованы носогубные зеркала 157 кошек, в том числе с повторным снятием отпечатков у 14 особей через определенный временной интервал. Установлено, что папиллярные узоры носогубного зеркала обладают тремя стабильными морфологическими свойствами: индивидуальностью (уникальность узора у каждой особи), неизменностью (сохраняются в течение жизни) и способностью к регенерации (восстановление узора при отсутствии разрушения микробного слоя кожи). Дополнительно установлено, что полученные отпечатки могут служить объективным материалом для идентификации животного при ветеринарном осмотре, регистрации, судмедэкспертизе или в условиях пропажи. Результаты показали возможность разработки биометрической системы учета домашних животных на основе анализа папиллярных структур носа. Практическая значимость исследования заключается в применении результатов в ветеринарных клиниках, судебной экспертизе, таможенных органах и при создании единой базы данных домашних животных

**Ключевые слова:** дерматоглифика животных; папиллярные узоры *Felis catus*; индивидуальная идентификация; морфологический анализ; биометрическая ветеринария; судебно-ветеринарная экспертиза

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# Role of breeding in the development of organic vegetable production in Kazakhstan

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**Abstract.** In the Republic of Kazakhstan, organic vegetable growing is at the initial stage of formation and requires comprehensive scientific support, including the development of specialised varieties and adapted agro-technologies. The aim of this study was to create new varieties of vegetable crops intended for organic farming, possessing a complex of economically valuable traits and adapted to different agro-ecological zones of the country. In the process of breeding research both classical and modern methods were used: obtaining inzucht lines, individual and mass selection, hybridisation, polycross, backcross, induction of polyploidy, formation of parental forms and analysis of parthenocarpy. Experimental work was carried out in a competition nursery where evaluation of 15 varietal samples was organised: 5 samples of onion, 7 of table beet and 3 of sweet pepper. As a result of multifactorial evaluation on a set of traits including yield, resistance to diseases and stresses, marketable qualities and suitability for organic production, the most promising samples were identified: 2 onion varieties, 3 beetroot varieties and 2 pepper varieties. According to the results of three-year field trials, these varieties showed stable performance and were recommended for transfer to the State Variety Trial as organic varieties. Practical significance of the study is to provide organic vegetable production of the Republic of Kazakhstan with highly productive and sustainable varieties that can be used in farming and economic structures of different regions of the country, contributing to food security and sustainable development of the industry

**Keywords:** organic farming; variety diversity; agroecological adaptation; stress resistance; selection of parental forms; biological features; nutritional value

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## Introduction

Vegetables are an integral part of a rational human diet due to their high content of vitamins (particularly C, B, P, provitamin A), organic acids, mineral compounds and biologically active substances. According to the Ministry of Agriculture of the Republic of Kazakhstan (n.d.), in 2023 vegetable crops were cultivated on an area of more than 150 thousand hectares, and the total gross harvest amounted to more than 4.3 million tonnes. At the same time, according to the Bureau of National Statistics (n.d.), the physiological norm of vegetable consumption per person is 126 kg, which forms the domestic demand at the level of 2.52 million tonnes. The actual supply of vegetables exceeds 170 per cent. Despite the high production volumes, there is practically no certified organic vegetable production in Kazakhstan (Grigoruk & Klimov, 2016). The structure of organic agriculture in the country is dominated by grain and oilseed crops. According to estimates of international organisations, organic products in the world are produced by more than 4.3 million agricultural producers in almost 190 countries, with the most developed regions remaining the countries of the European Union and North America (FiBL & IFOAM, 2025). The organic sector is also growing in transition countries.

Organic agriculture is seen as a more sustainable alternative to conventional agricultural production (Dukhnytskyi, 2019). It involves the use of environmentally friendly cultivation methods, avoiding synthetic fertilisers, pesticides and genetically modified organisms (GMOs). According to the study by J. Trap & E. Blanchart (2023), the sustainability of agroecosystems under organic farming is ensured by restoring the natural functions of soil, agrobiocoenosis and minimising the negative impact on the environment. As shown by M. Aliyeva *et al.* (2024), state support and legislative initiatives play a key role in stimulating organic agriculture, as exemplified by the experience of Azerbaijan, where targeted policies have led to a significant increase in the area of certified organic land.

The selection of organic varieties of vegetable crops is of particular importance, as variety is a key element of agro-technology in the conditions of organic production. As shown by the work of S. Singh *et al.* (2024), the use of varieties resistant to diseases and stresses can significantly reduce or completely eliminate the use of chemical plant protection products. Thus, organic varieties should have high plasticity, adaptability to different soil and climatic conditions and increased nutritional value. As noted by O. Clausen & L. Patryeva (2021), the motivation of consumers to purchase organic products is its safety, environmental purity and high biological value. In the conditions of Kazakhstan, the development of organic vegetable production can become not only a factor of food security, but also a competitive advantage in international markets.

Research on the development of organic vegetable production requires scientific support, including agrochemical assessment of soils, selection of biological plant protection products, introduction of drip irrigation systems and development of adapted varieties. Special attention should be paid to breeding aimed at developing non-GMO varieties with integrated resistance and nutraceutical properties (Hamdan & Tan, 2024). In addition, there is already considerable potential in the production practices of Kazakhstan in the form of local varieties suitable for organic vegetable production. Nevertheless, expansion of breeding programmes oriented specifically towards organic farming systems is required. This is due to the need to replace imported varieties adapted to other climatic conditions with local varieties with resistance to local pathogens and climatic stresses. In this context, the study of A. Aidarova *et al.* (2024) emphasised the relevance of rational land use and introduction of organic and biological technologies in Kazakhstan, especially in the context of land degradation, which demonstrates the synergistic potential for improving the efficiency of the agricultural sector and landscape condition.

The aim of this work was to develop new organic varieties of vegetable crops, plastic to different agro-ecological conditions of the Republic of Kazakhstan, with a complex of economically valuable and nutraceutical traits.

## Materials and Methods

Field breeding research was carried out on the basis of the Kazakh Research Institute of Fruit and Vegetable Growing (regional branch "Kainar") in the foothill zone of the south-east of the Republic of Kazakhstan. The trials were carried out during three growing seasons – from March to October in 2021, 2022 and 2023. Soils of the study area were represented by dark chestnut soils of medium loamy granulometric composition. Soil volume mass was 1.1-1.2 g/cm$^3$. The arable horizon contained 2.9-3.0% humus, 0.18-0.20% total nitrogen, 0.19-0.20% gross phosphorus, 2.2-2.4% gross potassium. The cation exchange capacity was at 20-21 mg-eq per 100 g of soil. The reaction of soil solution was slightly alkaline (pH 7.1-7.3).

The climate of the zone is characterised by sharp continentality. Mean monthly temperatures in July varied within +22 ... +24°C, and in January – from -6 to -10°C. The sum of active temperatures during the vegetation period reached 3,450-3,750°C. The duration of the frost-free period ranged from 140 to 170 days. Annual precipitation varied from 350 to 600 mm. The hydrothermal coefficient was between 0.7 and 1.0 (Kazhydromet, n.d.). Table 1 provides information on monthly climatic averages for the study period.

**Table 1.** Average monthly climatic indicators in the foothill zone of south-eastern Kazakhstan for 2021-2023 years

| Month | Average temperature, °C | Precipitation, mm | Average humidity, % |
|---|---|---|---|
| March | 5.4 | 45 | 65 |
| April | 12.3 | 55 | 60 |
| May | 18.7 | 62 | 58 |
| June | 22.5 | 48 | 52 |
| July | 24.3 | 38 | 48 |
| August | 23.9 | 36 | 50 |
| September | 18.2 | 40 | 55 |
| October | 11 | 32 | 60 |

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

The objects of the study were 15 varieties of vegetable crops, including 5 samples of onion (*Allium cepa*), 7 samples of table beetroot (*Beta vulgaris*) and 3 samples of sweet pepper (*Capsicum annuum*). Sowing was carried out at the end of March manually in the open ground with row spacing of 45 cm, repeated three times. The area of one plot was 5 $m^2$. Organic cultivation system was used: mineral fertilisers and chemical plant protection products were not used, the soil was enriched with biohumus and siderates. Breeding work included individual and mass selection methods, hybridisation, polycross, backcross, inzucht lines, and induction of polyploidy. Parthenocarpy was studied using Accelerated Plant Breeding techniques (Gosal & Wani, 2020). The trials were conducted according to the recommendations of UPOV (1961). All procedures were documented in accordance with the recommendations for the breeding process (Law of the Republic of Kazakhstan No. 422-I, 1999).

For sweet pepper, 3 promising varieties were studied in the nursery of competitive trial on the complex of economically valuable traits. The seedlings of pepper varieties were grown in the selection greenhouse of the Russian Federation "Kainar", by the time of planting pepper plants had 7-8 leaves, well-developed root system, seedling height – 25-30 cm. The evaluation of sweet pepper varieties was carried out according to the parameters of plasticity and stability of the variety. As source material for research were taken 2 varieties of sweet pepper and 3 promising varieties of domestic selection – Bayan Sulu and Safiya-1818, No. 2806 (promising), No. 1105 (promising), No. 2212 (promising), the standard was approved for use variety Safiya-1818. During the vegetation of sweet pepper, biometric measurements were carried out to observe the growth and development of plants in dynamics.

Onions for the creation of organic varieties, plastic to different agro-ecological conditions of Kazakhstan, with a complex of economically valuable traits, including nutraceutical, was laid nursery competitive trial. Biometric surveys on onion varieties in the nursery of competitive trial were conducted in the phase of mass growth of leaves in the 2nd decade of July. Morphological traits such as number of leaves, leaf length, leaf width and leaf surface area were studied. The yield of onion varieties was measured at the stage of technical ripeness. The yield from each plot was weighed in the field and the following parameters were calculated from this data:

- total yield (t/ha) – calculated as the ratio of the total weight of harvested crop to the whole plot area, converted per hectare;
- marketable yield (t/ha) – determined by weighing the marketable produce (without small, damaged and deformed bulbs), also converted per hectare;
- marketable yield (%) – calculated as the ratio of marketable yield to total yield and then multiplied by 100;
- weight of marketable bulb (g) – determined by the average weight of 30 typical bulbs from the sample;
- disease damage (%) – recorded visually by the presence of disease symptoms (rot, mould, bacteriosis) on 100 randomly selected bulbs. Results were presented as the proportion of affected specimens in the sample;
- pest damage (%) – determined similarly by visual indication of the presence of damage from soil and ground pests. Frequency and severity of damage were also recorded.

The assessment was carried out in threefold repetition, on the basis of which the mean values of indicators were calculated. Reliability of differences was assessed by analysis of variance (ANOVA), critical level of significance was $p < 0.05$.

Five new onion cultivars of different genetic nature were evaluated in a competitive variety trial nursery. All evaluated onion samples were compared with the standard variety Mereke. Phenological observations, biometric measurements and yield records were carried out. Morphological, phenological and productive parameters: fruit/root weight, disease resistance, yield, levelling and storage were used to evaluate the results. Statistical processing of data was carried out using standard methods of analysis of variance (ANOVA) with 95% confidence interval and significance criterion $p < 0.05$. Calculations were performed in Statistica 10.0 software.

For selective evaluation of economically valuable traits of 7 varieties of table beet (*Beta vulgaris* L.) under organic farming conditions, a competitive nursery was established on the basis of the Kazakh Research Institute of Fruit and Vegetable Growing (KazRIPO) (regional branch "Kainar"). The seed material consisted of collection and breeding samples that had previously passed inventory and laboratory tests for sowing qualities, including determination of germination energy, germination and weight of 1,000 seeds. All 7 table beet varieties studied were compared with the standard variety Kyzylkönkyr. Based on the obtained data, the seeding rate for field trials was calculated. Sowing was carried out in the first decade of May. Ridge wide-band planting scheme with row spacing of 70 cm was used. Repetition of the experiment was three times, the area of one plot was 5 m². All agrotechnical measures were carried out in accordance with the principles of organic farming: mineral fertilisers and chemical means of plant protection were not used. The soil was pre-fertilised with biohumus, and mechanical methods of cultivation were used to control weeds.

Phenological observations, morphological evaluation and yield records were carried out in accordance with the state variety evaluation methodology and FAO & ISTA (2023) recommendations. Morphological traits to be studied included: shape and colour of rootlets, ring expression, presence of head corking, colour and consistency of flesh. Yield was evaluated by gross weight, weight of marketable root crops, degree of marketability (%), weight of one marketable root crop (g), as well as by yield structure (proportion of underharvested, cracked, ugly, pest-damaged and disease-affected root crops). All measurements were carried out on a sample of at least 30 plants of each cultivar, followed by statistical processing of the data (mean, HCP05, precision, coefficient of variation).

## Results and Discussion

Mass sprouting of onion was obtained on day 17-19 after sowing. The number of days from mass sprouting to leaf lodging was 81-85 days. In samples 02-12(2) and 05-24, the vegetation period from mass sprouting to harvesting was 134 days, i.e. they belonged to the medium maturity group. Samples 959-9, 1440 and 1588 belong to the medium-late ripeness group by the number of days from mass sprouting to harvesting – 136, 137 and 138 days. The study of interphase periods of growth and development of varietal samples of competitive nursery are given in Table 2, and the dynamics of leaf surface development – in Table 3.

**Table 2.** Duration of the vegetation period of onion cultivar samples

| Onion variety | Number of days from sowing to sprouting | Number of days from mass sprouting to | | |
|---|---|---|---|---|
| | | bulb formation | leaf lodging | harvesting |
| Mereke, standard | 18 | 81 | 123 | 130 |
| 02-12 (2) | 19 | 81 | 127 | 134 |
| 05-24 | 19 | 84 | 128 | 134 |
| 959-9 | 17 | 82 | 129 | 136 |
| 1440 | 18 | 85 | 130 | 137 |
| 1588 | 17 | 83 | 132 | 138 |

**Source:** compiled by the authors according to the data of field variety trial of KazNIIPO (regional branch "Kainar"), 2021-2023

**Table 3.** Leaf surface development in onion varieties of the competitive trial

| Varieties, onion varieties | Number of leaves on the plant, pcs | Average length leaf, cm | Average leaf width, cm | Leaf area, cm² |
|---|---|---|---|---|
| Mereke standard | 10.5 | 43.6 | 1.3 | 868.9 |
| 02-12(2) | 10.3 | 44.4 | 1.2 | 867.99 |
| 05-24 | 10.8 | 45.4 | 1.3 | 930.62 |
| 959-9 | 11.2 | 47.3 | 1.5 | 1,160.1 |
| 1440 | 11.4 | 45.9 | 1.3 | 993.14 |
| 1588 | 10.1 | 43.2 | 1.4 | 891.83 |

**Source:** compiled by the authors according to the data of biometric measurements in the nursery of competitive trial KazNIIPO (regional branch "Kainar"), 2021-2023

Onion varieties 959-9 and 1440 had the largest number of leaves – 11.2-11.4 pieces, the standard Mereke had 10.5 pieces of leaves. In terms of leaf length, the studied samples differed slightly from the standard. The longest leaves were in variety 959-9 (47.3 cm). In terms of leaf area, samples 05-24 (930.62 cm²), 959-9 (1,160.1 cm²) , 1440 (993.14 cm²) differed from the standard in terms of leaf area (868.9 cm²). The economic and useful properties of the evaluated onion varieties in the competitive trial nursery are given in Table 4.

**Table 4.** Characteristics of onion varieties in the competitive trial nursery

| Varieties, varieties onion | Yield, t/ha | | Increase marketable yield, % | Marketable yield yield, % | Weight of marketable bulb, g | Disease damage, % | Damage pests pests, % |
|---|---|---|---|---|---|---|---|
| | total | marketable | | | | | |
| Mereke standard | 33.4 | 29.4 | – | 87.9 | 115 | 0.6 | 0.2 |
| 02-12(2) | 38.1 | 33.1 | 112.6 | 87.0 | 118 | – | 0.1 |
| 05-24 | 38.4 | 35.0 | 119.2 | 91.0 | 125 | 0.3 | 0.1 |
| 959-9 | 38.8 | 36.3 | 123.5 | 93.4 | 130 | – | – |
| 1440 | 37.6 | 34.2 | 116.4 | 90.8 | 123 | – | – |
| 1588 | 38.5 | 34.4 | 117.1 | 89.3 | 120 | 0.5 | 0.3 |

**Source:** compiled by the authors based on the results of yield records and phytosanitary assessment in field conditions KazNIIPO (regional branch "Kainar"), 2021-2023

All evaluated onion samples had a significant increase in marketable yield (12.6-23.5%) compared to the standard variety Mereke. The highest yield increase (23.5%) was in variety 959-9. High marketability of yield (90.8-93.4%) was observed in samples 1440, 05-24, 959-9. Onion disease damage in 2 samples was insignificant – 0.3-0.5%, here samples 02-15(2), 959-9 and 1440 were resistant. As a result of evaluation in the nursery of competitive trial on economic-valuable traits, 2 varieties were identified: 05-24 and 959-9. These samples will be further studied, multiplied and according to the results of 3-year evaluation 1 best sample will be transferred as an organic onion variety to the State Variety Trial and proposed for organic vegetable production.

Morphological features of table beet varieties were investigated in the nursery of the competitive trial. Morphological features of plants determine their resistance to biotic and abiotic environmental factors, responsiveness to agro-technological methods, intensity of formation and size of future crop yield. This is especially important for vegetable crops, including table root crops, which by their biological characteristics are very sensitive to all environmental factors and agro-technological methods. Plant morphological traits are individual and reflect the adaptive potential of each variety. In the present study, morphological characteristics of vegetative biomass and product organs of the studied table beet cultivars were evaluated. The obtained data are summarised in Tables 5 and 6. According to the obtained data, all the studied table beet samples differed significantly from each other in structure, shape, colour and other indicators of their organs.

**Table 5.** Morphological characteristics of rootlets in different table beet varieties in the competitive trial nursery

| Varieties of table beet | Shape of longitudinal section | Base shape | Head pollination characteristic | External colouring | Basic colouring of pulp | Intensity of basic colouring | Expression of rings |
|---|---|---|---|---|---|---|---|
| Kyzylkönkyr | rounded | rounded | medium | red | red | medium | medium |
| VR 1230 | rounded | rounded | medium | red | red | dark | weak |
| VR 1229 | rounded | rounded | medium | red | violet | medium | mild-medium |
| VR 1216 | rounded | rounded | weak | red | red | dark | weak |
| VR 1209 | rounded-oval | pointed | medium | red | red | dark red | medium |
| VR 1150 | rounded | rounded | medium | red | red | dark | weak |
| VR 1148 | rounded | rounded | weak | red | red | dark | very weak |
| VR 1140 | rounded | rounded | weak | red | red | dark red | weak |

**Source:** compiled by the authors according to the data of morphological evaluation of samples in field conditions KazNIIPO (regional branch "Kainar"), 2021-2023

Root crops of different varieties of table beet differed significantly from each other in morphological features (Table 6). Root skin colour of the studied samples was of different shades and differed significantly among the cultivars. In most of the samples, the intensity of the basic colour was dark and dark red, and the expression of rings was weak. The main colour of the flesh of varietal samples was mainly red, only one sample (VR 1229) had a violet tint. Root head sampling in cultivars VR 1140, VR 1148, VR 1216 was weak, while in the other four accessions it was medium. In the study of S. Rakutko *et al.* (2022) noted that for obtaining high yields of table beet under organic production, the shape and intensity of colour of root crops plays an important role, which is consistent with the identified characteristics of sample BR 1229 in the conducted experiment.

**Table 6.** Yield data of table beet varieties in the competition nursery

| Table beet varieties | Gross yield, t/ha | Marketable yield, t/ha | Yield merchantability, % | Weight of marketable root crop, g |
|---|---|---|---|---|
| BR 1230 | 18.3 | 12.3 | 67.3 | 108 |
| BR 1229 | 24.2 | 15.5 | 64.4 | 172 |
| BR 1216 | 26.2 | 17.5 | 66.7 | 124 |
| BR 1209 | 52.1 | 34.9 | 67.0 | 265 |
| BR 1150 | 16.6 | 8.7 | 52.1 | 121 |
| BR 1148 | 19.9 | 16.0 | 80.4 | 102 |
| BR 1140 | 31.0 | 26.2 | 84.6 | 161 |
| Kyzylkönkyr (st.) | 46.3 | 42.4 | 91.6 | 229 |
| $NDS05._{05}$, t/ha | 2.3 | 1.9 | 6.72 | – |
| Experimental accuracy, % | 2.5 | 2.7 | 3.12 | – |

**Note:** accuracy of the experiment (%) – the indicator of repeatability of results, calculated as the ratio of standard deviation to the mean value, multiplied by 100; NSR05 (the smallest significant difference) – the minimum value of the difference between the variants, considered statistically significant at the significance level $p < 0.05$

**Source:** compiled by the authors on the basis of field experience KazNIIPO (regional branch "Kainar"), 2021-2023

Root yield of all studied varieties of table beet (64.4-84.6%) was lower than that of the standard variety Kyzylkönkyr (91.6%). All varieties of table beet competitive nursery after harvesting laid on storage in cold storage chambers of the Institute for further research. In table root crops, including table beetroot, the yield structure is important. Therefore, the yield structure of root crops in the studied cultivars was evaluated (Table 7). Root galls (small, underdeveloped) in the table beet competition nursery were observed in all cultivars. There were no rootstocks affected by galls in the nursery. Damage of rootlets by soil pests was found only in variety BR 1209 – 2.5%, it had a lot of cracked rootlets – 24.5%. Root crops with ugly forms were noticed only in sample BR 1229 – 10.8%. No deviation from the main variety was observed in all table beet samples.

**Table 7.** Root yield structure of table beet varieties evaluated in the competitive selection nursery (trials)

| Table beet varieties | Root rot, % | Rots, % | Damaged by pests, % | Cracked, % | Ugly | Deviation from the main grade, % |
|---|---|---|---|---|---|---|
| Kyzylkönkyr | 8.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| VR 1230 | 32.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| VR 1229 | 35.6 | 0.0 | 0.0 | 0.0 | 10.8 | 0.0 |
| VR 1216 | 22.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| VR 1209 | 6.0 | 0.0 | 2.5 | 24.5 | 0.0 | 0.0 |
| VR 1150 | 47.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| VR 1148 | 19.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| VR 1140 | 15.4 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 |

**Source:** compiled from data of yield structure evaluation in field conditions KazNIIPO (regional branch "Kainar"), 2021-2023

Thus, in 2024 in the competitive nursery of table beet 7 varieties were evaluated, of which the best economic-value indicators were noted in 3 varieties – BR 1229, BR 1209 and BR 1140. To obtain high and stable yields of vegetables, it is necessary to have information about the degree of adaptability of varieties and hybrids of vegetable crops to a particular soil and climatic zone of their cultivation. The results of the field experiment on varietal testing of sweet pepper were analysed (Tables 8, 9, 10). The studied sweet pepper varieties proved to be medium-maturing: the period from sprouting to maturity – 128-177 days. Phenological phases from sprouting to flowering were marked by 73-79 days. The earliest flowered variety Safiya-1818, 73 days from mass sprouting. Bayan Sulu variety showed flowering at 76 days, variety No. 2806 at 79 days, variety No. 1105 at 76 days, and variety No. 2212 at 78 days from seedlings. The flowering-ripening period was 60-64 days, while the sprouting-ripening period was 128-137 days (Table 8).

**Table 8.** Phenological parameters of sweet pepper varieties

| No. | Variety, hybrid of sweet pepper | Number of days | | | Groups of ripeness |
|---|---|---|---|---|---|
| | | sprouting – flowering | flowering – ripening | sprouting – beginning ripening | |
| 1 | No. 2806 (promising) | 79 | 64 | 137 | medium-maturing |
| 2 | No. 1105 (promising) | 76 | 60 | 129 | medium-maturing |
| 3 | No. 2212 (promising) | 78 | 63 | 131 | medium-maturing |
| 4 | Bayan Sulu | 76 | 61 | 132 | medium-maturing |
| 5 | Safiya-1818 st. (standard) | 73 | 60 | 128 | medium-maturing |

**Source:** compiled by the authors according to the data of yield structure assessment in field conditions KazNIIPO (regional branch "Kainar"), 2021-2023

**Table 9.** Biometric parameters of sweet pepper varieties (2024)

| No. | Varieties of sweet pepper | Beginning of fruiting (technical ripeness) | | | |
|---|---|---|---|---|---|
| | | Plant height, cm | Number of leaves, pieces | Number of flowers, pieces | Number of fruits, pieces |
| 1 | No. 2806 (promising) | 78-90 | 71 | 12 | 8 |
| 2 | No. 1105 (promising) | 87-98 | 69 | 14 | 7 |
| 3 | No. 2212 (promising) | 89-97 | 67 | 15 | 10 |
| 4 | Bayan Sulu | 65-68 | 68 | 10 | 7 |
| 5 | Safiya-1818 st. (standard) | 68-72 | 70 | 12 | 8 |

**Source:** data of field observations and measurements of KazNIIPO, Vegetable Crops Breeding Department, 2024

Plant height of variety No. 2806 was 78-90 cm, No. 1105 – 87-98 cm, No. 2212 – 89-97 cm, Bayan Sulu – 65-68 cm, Safiya-1818 – 68-72 cm. The highest foliage was observed in variety No. 2806, the number of leaves was 71 pieces, the number of flowers in this sample was also higher – 12 pieces. At the beginning of technical ripeness the number of fruits was 7-10 pieces, the largest number of fruits was observed on the sample No. 2212.

**Table 10.** Yield and yield structure of sweet pepper varieties and samples

| No. | Variety, varietal sample of sweet pepper | Total yield, kg/m$^2$ | Share in % | | Fruit weight, g |
|---|---|---|---|---|---|
| | | | technical technical ripeness | biological ripeness | |
| 1 | No. 2806 (promising) | 21.8 | 35.4 | 59.7 | 270-360 |
| 2 | No. 1105 (promising) | 21.7 | 44.0 | 60.0 | 170-250 |
| 3 | No. 2212 (promising) | 20.6 | 38.6 | 61.3 | 180-225 |
| 4 | Bayan Sulu | 19.0 | 36.3 | 58.6 | 150-210 |
| 5 | Safiya-1818 st. (standard) | 20.2 | 33.8 | 64.1 | 250-300 |

**Source:** results of field trials at the Kazakh Research Institute of Fruit and Vegetable Growing, 2024

Yield of fruits above the control was formed by varieties No. 2806 (21.8 kg/m$^2$), No. 1105 (21.70 kg/m$^2$), the yield of variety No. 2212 was at the level of the standard – 20.6 kg/m$^2$, slightly lower compared to the control was the yield of variety Bayan Sulu – 19.0 kg/m$^2$, the standard yield was 20.2 kg/m$^2$ (Table 10). According to the number of fruits in biological ripeness to harvesting varieties and hybrids of sweet pepper can be divided into early-ripening: the proportion of fruits in biological ripeness more than 64.1% was observed in the variety Safiya-1818. In terms of fruit weight, all the evaluated pepper varieties can be classified as large-fruited, with a weight of more than 250 g. The largest fruit was sample No. 2806, which had a weight of 1 fruit up to 360 g. Fruit weight in most varieties and hybrids of sweet pepper depends on growing conditions. Lower air temperature during the period of fruit formation favours the setting of more fruits and a decrease in fruit weight. According to the results of the 3-year evaluation, the best variety of sweet pepper selected for the complex of economically valuable traits will be transferred as a new organic variety to the State Variety Trial.

The results obtained during the study demonstrate the significant potential of breeding organic varieties of vegetable crops for the conditions of Kazakhstan. High yields and quality of the developed varieties of onion, table beet and sweet pepper, grown without the use of synthetic fertilisers and pesticides, confirm the fundamental possibility of developing organic vegetable production in the region (Karamatov, 2021). These data are consistent with the general trends of global organic agriculture, which is actively developing as a response to the growing consumer demand for safe and environmentally friendly products, as well as in the

context of the search for sustainable agricultural practices (Zhang *et al.*, 2024). Many studies emphasise that organic farming practices improve soil health, increase biodiversity and reduce negative environmental impacts compared to conventional systems (Tuomisto *et al.*, 2012; Biswas *et al.*, 2014; Nghia *et al.*, 2025).

In particular, the successful adaptation of developed varieties to local soil and climatic conditions demonstrated in this study is a critical aspect. Resistance to abiotic and biotic stresses, achieved through targeted breeding, can minimise yield losses and reduce dependence on external influences, which is particularly relevant for organic systems, as indicated in the study by M. González Guzmán *et al.* (2022). This confirms the importance of genetic diversity and the development of local varieties that are better adapted to the specificities of the region. One of the aspects identified was the possibility of obtaining varieties with improved nutraceutical properties. The increased content of vitamins and other bioactive substances in organic produce is one of the main motivations for consumers. Research suggests that organic growing methods may favour the accumulation of certain beneficial compounds in plants, although this issue requires further study and depends on multiple factors, say researchers X. Zhao *et al.* (2006) and G. Feliziani *et al.* (2025) The development of such a direction of breeding is promising for improving the competitiveness of Kazakhstani organic products in domestic and international markets.

Despite the positive results obtained, further development of organic vegetable production in Kazakhstan requires a comprehensive approach. It is necessary to take into account economic barriers, such as high costs of certification and marketing of organic products, which may restrain the wide introduction of these methods (Khasanov & Kirchner, 2024). The development of effective agrochemical soil assessment systems and the selection of biological plant protection products also remain important challenges. Overall, this study lays the foundation for further breeding programmes aimed at developing high-yielding, resistant and nutritionally valuable organic varieties of vegetable crops that contribute to sustainable agricultural development in Kazakhstan.

## Conclusions

The conducted breeding research in the conditions of Kazakhstan was aimed at the creation of new organic varieties of vegetable crops, resistant to different agro-ecological conditions and possessing a complex of economically valuable and nutraceutical traits. As part of the work in the nursery of competitive variety testing were studied 15 varieties: 5 – onions, 7 – table beetroot and 3 – sweet pepper. According to the results of research among onion varieties, the best performance showed the samples 05-24 and 959-9. Sample 959-9 was distinguished by high marketable yield (36.3 tonnes/ha), the largest leaf area (1,160.1 $cm^2$), as well as resistance to diseases and pests. Variety 05-24 stood out for its high bulb weight (125 g) and marketability (91.0%). These samples will be pre-tested and if the results are positive, one of them will be recommended as an organic variety for inclusion in the State Register.

Among the table beet samples, BR 1229, BR 1209 and BR 1140 were the leaders. BR 1209 was particularly notable for its highest gross yield (52.1 tonnes/ha), marketable root weight (265 g) and pest resistance. Sample BR 1140 had the highest marketability of 84.6 per cent. These varieties are characterised by pronounced adaptive traits and are suitable for organic vegetable production. For sweet pepper, the samples No. 2806 and No. 1105 were recognised as promising, showing yields above the standard, good plasticity, large fruitfulness (up to 360 g) and a high percentage of biological ripeness. Thus, the practical significance of the work lies in the selection of stable and productive genotypes suitable for organic farming. Prospects for research include in-depth biochemical and molecular evaluation of the isolated samples, as well as the development of elements of organic cultivation technology for implementation in agropractice.

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## Conflict of Interest

None.

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# Казакстанда органикалык жашылча өстүрүүнү өнүктүрүүдөгү селекциянын ролу

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**Аннотация.** Казакстан Республикасында органикалык жашылча өстүрүү азырынча калыптануу стадиясында болуп, атайын сортторду чыгарууну жана адаптацияланган агротехнологияларды иштеп чыгууну камтыган комплекстүү илимий колдоону талап кылат. Бул изилдөөнүн максаты – органикалык дыйканчылык үчүн арналган, чарбачылыкка пайдалуу белгилердин комплекси бар жана өлкөнүн ар түрдүү агроэкологиялык зоналарына ылайыкташкан жаңы жашылча өсүмдүктөрүнүн сортторун жаратуу болгон. Селекциялык изилдөөлөрдүн жүрүшүндө классикалык жана заманбап ыкмалар колдонулган: инцухт-линияларды алуу, индивидуалдык жана массалык тандоо, гибриддештирүү, поликросс, беккросс, полиплоидияны индукциялоо, аталык-энелик формаларды түзүү жана партенокарпияны талдоо. Эксперименттик иштер сынак питомнигинде жүргүзүлүп, 15 торттун туруктуулугу бааланган: 5 баштык пияз, 7 баштык кызылча жана 3 баштык таттуу калемпир. Көп факторлуу баалоонун жыйынтыгында, түшүмдүүлүк, ооруларга жана стресс факторлорго туруктуулук, товардык сапаттар жана органикалык өндүрүшкө жарактуулугу сыяктуу көрсөткүчтөрдүн жыйындысы боюнча эң перспективалуу үлгүлөр бөлүнүп чыккан: 2 пияз сорту, 3 кызылча сорту жана 2 калемпир сорту. Үч жылдык талаа сыноолорунун негизинде бул сорттордун туруктуу көрсөткүчтөрдү көрсөтүп, органикалык сорт катары Мамлекеттик сорт сыноого өткөрүү үчүн сунушталган. Изилдөөнүн практикалык мааниси – Казакстан Республикасынын органикалык жашылча өстүрүү тармагын жогорку түшүмдүү жана туруктуу сорттор менен камсыз кылууда, алар өлкөнүн ар кандай аймактарындагы фермердик жана чарбалык түзүмдөрдө колдонулуп, азык – түлүк коопсуздугуна жана тармактын туруктуу өнүгүшүнө өбөлгө түзөт

**Негизги сөздөр:** органикалык дыйканчылык; сорттук ар түрдүүлүк; агроэкологиялык ылайыкташуу; стресске туруктуулук; аталык-энелик формаларды тандоо; биологиялык өзгөчөлүктөр; азыктуулук баалуулугу

# Роль селекции в развитии органического овощеводства в Казахстане

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**Аннотация.** В Республике Казахстан органическое овощеводство находится на начальном этапе становления и требует комплексной научной поддержки, включая выведение специализированных сортов и разработку адаптированных агротехнологий. Целью настоящего исследования было создание новых сортов овощных культур, предназначенных для органического земледелия, обладающих комплексом хозяйственно-ценных признаков и приспособленных к различным агроэкологическим зонам страны. В процессе селекционных исследований применялись как классические, так и современные методы: получение инцухт-линий, индивидуальный и массовый отбор, гибридизация, поликросс, беккросс, индукция полиплоидии, формирование родительских форм и анализ партенокарпии. Экспериментальная работа проводилась в конкурсном питомнике, где была организована оценка 15 сортообразцов: 5 образцов лука репчатого, 7 – столовой свеклы и 3 – сладкого перца. В результате многофакторной оценки по совокупности признаков, включая урожайность, устойчивость к болезням и стрессам, товарные качества и пригодность к органическому производству, были выделены наиболее перспективные образцы: 2 сорта лука, 3 сорта свеклы и 2 сорта перца. По итогам трехлетних полевых испытаний эти сортообразцы показали стабильные показатели и рекомендованы к передаче на Государственное сортоиспытание как органические сорта. Практическая значимость исследования заключается в обеспечении органического овощеводства Республики Казахстан высокопродуктивными и устойчивыми сортами, которые могут быть использованы в фермерских и хозяйственных структурах различных регионов страны, способствуя продовольственной безопасности и устойчивому развитию отрасли

**Ключевые слова:** органическое земледелие; сортовое разнообразие; агроэкологическая адаптация; устойчивость к стрессам; отбор родительских форм; биологические особенности; питательная ценность

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# Organoleptic evaluation of meat quality of Tian Shan lambs of different ages

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**Abstract.** The present study was devoted to a comprehensive organoleptic evaluation of the quality of meat of lambs of the Tian Shan breed, raised in a small farm in the mountainous regions of Kyrgyzstan. The aim of the work was to determine in detail the taste, aromatic and textural characteristics of lamb meat at the age of 4, 6 and 8 months, as well as to establish compliance of the obtained indicators with the current quality standards. The research methodology included strict sampling of the longest muscle of the back (*m. longissimus dorsi*) from animals of each age group. To ensure the reliability of the results, heat treatment of meat was carried out in accordance with the GOST 9959-2015 standard, which guaranteed standardised preparation conditions. Tasting evaluation was carried out by a qualified commission of seven experts, and the obtained data were subjected to biometric processing. According to the results of the analysis, it was found that all the meat samples tested demonstrated exceptionally high performance in key organoleptic parameters, including appearance, aroma, flavour, juiciness and consistency. Average scores on a 9-point scale ranged from 8.3 to 8.7 on average, indicating high product quality. Particular attention was paid to the tenderness indicator, for which the meat received the highest scores, which confirms such a biological feature of the Tian Shan breed as precocity and its suitability for early slaughter to obtain tender lamb. No defects or off-flavours were detected during the study, underlining the high level of animal rearing and the premium quality of the product. The findings confirmed the significant potential of the Tian Shan breed to produce high quality lamb in a small business environment, providing a competitive advantage in the marketplace

**Keywords:** lamb meat; sensory evaluation; pasture-based rearing; quality of meat; sheep; small-scale farming

## Introduction

Lamb has traditionally occupied an important place in the diet of people in many countries, being characterised by its high nutritional value and flavour. Lamb meat is superior to beef and poultry in the content of essential amino acids and vitamins, which explains the increase in the production of this meat worldwide (Turynskiy *et al.*, 2020). Young lamb has a low cholesterol content in fatty tissue, due to which the prevalence of atherosclerosis is lower among peoples who consume predominantly lamb (Zhang *et al.*, 2023).

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According to the National Statistical Committee of the Kyrgyz Republic (n.d.), mutton accounts for 22.4 per cent of total meat production in the Kyrgyz Republic. Small farms and household owners play a significant role in increasing mutton production. Small businesses in sheep farming are flexible in responding to market demands, but must ensure stable product quality to be competitive.

At the same time, meat quality is determined by a number of factors, including the age of the animals, breed characteristics and rearing conditions. In older sheep, the taste of meat deteriorates with a pronounced greasy odour and flavour, while the meat of young animals has a delicate consistency and a mild taste without strong odours. Therefore, to meet consumer demands, it is optimal to use lamb meat – meat of animals under 12 months of age, which has the best organoleptic properties. Organoleptic evaluation of meat is the most important tool for quality control and consumers' perception of the product. Tasting analysis is widely used as one of the most objective and reliable ways to evaluate food products – provided the correct methodology and qualification of experts (Tsydenova & Larionova, 2016). Meat quality is tested by laboratory and organoleptic methods, with the latter analysing characteristics such as carcass appearance, colour of muscle tissue and fat, consistency, smell and broth quality (Teixeira *et al*., 2020). For standardised evaluation of meat in the Eurasian Union countries, the interstate standard GOST 9959-2015 (2016) has been adopted, which regulates the requirements for tasting rooms, sample preparation, tasting procedures and processing of results.

Of particular importance in assessing the quality characteristics of lamb is the breed factor. Differences between breeds of sheep can influence the chemical composition and structure of muscle tissue and consequently the juiciness, tenderness and flavour of the meat (Kruk & Ugnivenko, 2024). A comparative study by J. Wang *et al*. (2024) showed that meat from lambs of a local breed had lower shear force (higher tenderness) compared to another breed under similar fattening conditions. At the same time, proper selection of breeds for local conditions can provide a combination of high productivity and quality. Tian Shan breed of sheep is one of the important selection achievements of sheep breeding in Kyrgyzstan, bred to increase meat productivity in the conditions of mountain pastures (Bekturov *et al*., 2017). However, in the available literature there is insufficient data on organoleptic indicators of meat of lambs of this breed, especially those raised on small subjects. Therefore, the aim of the present study was to conduct organoleptic evaluation of meat of lambs of the Tian Shan breed produced under small-scale business conditions and to compare the results obtained with the literature data on mutton qualities.

## Literature Review

The Tian Shan breed belongs to the semi-thin-cropped meat-and-wool sheep of the early maturing type. The breed was bred in the high mountainous area (Kara-Kudjer plateau, Central Tian Shan) at the Tian Shan experimental station of cattle breeding by a complex reproductive crossing of prekos x kurdish crossbred sheep with lincol rams. According to G. Druzhenkov & E. Druzhenkova (1974), sheep of Tian Shan breed are characterised by good meat and wool productivity and high adaptability to severe conditions of pasture keeping. The average live weight of rams-producers is 107-110 kg, and of ewes – 60-65 kg. A valuable biological property of the breed is its high precocity. Yarki at birth has a live weight of 4.2 kg, at weaning (4 months) – 33-35 kg, at the age of 18 months – 58.5 kg. It is distinguished by good meat quality, high precocity. Slaughter yield of meat of lambs – 48%, specific weight of flesh in carcasses – 82%. Growth rate of young stock from birth to 5 months is within 7.7-9.0 times with an average daily gain of 206-284 grams per day, which is convincing evidence of their precocity, the potential opportunity to increase the production of mutton at the expense of lamb meat.

Intensive development of lambs at an early age in the conditions of high mountains is of great biological and economic importance, representing the slaughter of lambs for meat in the year of birth. Meat productivity of sheep, its production level is primarily determined by the demand for mutton, which largely depends on the qualitative features of sheep meat, its taste and dietary properties and nutrition (Babushkin *et al*., 2016). However, for a long time in the conditions of high mountains, the main meat contingent was adult dead sheep and culled ewe lambs after fattening on summer pastures. Thus, for 80-90 days of fattening on high-mountain alpine pastures the dead ewes increase staging weight by 13-15 kg with an average daily gain of 150-165 grams. The slaughter yield of walukhs is 53-55% (Druzhenkov, 1970).

An important advantage of the Tian Shan breed is its adaptability to the sharply continental climate of the high mountains. Sheep of this breed well tolerate significant daily and seasonal temperature fluctuations, thin mountain air and intensive insolation. High immunity and general viability of the livestock are noted (Chernyshova, 2013). Due to these qualities, the breed is spread in the mountainous areas of Kyrgyzstan (Naryn Region) where breeding farms of Tian Shan sheep are concentrated. The number of purebred stock in the country exceeds 330 thousand heads and continues to grow (NSCKR, n.d.). It testifies to the demand for the breed in farms of different scales. In conditions of high-mountain pastures Tian Shan sheep show better safety and productivity in comparison with other breeds, which makes them irreplaceable for local farmers.

Organoleptic properties of mutton are influenced by genetic and environmental factors (Shekhovtsev *et al.*, 2022). As noted by A. Priolo *et al.* (2002), breed differences can manifest themselves in the degree of fatness of carcasses, the ratio of red and white muscle fibres, which is reflected in the taste and consistency of meat. However, under comparable fattening and housing conditions, meat quality parameters of different breeds may not differ significantly (Panov *et al.*, 2020). Thus, tasting tests of cooked meat and broth in one of the studies revealed no significant differences in organoleptic indicators between control and experimental groups of lambs of different genotypes (Dabaev *et al.*, 2020). Nevertheless, there is evidence that feeding regime can significantly influence the flavour nuances of lamb meat. In particular, meat from grass-fed lambs often has a more pronounced flavour (e.g. "liver" flavour), whereas intensive stall feeding produces a more fatty flavour. A. Priolo *et al.* (2002) noted that there may be no significant differences in tenderness and overall meat evaluation under different lamb feeding systems, but the flavour profile changes. For farms practising pasture-based rearing, this means that the possible formation of specific flavour notes (grassy, milky, etc.) needs to be taken into account. On the other hand, in Central Asia, it is the mild "milky" flavour of young lamb that consumers appreciate, for which the animals are slaughtered at an early age to avoid the strong lamb odour. In traditional feeding practices in the Balkans and Spain, lambs are provided with prolonged milk feeding under the uterus and grazing on natural pastures, which gives the meat a delicate flavour with milky tones (Gutiérrez-Peña *et al.*, 2022). This approach is similar to smallholder production in Kyrgyzstan, where Tian Shan lambs are raised on mother's milk and mountain grazing. Thus, according to the literature review, optimal organoleptic properties of lamb are achieved with a complex combination of favourable genetics (breed), young age of slaughter and natural fattening. The Tian Shan breed, characterised by its early maturity and adaptability to pastures, is of great interest from the point of view of obtaining high quality lamb meat under small business conditions.

## Materials and Methods

The study was conducted during the period from August to December 2023. Location: Min-Bulak village, Naryn district, Kyrgyz Republic. Organoleptic evaluation was carried out on samples of meat of Tian Shan lambs raised on private small farms in mountainous areas (Naryn district, Min-Bulak village). All animal slaughtering and sampling activities were carried out in accordance with Law of the Kyrgyz Republic No. 175 (2014), Resolution of the Government of the Kyrgyz Republic No. 377 (2015) and GOST 9959-2015 (2016). The conditions of storage and tasting analyses were also in accordance with GOST 9959-2015 (2016) and the involvement of tasters was in accordance with the principles of the Declaration of Helsinki (1964).

Three lambs each of 4, 6 and 8 months of age, receiving traditional pasture feed, were selected for the study. The choice of ages 4, 6 and 8 months for the study was conditioned by their correspondence to the main commercial categories of lamb meat and the stages of physiological development of animals, optimal for the production of meat of high nutritional value. The selection of animals for each age group (3 lambs each) was done by random sampling from the total population to ensure representative samples and minimise potential systematic errors. The average live weight of lambs before slaughter was 25, 30 and 32 kg. Carcasses were chilled at +4...+6°C for 24 hours. From each chilled carcass, samples of the longest muscle of the back (*m. longissimus dorsi*) in the lumbo-pectoral region were taken for further organoleptic analysis. Before tasting, the meat was stored at 0...+2°C for no more than 48 hours. The tasting analysis was carried out in accordance with GOST 9959-2015 (2016). A tasting commission was formed from seven experts previously trained in sensory analysis methodology. The composition of the panel met the requirements described by R. Papaev *et al.* (2022). The evaluation was carried out in a specialised room free of extraneous odours and distractions. Organoleptic evaluation of meat of different types of productive and commercial animals was carried out after its heat treatment. Simultaneously with the evaluation of cooked meat the quality of broth was determined. Heat treatment of meat was carried out as follows: meat weighing about 1 kg was placed in a pot with cold water in the ratio of 3:1 (water to meat). The pot was covered with a lid, brought to a boil and cooked over low heat for 1-1.5 hours until the temperature in the centre of the piece of meat reached 75 ± 5°C. After completion of cooking, the meat was removed from the broth and cooled to a temperature of 35 ± 5°C. Then the meat was cut into slices weighing at least 50 g and sent for tasting. To assess the organoleptic parameters of the broth, it was poured into glass beakers, filling at least 50 $cm^3$, and determined: appearance and colour, smell (aroma), taste and richness (saturation of nitrogenous extractive substances). Each panel member was given a set of samples and a glass of broth from the corresponding sample. Between samples, tasters cleared their receptors with neutral foods (sip of water, unsalted cracker). After organoleptic evaluation of 7-8 samples, a break of at least 10 minutes was taken.

The commission evaluated the following organoleptic indicators of meat: appearance and colour (appetite, surface and cut colour); smell (aroma) of meat (both raw and cooked, in terms of intensity and pleasantness); taste of cooked meat (harmony, presence of extraneous flavours); juiciness (expression of meat juice, feeling of moisture when chewing); consistency (tenderness) – softness and ease of chewing meat;

overall organoleptic evaluation (holistic perception of product quality). The evaluation was carried out according to the 9-point system recommended by GOST 9959-2015 (2016). Thus 9 points corresponded to exceptional properties (excellent), 8 – very good, 7 – good, 6 – satisfactory, 5 – mediocre, 4 and below – unsatisfactory qualities. According to the requirements of the standard, the minimum acceptable score for each indicator is 4; samples scoring below 4 for at least one criterion are considered to be non-conforming in quality (Sarbatova *et al*., 2019). Tasters were given individual tasting sheets for scoring each indicator and recording verbal descriptions (if desired). Panel members did not exchange opinions during the tasting (a requirement of the instructions). After the individual evaluation was completed, a general discussion was held to collect comments and remarks not formally counted in the scores. From the tasting sheets of each expert, the data were transferred to a summary table. For each indicator, the average panel score and standard deviation (σ) were calculated. The spread of opinions between tasters and compliance with minimum requirements were also evaluated. Since all evaluated samples belonged to the same sample (Tian Shan lamb, same type of content), no statistical test of differences between them was performed; instead, the main results are given as an aggregate characterisation of the quality of this sample.

## Results and Discussion

According to the results of tasting analysis, it was found that meat of young Tian Shan breed raised on a small farm has good organoleptic properties. All the samples studied received high scores on key indicators (Table 1). None of the samples had scores below the minimum 4 points; on the contrary, the average scores for all criteria exceeded 8 out of 9 possible, which corresponds to the "excellent" category. The commission noted the characteristic for young lamb pleasant flavour without extraneous tones, juiciness and tenderness of meat. The colour of boiled meat was assessed as pink-red, uniform, appetite-inducing. The consistency of the meat when chewed is very soft, the fibres are easily separated, which is reflected in the highest score for tenderness. The flavour was described by tasters as rich, meaty, without excessive fatness, with a sweetish tinge typical of well-fed lamb. The juice released when biting is clear and fragrant, abundantly moistens the mouth, which confirms the high score for juiciness. The summarised score (overall acceptability) is also close to the maximum, indicating that the product was extremely well liked by the experts on the basis of the sum of impressions.

**Table 1.** Results of organoleptic tasting of meat of lambs of Tian Shan breed at the age of 4, 6 and 8 months old

| Indicator | 4 months | 6 months | 8 months |
|---|---|---|---|
| Appearance | 8.0 | 8.3 | 8.1 |
| Odour (flavour) | 7.5 | 8.0 | 7.8 |
| Flavour | 7.8 | 8.5 | 8.3 |
| Juiciness | 7.0 | 8.0 | 8.5 |
| Consistency (tenderness) | 9.0 | 8.5 | 7.5 |
| Total score, score | 8.0 | 8.6 | 8.4 |
| Fat content of meat (category) | 16.11<br>low | 20.10<br>average | 24.76<br>elevated |
| Broth: flavour | 7.8 | 8.5 | 8.7 |
| Broth: flavour | 7.5 | 8.5 | 8.9 |
| Broth: transparency | 9.0 | 8.5 | 8.0 |
| Broth: colour | 7.0 | 8.5 | 9.0 |

**Note:** the table shows average scores on a 9-point scale
**Source:** developed by the authors

As can be seen from Table 1, the spread of scores for all parameters is small (σ does not exceed 0.4), which indicates the consistency of tasters' opinions and the homogeneity of sample quality. The highest average score was obtained for tenderness (8.7), which is expected for the meat of a young animal – it is easy to chew due to thin muscle fibres and moderate content of connective tissue. High marks for taste and aroma (8.6 and 8.4 respectively), the tasters described the broth as fragrant and transparent, the meat as having a "juicy mutton flavour without a rough taste". The juiciness of the meat was also high (8.3 points), which is due to the sufficient intramuscular fat content of the lamb and the lack of over-drying during preparation. Opinions on colour were slightly more variable (σ = 0.3) – some experts noted a slightly pale shade of cooked meat, but in general the colour was assessed as typical for lamb meat of high quality (score 8.5). In general, the obtained results indicated that the lambs of the Tian Shan breed, produced in a small farm, corresponds to the category of products of the highest grade by organoleptic indicators.

High tasting evaluations of the meat quality of Tian Shan lambs are largely consistent with the biological features of this breed and the conditions of its cultivation. Tian Shan sheep are characterised by rapid maturity – by 4 months of age, lambs accumulate sufficient muscle mass and a moderate amount of fat, reaching slaughter condition (Chernyshova, 2013). The meat obtained in the study had fine, tender fibre and a sufficient level of marbling (fat layers), which ensured high tenderness and juiciness as assessed by experts. In addition, grazing lambs on mountain grasses may have contributed to a rich flavour profile. Keeping animals on pasture gives lamb its own nuances of flavour – in particular, less fat flavour and more hints of game or liver (Priolo *et al*., 2002). The tasters did not note any extraneous or unpleasant flavours, which may be explained by the young age of the lamb (no "aged" lamb flavour). On the contrary, some experts noticed the sweetish flavour of the meat. As noted by R. Gutiérrez-Peña *et al*. (2022), this tone is often present in 4-month-old lambs that have received enough lactose with their mother's milk. Thus, the quality characteristics of the samples studied reflect an optimal combination of factors: the breed potential of Tian Shan sheep for high meat quality and the traditional technology of raising young animals in a small farm (on natural land).

The work by M. Cabrera & A. Saadoun (2014) showed that lamb is superior to other meats in terms of nutrient content. However, the organoleptic advantages may be offset by improper fattening. In the study, all lambs were reared on natural grasses only. In Spain, sensory testing of local Mallorquina breeds in the work of R. Gutiérrez-Peña *et al*. (2022) showed tenderness and flavour scores of 7.2 out of 10 (roughly corresponding to 6.5 out of 9), which is lower than the results obtained in the present study. The authors attribute this to the fact that some of the animals were reared to an older age on pasture and grain (4-5 months versus 3-4 months for "light" lambs in Spain). On the other hand, in the experiment of A. Priolo *et al*. (2002) observed that the overall perception of quality was not significantly different between groups of lambs on grass and on grain, although certain flavours differed.

The expert tasters gave high scores and no defects in any of the criteria, indicating that there are no negative effects of pasture rearing. This favourably distinguishes the products of small farming, where grazing of animals is mainly used, and intensive fattening technology sometimes results in excessive fat deposition and associated reduction in palatability (e.g. excessive fatness) (Pethick *et al*., 2006; Lushchikhina, 2013). Thus, the tasting confirmed the literature evidence that optimal organoleptic properties of lamb are achieved when slaughtered at milk-weaning age and pasture-fed (Cañeque *et al*., 2001). The Tian Shan breed realises its genetic potential under these conditions, giving meat with excellent colour, aroma, flavour and consistency. The absence of significant defects (extraneous odours, dryness, hardness) in the samples studied indicates a high level of farming technology. It can be concluded that the meat of lambs of the Tian Shan breed of small farm meets the requirements of the standard on all organoleptic parameters and can be referred to the products of premium class. This is especially important for small businesses: high quality products provide competitive advantages in the lamb market and enhance the reputation of local farmers.

## Conclusions

The obtained results of organoleptic evaluation demonstrated high quality of meat of lambs of Tian Shan breed, raised in conditions of a small farm. High taste merits of the studied lamb meat were manifested in attractive colour of cooked meat (pink-red, appetising appearance), saturated meat aroma without extraneous tones, harmonious taste with barely perceptible sweetness, extreme tenderness and juiciness of consistency. Average scores on a 9-point scale ranged from 8.3-8.7, which corresponds to the highest quality category. None of the organoleptic criteria revealed any defects or unsatisfactory properties.

The characteristics of the Tian Shan breed – early maturity, moderate fat content and adaptation to pasture – determined high sensory characteristics of the products. The absence of negative flavours characteristic of older animals confirms the importance of choosing the right age of slaughter (4-6 months) for natural feeding. The conditions of small business (small flock on natural pastures) are favourable for the production of high quality mutton. The obtained data expand scientific ideas about the quality of mutton of the Tian Shan breed and confirm its prospects for farms.

Thus, the Tian Shan breed of sheep shows significant potential for the production of high-quality lamb suitable for positioning as a premium product. This makes it particularly promising for small businesses focused on the market for natural and organic products. In the future, it is promising to expand the research – for example, to compare the organoleptic evaluation of meat of the Tian Shan breed with other breeds (Edilbayev, Gissar, etc.) under the same growing conditions, as well as to study the influence of grazing season and type of feed on the formation of flavour. In addition, in parallel with sensory analysis, it is useful to carry out instrumental measurements (content of volatile aromatic compounds, fatty acid profile) to link objective indicators with tasters' perception.

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## Conflict of Interest

The authors declare that there is no conflict of interest. The conduct of the study and the presentation of its results were not intended for commercial purposes, but were aimed solely at obtaining scientific data. All mentioned trademarks or company names are for information purposes and do not affect the conclusions of the work.

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# Тянь-Шань тукумундагы ар кандай куракtагы козулардын этинин органолептикалык сапатын баалоо

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**Аннотация.** Бул изилдөө Кыргызстандагы тоолуу аймактарда чакан фермердик чарба шартында өстүрүлгөн Тянь-Шань тукумундагы ар кандай жаштагы козулардын этин комплекстүү органолептикалык баалоого арналган. Изилдөөнүн максаты – 4, 6 жана 8 айлык козулардын этиндеги даамдык, жыттык жана текстуралык мүнөздөмөлөрдү терең изилдеп, алынган көрсөткүчтөрдүн сапат стандарттарына шайкештигин аныктоо болуп саналат. Изилдөө методологиясы ар бир жаш куракtык топко кирген жаныбарлардын узун арка булчуңдарынын (*m. longissimus dorsi*) кылдат тандоону камтыган. Натыйжалардын ишенимдүүлүгүн камсыз кылуу үчүн этке термикалык иштетүү ГОСТ 9959-2015 стандарты боюнча жүргүзүлүп, даярдоонун бирдей шарттары камсыздалган. Дегустациялык баалоо жети адистен турган квалификациялуу комиссия тарабынан жүргүзүлүп, алынган маалыматтар биометрикалык иштеп чыгууга дуушар болгон. Анализдин жыйынтыгында бардык үлгүлөр негизги органолептикалык көрсөткүчтөр боюнча – сырткы көрүнүшү, жыты, даамы, ширелүүлүгү жана консистенциясы боюнча өтө жогорку натыйжаларды көрсөткөнү белгиленди. 9 баллдык шкала боюнча орточо баалар 8,3төн 8,7ге чейин өзгөрүп, продукциянын жогорку сапатын тастыктады. Өзгөчө көңүл эттин назиктик көрсөткүчүнө бурулуп, ал эң жогорку бааларга ээ болгон. Бул тянь-шань тукумундагы козулардын тез жетилишинин жана аларды эрте союуга ылайыктуулугунун биологиялык өзгөчөлүгүн далилдейт. Изилдөө учурунда эч кандай кемчилик же бөтөн даам аныкталган эмес, бул малды багуунун жогорку деңгээлин жана продукциянын премиум-класска шайкештигин көрсөтөт. Алынган маалыматтар тянь-шань тукумундагы койлор чакан бизнестин шартында жогорку сапаттагы козу этин өндүрүүдө чоң потенциалга ээ экенин жана бул тармакта атаандаштык артыкчылыктарды түзөөрүн далилдейт

**Негизги сөздөр:** козу эти; даам баалоо; жайытта өстүрүү; эттин сапаты; койлор; фермердик чарба

# Органолептическая оценка качества мяса ягнят тянь-шаньской породы разного возраста

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**Аннотация.** Настоящее исследование посвящено комплексной органолептической оценке качества мяса ягнят тянь-шаньской породы, выращенных в условиях малого фермерского хозяйства в горных регионах Кыргызстана. Целью работы было детальное определение вкусовых, ароматических и текстурных характеристик мяса ягнят в возрасте 4, 6 и 8 месяцев, а также установление соответствия полученных показателей действующим стандартам качества. Методология исследования включала строгий отбор образцов длиннейшей мышцы спины (*m. longissimus dorsi*) от животных каждой возрастной группы. Для обеспечения достоверности результатов термическая обработка мяса проводилась в соответствии со стандартом ГОСТ 9959-2015, что гарантировало стандартизированные условия подготовки. Дегустационная оценка осуществлялась квалифицированной комиссией из семи экспертов, а полученные данные подверглись биометрической обработке. По результатам анализа установлено, что все исследованные образцы мяса демонстрировали исключительно высокие показатели по ключевым органолептическим параметрам, включая внешний вид, аромат, вкус, сочность и консистенцию. Средние баллы по 9-балльной шкале варьировали в среднем от 8,3 до 8,7, что свидетельствует о высоком качестве продукта. Особое внимание было уделено показателю нежности, по которому мясо получило наиболее высокие оценки, что подтверждает такую биологическую особенность тянь-шаньской породы, как скороспелость, и ее пригодность к раннему убою для получения нежной ягнятины. В ходе исследования не было выявлено никаких дефектов или посторонних привкусов, что подчеркивает высокий уровень выращивания животных и соответствие продукции премиум-классу. Полученные данные подтвердили значительный потенциал тянь-шаньской породы для производства высококачественной ягнятины в условиях малого бизнеса, обеспечивая конкурентные преимущества на рынке

**Ключевые слова:** ягнятина; дегустационная оценка; пастбищное выращивание; мясное качество; овцы; фермерское хозяйство

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# Stress-strain state of highland dams under the influence of volumetric and seismic forces for sustainable water resources management and agrarian security

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**Abstract.** Ensuring the reliability of hydraulic structures, in particular highland dams, is of particular importance for sustainable water supply in the agro-industrial complex, especially under conditions of water scarcity and seismic activity. The purpose of this work was to evaluate the stress-strain state of highland dams taking into account the complex action of volumetric, seismic and hydrostatic loads to improve the reliability of water infrastructure serving agriculture. The Kolosov-Muskhelishvili method was used in the study to model stresses in elastic media taking into account the interaction of rocks, tectonic stresses and external loads. The peculiarities of stress redistribution in the dam massif under changes in the reservoir level and water saturation were analysed, and the influence of seismic effects on the formation of shear zones in isotropic rocks was revealed. It was found that in mountainous relief conditions horizontal stresses may exceed vertical stresses, which requires revision of design approaches. The combined effects of gravitational, seismic and hydrostatic forces on the stability of

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structures have been analysed. Special attention was paid to the influence of tectonic processes and relief on the stress state of the soil mass. The results of the study can be used in the design and operation of highland dams that provide water supply to reclamation systems and agricultural areas in earthquake-prone regions. Modern methods of mathematical modelling significantly increase the accuracy of engineering calculations and ensure the reliability of hydraulic structures, which is especially important for ensuring agrarian safety. The assessment of stress-strain state of structures serves as a basis for predicting their behaviour under various loads and taking effective measures to maintain stability. The practical value of the performed work lies in the use of the results by design and engineering survey organisations in the design and construction of highland dams, allowing designers to accurately predict the behaviour of hydraulic structures under various operating conditions, ensuring reliable and sustainable water supply in agriculture, especially in areas with increased seismic activity and complex engineering and geological conditions

**Keywords:** gravitational force; conformal mapping; initial stress state; boundary conditions; dam modelling; hydrostatic pressure; filtration processes

## Introduction

Kyrgyzstan, located in a mountainous area, faces a special problem in water supply and irrigation of agricultural land. The accumulation of water resources is an essential part of hydropower and agro-industrial development, as it provides a stable water supply for agriculture and allows efficient use of water bodies for irrigation. To provide water resources, it is necessary to develop and operate reservoirs at different elevations. However, dam failure, especially in mountainous areas with large volumes of stored water, poses a serious threat to human life and can also lead to flooding of settlements and agricultural land.

The performance of dams in mountainous conditions has many characteristics, which makes the assessment of their stability a complex task, especially considering the specifics of agriculture and water management. As noted by U. Hansamali *et al.* (2025), the failure of dams and levees can be caused by a variety of factors, including seismic activity, the impact of water from reservoirs, and the design and materials of both natural and man-made dams. The location of dams relative to sea level is also important, which is directly related to the temperature regime and operating conditions of the dam during different seasons (Ouma *et al.*, 2022). These aspects need to be taken into account in the design and operation of hydraulic structures to ensure their long-term safety and minimise risks to agriculture and water supply.

However, dam failures in such high-altitude zones, as well as accidents at large hydroelectric power plants (HPPs) located in river canyons, pose a real threat to human life and safety, and can lead to massive destruction of settlements and agricultural lands. These problems become especially urgent in the conditions of complex geography of the country, where climatic conditions, seismic activity and geological features significantly affect the strength and stability of hydraulic structures (Montayev *et al.*, 2025). One of the most important tasks is to assess the stability of dams in mountainous areas, which requires consideration of many factors such as seismicity, temperature fluctuations, hydrostatic water pressure, water filtration through the dam body, and structural features. The stability of dams in such conditions is related to the preservation of structural stability, prevention of failure and deformation, which is key for the long-term operation of these facilities (Popov *et al.*, 2023).

M. Sainov (2022) has made a significant contribution to the study of the stress-strain state and stability of various types of dams. In his work, the influence of pore pressure on the fracture resistance of an ultra-high rock-fill dam with a central clay core is considered. Using numerical modelling techniques, the author investigates the stress distribution and identifies critical zones prone to crack formation. The results emphasise the importance of considering internal water head in dam design, especially under conditions of varying water saturation. The author also investigates the stress-strain state of a concrete dam with a concrete screen when the friction coefficient in the screen-sidewall contact zone is reduced. It is established that friction reduction leads to redistribution of stresses and potential reduction of stability of the structure. The author emphasises the need for accurate setting of boundary conditions when modelling structures of this type. In addition, M. Sainov (2023) summarises theoretical and practical aspects of the design, construction and operation of earth dams in a textbook intended for training specialists in hydraulic engineering. The manual covers a wide range of engineering solutions and contains a structured presentation of basic and applied principles applicable in real dam operating conditions.

In the work of S. Pari (2025) provides a probabilistic analysis of the stability of an earthen dam under steady-state seepage conditions. Special attention is paid to the influence of the clay core location on the overall stability coefficient. The author uses stochastic modelling techniques to account for uncertainties in the geotechnical parameters of the foundation and dam body. It is found that the displacement of the core from

the centre of the structure can significantly reduce the stability of the structure, especially in conditions of prolonged saturation. The analysed studies reflect modern scientific approaches to the assessment of stress-strain state and stability of dams. E. Argal (2024) in his work analyses the causes of seepage, methods of controlling it and offers recommendations on how to improve the condition of a dam.

The purpose of the study of the stress-strain state (SS) of highland dams was to evaluate the distribution of stresses and strains in the dam structure to ensure its stability, safety and durability during operation. This included analysing the effects of external factors such as hydrostatic pressure, seismic activity on the dam structure. Objectives of the study:

- modelling of the stress-strain state of rock dams taking into account seismicity, temperature, water pressure in reservoirs, and geological features;
- analysing existing methods of calculating the VAT of dams in mountainous areas, taking into account the impact of various natural and geophysical factors;
- development of recommendations for strengthening the design of dams in mountainous areas to ensure their long-term stability and safety for the population and agriculture.

This study can make it possible to solve the complex problem of dam stability in mountainous conditions, which is an important step to ensure the reliability of hydraulic structures, minimise risks for the population, safety of irrigated lands and stable water supply in agriculture.

## Materials and Methods

The Kolosov-Muskhelishvili analytical method for modelling the stress-strain state of a mountain dam taking into account various natural and anthropogenic factors, described in detail in R. Abdikarimov *et al.* (2011). The application of this method made it possible to conduct a comprehensive study of the influence of hydrostatic, thermal and seismic loads on the stability of the structure, as well as to determine the critical stress zones and develop recommendations for structural optimisation taking into account the developments presented in the study by N. Kobeleva (2017). The stability of the dam under various external influences was assessed. The most vulnerable sections of the structure subjected to maximum stress were identified according to the methodology described in E. Askarbekov *et al.* (2019). The proposed methodology made it possible to assess the stability of the dam under the combined effects of natural factors.

Analytical modelling of highland dams was carried out by using the mapping functions $\omega(\zeta)$ and deriving relations for the complex potentials $\Phi(\zeta)$ and $\Psi(\zeta)$ based on the given boundary conditions (1):

$$\Phi(t) + \overline{\Phi(t)} + \frac{1}{\omega'(t)}\{\overline{\omega(t)}\Phi'(t) + \omega'(t)\Psi(t)\} = N(t) + iT(t). \quad (1)$$

In the present study, a semi-infinite region corresponding to the centre plane of the dam was considered, with two characteristic protrusions on the contour taken as the initial points of the mapping ($\zeta = 0$) (Baialieva *et al.*, 2023). This approach allowed us to precisely set the geometry of the computational domain and ensure correct imposition of boundary conditions. The creation of the mapping function consisted of two steps: 1) selection of the general form of the mapping function; 2) development of a technique for selecting the values of the parameters of this function a (to = 1, 2, 3). The general form of the function representing the proposed class is shown as (2):

$$z = \omega(\zeta) = \frac{a\zeta + \sum_{k=0}^{3} a_k \cdot (\zeta - i)^k + b_1}{(\zeta + t_0 - i)}, \quad (2)$$

where $z$ $x$ = + iy; $i = \sqrt{-1}$; $b_1$, $\alpha$, $t_0$ are constants, $a$ (to = 1, 2, 3) are complex constants.

The second part of the problem was solved by graphical packages in MATCAD #14 to vary the constants in the parametric equations, which follows (2) when $\zeta$ = t:

$$x(t) = \frac{f_1(t)}{(t^2+1)^3} + \frac{b_1(t+t_0)}{[(t+t_0)^2+1]}$$
$$y(t) = \frac{f_2(t)}{(t^2+1)^3} + \frac{b_1}{[(t+t_0)^2+1]}. \quad (3)$$

The proposed mapping technique differs from the previously known one in its flexibility, clarity and high operability in modelling dam shapes (Mirsaidov *et al.*, 2013). After creating the dam computational model (Fig. 1), i.e. when all parameters $\omega(\zeta)$ in (2) are determined, the equation (1) was integrated and its conjugate equation in closed form under given arbitrary external loads to calculate the stress state of the semi-infinite region.

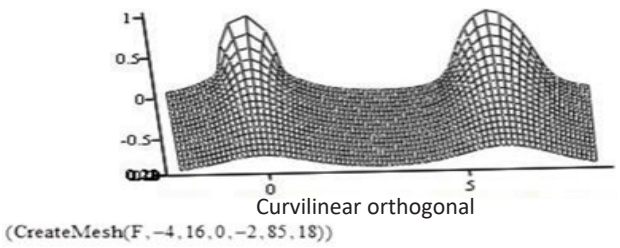


**Figure 1.** Dam model

**Source:** B. Zhumabaev & K. Ismailova (2005)

The formulated boundary value problem (1) was solved by constructing relations of two complex potentials $F(\zeta)$ and $\Psi(\zeta)$ in the form:

$$\overline{\omega'}(\zeta)F(\zeta+\overline{\omega}(\zeta)\,F'(\zeta)+k_1/(\zeta+i)^2+2k_{(2)}/(\zeta+i)^3+$$
$$+3k_{(3)}/(\zeta+i)^4+\kappa_4/(\zeta+t_{(0)}+i)^2+$$
$$+\omega'(\zeta)\Psi(\zeta)=A(\zeta);$$

$$(\omega'\zeta)F(\zeta)-\overline{\kappa_1}/(\zeta-i)^2-2\overline{\kappa_2}/(\zeta-i)^3-$$
$$-3\overline{\kappa_3}/(\zeta-i)^4-\overline{\kappa_4}/(\zeta+t_{(0)}-i)^2=B(\zeta), \quad (4)$$

where $A(\zeta)$ and $B(\zeta)$ depend only on the external loads N and T and are computed as Cauchy type integrals:

$$A(\zeta)=\frac{1}{2\pi i}\int\frac{(N+iT)\overline{\omega'(t)dt}}{1-\zeta}\ \mathrm{B}(\zeta)=\frac{1}{2\pi i}\int\frac{(N-iT)\omega'(t)dt}{1-\zeta}, \quad (5)$$

where $\zeta$ belongs to the lower half-plane, $\eta = 0$ in the plane of the omnipotent complex variable $\zeta=\xi+i\eta$.

The operator $\omega(\zeta)=a\zeta+\omega_0(\zeta)$ is instantiated as:

$$\omega_0(\zeta)=\sum_{e=1}^{3}\frac{a_e'}{(\zeta-i)^e}+\frac{b_1}{\zeta+t_0-i}. \quad (6)$$

The general model of the stress state of surge dams as a sum of three stress fields:

$$\sigma x^0=\sigma(x)^{(n)}+\sigma(x)^{(p)}+\sigma(x)^{(c)},\ \sigma(y)^{(0)}=\sigma(y)^{(n)}+$$
$$+\sigma(y)^{(p)}+\sigma(y)^{c},\ \tau_{(y)}^{(0)}=\tau^{(y)(n)}+\tau^{(y)(p)}+\tau^{(y)(c)}. \quad (7)$$

This stress field is defined as the integral of the inhomogeneous differential equation of equilibrium for the half-plane (Zhumabaev & Ismailova, 2005):

$$\frac{\partial\sigma_{\tilde{0}}^{\tilde{i}}}{\partial\tilde{0}}+\frac{\partial\tau_{\tilde{0}\,0'}^{\tilde{i}}}{\partial 0'}+\rho_{\tilde{0}}=0,\frac{\partial\tau_{\tilde{0}}^{\tilde{i}}}{\partial x}+\frac{\partial\sigma_{0'}^{\tilde{i}}}{\partial 0'}+\rho_{0'}=0, \quad (8)$$

where $\rho_x=\gamma k_c\sin\delta$; $\rho_y=\gamma(1-k_c\cos\delta)$ are the horizontal and vertical components of the volume force; $g$ – gravitational acceleration; $k_c$ – seismicity coefficient.

The integrals from (8) have the form

$$\sigma_x^{i}=A_1 y;\ \sigma_y^{i}=A_2 y;\ \tau_{xy}^{i}=A_3 y, \quad (9)$$

where $A_1=\lambda\gamma(1-k_c\cos\delta)$; $A_2=\gamma(1-k_c\cos\delta)$; $A_3=k_c\cdot\gamma\sin\delta$; $\lambda$ is the coefficient of lateral spreading.

The initial stress state of rock dam arrays under the action of the above forces is represented as the sum of the first two stress fields (7) with upper indices "n" and "p" and satisfies the boundary conditions on the contour:

$$X(n)^{(*)}=(\sigma(x)^{(p)}+\sigma(x)^{(p)})\cos(n,x)+$$
$$+(\tau(x)^{(p)}+\tau(x)^{(p)})\cos(n,y)=0;$$

$$U(n)^{(*)}=(\tau(hu)^{(p)}+\tau(hu)^{(p)})\cos(n,x)+$$
$$+(\sigma(y)^{(p)}+\sigma(y)^{(p)})(\cos)(n,y)=0, \quad (10)$$

where $n$ is the direction of the external normal at the contour point under consideration.

Condition (10) contains the sum of fictitious loads N and T and load-force. The latter arises from the first stress field (9) at the contour points. Denoting by $F_1$ and $F_2$, the boundary conditions are obtained:

$$F_1(t)=\left[\omega_0(t)-\overline{\omega_0(t)}\right]\cdot[T_5+T_6\overline{\omega_0'(t)}+T_7\omega_0'(t)]$$
$$F_2(t)=\left[\omega_0(t)-\overline{\omega_0(t)}\right]\cdot[T_2+T_3\overline{\omega_0'(t)}+T_4\omega_0'(t)], \quad (11)$$

where

$$T_2=-\alpha\frac{iA_2+A_3}{2};\ T_3=-i\frac{A_1+A_2}{4};\ T_4=i\frac{A_1-A_2+2iA_3}{4};$$
$$T_5=\alpha\frac{iA_2-A_3}{2};\ T_6=i\frac{A_1+A_2}{4};\ T_7=-i\frac{A_1-A_2-2iA_3}{4}.$$

The solution of this boundary problem on the initial stress state of the surge dams is given by calculating the Cauchy type integrals in (5) from the boundary conditions in (11). They are of the form:

$$A(\zeta)=-\frac{1}{2\pi i}\int F_1(t)\frac{dt}{t-\zeta}=[T_5+T_7\omega_0'(\zeta)]\cdot\omega_0(\zeta)+$$
$$+T_6\left(\sum_{k=1}^{3}\frac{C_k}{(t-i)^k}+\frac{C_4}{t+t-i}\right)-$$
$$-T_7\left(\sum_{k=1}^{4}\frac{S_k}{(t-i)^k}+\frac{S_5}{t+t-i}+\frac{S_6}{(t+t-i)^2}\right)$$

$$\mathrm{B}(\zeta)=-\frac{1}{2\pi i}\int F_1(t)\frac{dt}{t-\zeta}=T_3\omega_0(\zeta)\omega_0'(\zeta)+$$
$$+T_2\omega_0(\zeta)+T_4\left(\sum_{k=1}^{3}\frac{C_k}{(t-i)^k}+\frac{C_4}{t+t-i}\right)-$$
$$-T_3\left(\sum_{k=1}^{4}\frac{S_k}{(t-i)^k}+\frac{S_5}{t+t-i}+\frac{S_6}{(t+t-i)^2}\right). \quad (12)$$

The stress-strain state of the upland dam, when the depression between the mountains is filled with water, experienced the action of external load (influence of the reservoir (Fig. 2).

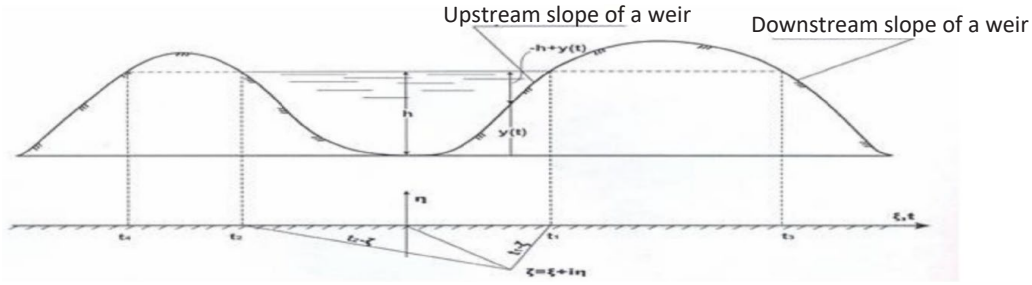


**Figure 2.** Calculation scheme of the reservoir

**Source:** B. Zhumabaev & K. Ismailova (2005)

In this case, the solution of the problem on the influence of the reservoir on the stress-strain state of the dams according to the boundary conditions $F_1(t) = N(t)\omega'(t)$ and $F_{(2)}(t) = F_{(1)}(t)$ were determined by the relations:

$$A(\zeta) = \left[r_0 + \sum_{k=1}^{7}\frac{r_{1k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{r_{2k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{r_{3k}}{(\zeta+t_0-i)^k} - \frac{r_{41}}{\zeta+t_0+i}\right] \ln\frac{t_1-\zeta}{t_2-\zeta} + \sum_{k=1}^{7}\frac{c_{1k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{c_{2k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{c_{3k}}{(\zeta+t_0-i)^k} + \frac{c_{41}}{\zeta+t_0+i}$$

$$B(\zeta) = \left[R_0 + \sum_{k=1}^{7}\frac{R_{1k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{R_{2k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{R_{3k}}{(\zeta+t_0-i)^k} + \frac{R_{41}}{\zeta+t_0+i}\right] \ln\frac{t_1-\zeta}{t_2-\zeta} + \sum_{k=1}^{7}\frac{S_{1k}}{(\zeta-i)^k} + \sum_{k=1}^{3}\frac{S_{2k}}{(\zeta+i)^k} + \sum_{k=1}^{3}\frac{S_{3k}}{(\zeta+t_0-i)^k} + \frac{S_{41}}{\zeta+t_0+i}. \quad (13)$$

The initial stress state was determined for the selected computational model. All relations required for the calculation of stress components were algorithmised in MATCAD environment.

## Results and Discussion

The modelling results satisfy all the conditions of the problem on the influence of the reservoir on stress redistributions in the massifs of the upland dams. Stress values are presented in relative values. This circumstance allows to reflect more objectively the established regularities of stress distribution. The use of the Kolosov-Muskhelishvili method in calculations allows to improve the design of dams, taking into account the interaction of materials and soils, which contributes to a more accurate and efficient approach in construction, it also allows to identify potential zones with high stresses and deformations at early stages and take timely measures to strengthen the structure and prevent failures (Botokanova & Isaeva, 2024). It is based on the classical theory of elasticity and complex potentials, which guarantees theoretical validity of calculations and applicability in engineering practice for modelling the stress-strain state of dams. This method has proven its effectiveness in modelling complex hydraulic structures such as mountain dams, where the interaction of materials and external factors is crucial for the stability of the structure (Nikolaevsky, 2012). Thus, the results of the study have significant practical value for the design and operation of mountain dams, and the methodological correctness is ensured by theoretical validity of the method and its integration with modern numerical methods (Botokanova, 2024).

In the work of B. Zhumabaev & K. Ismailova (2005) performed an in-depth mathematical analysis of the stress state of rock massifs of canyons in the zone of reservoir formation. Particular attention was paid to the influence of water pressure regime on the redistribution of stresses near the surface of the canyon, taking into account the different orientation of the slope of the layering of the geological massif. On the basis of the developed mathematical model private analytical solutions describing the stress state of rock massifs under different variants of load combinations are obtained. The following types of combined effects are considered: joint action of gravitational and hydrostatic loads; simultaneous effect of gravitational, seismic forces and hydrostatic loads; superposition of gravitational, horizontal tectonic and hydrostatic effects. The results of the analysis show that water saturation of the massif and changes in the reservoir level lead to significant local redistributions of stresses, especially in zones of disturbed layering and on sloping slopes (Fig. 3).

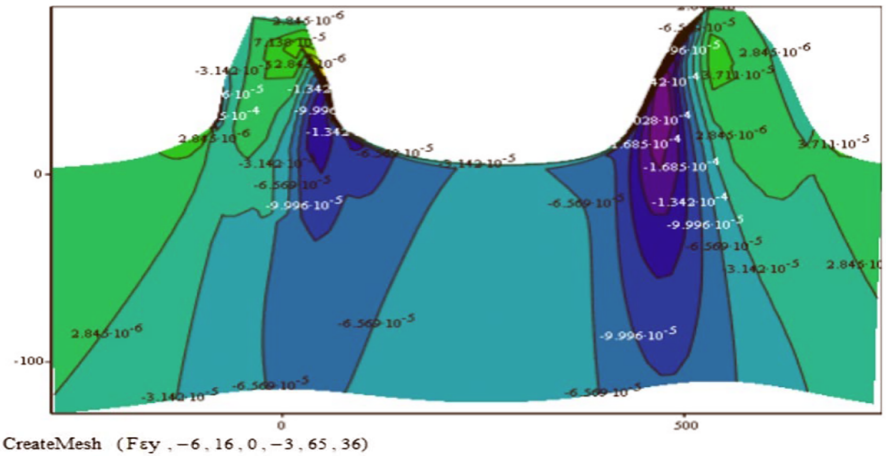


**Figure 3.** Stress components

**Source:** B. Zhumabaev & K. Ismailova (2005)

It has been found that when hydrostatic pressure increases in combination with seismic effects, the probability of shear deformations in weakly cemented layers increases (Baialieva *et al.*, 2023). Under the action of horizontal tectonic stresses, additional hydrostatic pressure favours the activation of already existing

dislocation zones and fracturing. B. Zhumabaev & K. Ismailova (2005) focus their research on the stress-strain state of dams, especially in mountainous areas. They consider the influence of physical and mechanical properties of materials, water pressure, temperature and seismicity on the behaviour of dams. Particular attention is paid to the evaluation of filtration processes in the dam body and their influence on the deformations and stability of the structure. B. Zhumabaev & K. Ismailova (2005) offer a methodology for calculating the VAT of rock dams, which takes into account both static and dynamic loads, as well as seasonal temperature fluctuations, which is especially important for frozen and seismically active regions. Their work emphasises the use of multilink models to more accurately account for the interaction of various factors such as water filtration, changes in geology and heat transfer, which improves the accuracy and reliability of the calculations.

Conclusions of B. Zhumabaev & K. Ismailova (2005) confirm the need to integrate the water storage factor into geomechanical calculations, especially in the design and operation of reservoirs in complex engineering and geological conditions. As part of the research conducted by K. Abdyldaev (2015), a comprehensive analysis of the stress-strain state of rocks in mountainous terrain was carried out. Particular attention is paid to the identification of the relationship between tectonic processes, gravitational forces and redistribution of horizontal stresses in the massif. Based on analytical calculations and modelling, it was found that in zones of complex relief the maximum horizontal stresses significantly exceed the values predicted by classical theories of elasticity for flat conditions (Baialieva, 2015). This is due to a combination of the following factors: the effects of redistribution of the massif weight in the presence of height differences; directional tectonic compression, characteristic of active mountainous regions of Central Asia; local redistribution of stresses in the zones of slope bends and contacts of rocks of different stiffness.

K. Abdyldaev (2015) also revealed that in some cases horizontal stresses can reach values comparable to vertical stresses, and in some zones even exceed them. This effect is enhanced in the presence of pre-formed tectonic disturbances, faults and weak interlayers. The analysis confirmed that the traditional approaches of VAT calculation, based on the assumption of homogeneity of the stress field, are unacceptable for engineering calculations in mountain conditions. Ignoring spatial variability of stresses can lead to underestimation of risks of deformation processes (landslides, slope failures) during construction of hydraulic structures, dams and mountain roads. The work of K. Abdyldaev & A. Toktosunov (2017) demonstrates the necessity of complex consideration of tectonic and gravitational factors in modelling of VAT in massifs with mountainous relief and underlines the relevance of application of three-dimensional geomechanical models based on real geological and structural data.

The analysis of the stress-strain state of the soil massif in the area of the Ust-Ilimskaya HPP construction was based on a comprehensive study of geological conditions, including relief and tectonic features. A significant contribution to the study of these processes was made by N. Bondarchuk *et al.* (1978) and other specialists engaged in the assessment of stresses in the base of hydraulic structures. In the process of research it was established that against the background of general gravitational loading the massif experiences a significant influence of horizontal tectonic stresses. The latter are caused by both ancient tectonic processes associated with the formation of the Siberian platform and active modern deformations of the Earth's crust within the southern margins of Siberia.

The relief of the Ust-Ilimskaya HPP territory, characterised by alternation of river terraces, erosion scarps and slopes, additionally increases the unevenness of stress distribution. As calculations on the basis of elastic-plastic models have shown, areas of increased horizontal compression and vertical tension are formed in the zones of slope bends, which leads to localisation of plastic deformations and reduction of bearing capacity of the massif (Bychkov, 1981). The influence of the reservoir filling process is of particular complexity. Reservoir filling leads to an increase in pore pressure, changes in effective stresses and, as a consequence, to redistribution of stress fields in the coastal zone (Kasparyan *et al.*, 2006). According to the studies, as a result of water level rise by 20-30 m, redistribution of horizontal stresses occurs up to the depth of 100-150 m, which is accompanied by an increase in the risk of landslide deformation formation on coastal slopes.

The work of C. Li *et al.* (2020) confirms that in conditions of high reservoirs of similar type, the character of stress changes depends significantly on the shape of the base relief, the depth of tectonic faults and the nature of watered rocks. According to field observations and theoretical modelling, the greatest redistribution of stresses is recorded within the coastal slopes composed of poorly consolidated or disturbed tectonic rocks, where additional load from the reservoir can initiate slow creeping deformations or rapid failures such as rockfalls and landslides (Khusanov & Khaydarova, 2019). These results are relevant not only for the conditions of the Ust-Ilimskaya HPP, but also for the design of new large hydraulic structures in regions with pronounced relief and active tectonics. Thus, the works of these scientists are of great practical importance for the design and operation of dams in mountainous areas such as Kyrgyzstan. Given the high seismicity and difficult climatic conditions, the development of effective methods for calculating the VAT of dams, taking into account all these factors, becomes a key aspect for ensuring the safety of hydraulic structures and preventing potential failures.

## Conclusions

In the course of the study, a methodology was developed for calculating the stress-strain state (SS) of upstream dams, taking into account the influence of volumetric forces and changes in this state before and after filling the reservoir. This approach allowed a more accurate prediction of the distribution of stresses arising in the dam structure, which is of key importance for ensuring its durability and stability, especially in the context of hydraulic structures serving agriculture. The analysis showed that horizontal stresses reach their maximum values in the contour part of the reservoir bowl, along the loaded section. At the same time, small tensile stresses are observed in the area just above the level of the reservoir mirror, and the compressed section occurs only in a small part of the dam massif, where the thickness of this zone is about 1.1-1.15 of the dam height. A zone of tensile stresses is formed along the depth of the reservoir, the intensity of which gradually decreases. Vertical stresses show a similar pattern, but their decrease is somewhat slower in depth.

Particular attention is paid to the tangential stresses, which reach their maximum values in the zone of slope inflection, as well as in the contour part of the dam localised at the base. These data are critical for analysing potential weakening zones of the structure and minimising failure risks. Application of the Kolosov-Muskhelishvili method makes it possible to take into account a wide range of factors affecting the stability and stability of dams, such as hydrostatic pressure, seismic activity and geological conditions. This method significantly improves the accuracy of predicting the behaviour of structures and helps to optimise the design and operation of hydraulic structures. Thus, the performed VAT calculations have become an important step in ensuring the reliability of upstream dams used in agricultural and water management. Taking into account complex loads, including seismic and gravitational forces, as well as peculiarities of canyon slopes in reservoir zones, allows increasing the stability of structures to various external influences. Prospects for further research are aimed at developing more detailed models that will take into account the effects of climate change, seasonal temperature fluctuations and other factors, as well as improving calculation methods to ensure the long-term safety of water management facilities and minimise risks to agriculture, which depends on the stability of water supply.

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## Conflict of Interest

The authors are interested in the publication of this article, there is no conflict of interest.

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# Суу ресурстарын туруктуу башкаруу жана айыл чарба коопсуздугун камсыз кылуу максатында көлөмдүк жана сейсмикалык күчтөрдүн таасири астында бийик тоолордогу дамбалардын стресс-деформациялык абалы

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**Аннотация.** Гидротехникалык курулмалардын, атап айтканда, бийик тоолордогу дамбалардын ишенимдүүлүгүн камсыз кылуу агроөнөр жай комплексинде, өзгөчө суунун тартыштыгынын жана сейсмикалык активдүүлүктүн шарттарында туруктуу суу менен камсыз кылуу үчүн өзгөчө маанеге ээ. Бул иштин максаты айыл чарбасын тейлеген суу чарба инфраструктурасынын ишенимдүүлүгүн жогорулатуу үчүн көлөмдүк, сейсмикалык жана гидростатикалык жүктөрдүн комплекстүү аракетин эске алуу менен бийик тоолордогу дамбалардын чыңалуу-деформациялык абалын баалоо болгон. Изилдөөдө тектердин өз ара аракеттенүүсүн, тектоникалык чыңалууларды жана тышкы жүктөрдү эске алуу менен серпилгич чөйрөлөрдөгү чыңалууларды моделдөөгө мүмкүндүк берүүчү Колосов-Мусхелишвили ыкмасы колдонулган. Суу сактагычтын деңгээлинин жана сууга каныккандыгынын өзгөрүшү менен плотина массивиндеги чыңалуулардын кайра бөлүштүрүлүшүнүн өзгөчөлүктөрү талдоого алынып, изотроптук тоо тектериндеги жылышуу зоналарынын пайда болушуна сейсмикалык таасирлердин таасири аныкталган. Тоолуу рельефте горизонталдык чыңалуу вертикалдуудан ашып кетиши мүмкүн экендиги аныкталды, бул долбоорлоо ыкмаларын кайра карап чыгууну талап кылат. Конструкциялардын туруктуулугуна гравитациялык, сейсмикалык жана гидростатикалык күчтөрдүн биргелешкен таасирин талдоо жүргүзүлөт. Топурак массивинин стресс абалына тектоникалык процесстердин жана рельефтин таасирине өзгөчө көңүл бурулат. Изилдөөнүн натыйжалары сейсмикалык кооптуу региондордогу мелиорация системаларын жана айыл чарба аймактарын суу менен камсыз кылуучу бийик тоолуу дамбаларды долбоорлоодо жана эксплуатациялоодо колдонулушу мүмкүн. Математикалык моделдештирүүнүн заманбап методдору инженердик эсептөөлөрдүн тактыгын олуттуу түрдө жакшыртат жана гидротехникалык курулуштардын ишенимдүүлүгүн камсыз кылат, бул айыл чарба коопсуздугун камсыз кылуу үчүн өзгөчө маанилүү. Конструкциялардын чыңалуу-деформациялык абалын баалоо алардын ар кандай жүктөмдөрдөгү жүрүм-турумун болжолдоо жана туруктуулукту сактоо боюнча натыйжалуу чараларды көрүү үчүн негиз болуп саналат. Аткарылган иштердин практикалык баалуулугу долбоордук-инженердик изилдөө

уюмдары тарабынан бийик тоолуу дамбаларды долбоорлоодо жана курууда натыйжаларды пайдалануууда, долбоорлоочуларга ар кандай эксплуатациялык шарттарда гидротехникалык курулмалардын жүрүм-турумун так болжолдоого мүмкүндүк берет, айыл чарбасында, өзгөчө сейсмикалык активдүүлүк күчөгөн жана татаал инженердик-геологиялык шарттарда сууну ишенимдүү жана туруктуу камсыз кылууда

**Негизги сөздөр:** гравитация; конформдык карта түзүү; баштапкы стресс абалы; чек ара шарттары; дамбаны моделдөө; гидростатикалык басым; фильтрация процесстери

# Напряженно-деформированное состояние нагорных плотин под воздействием объемных и сейсмических сил в целях устойчивого управления водными ресурсами и аграрной безопасности

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**Аннотация.** Обеспечение надежности гидротехнических сооружений, в частности нагорных плотин, имеет особую значимость для устойчивого водообеспечения в агропромышленном комплексе, особенно в условиях дефицита водных ресурсов и сейсмической активности. Целью настоящей работы была оценка напряженно-деформированного состояния нагорных плотин с учетом комплексного действия объемных, сейсмических и гидростатических нагрузок для повышения надежности водохозяйственной инфраструктуры, обслуживающей сельское хозяйство. В исследовании использован метод Колосова-Мусхелишвили, который позволяет моделировать напряжения в упругих средах с учетом взаимодействия горных пород, тектонических напряжений и внешних нагрузок. Были проанализированы особенности перераспределения напряжений в массиве плотины при изменении уровня водохранилища и водонасыщении, а также выявлено влияние сейсмических воздействий на формирование сдвиговых зон в изотропных породах. Установлено, что в условиях горного рельефа горизонтальные напряжения могут превышать вертикальные, что требует пересмотра проектных подходов. Проведен анализ комбинированных воздействий гравитационных, сейсмических и гидростатических сил на устойчивость сооружений. Особое внимание уделено влиянию тектонических процессов и рельефа на напряженное состояние грунтового массива. Результаты исследования могут быть использованы при проектировании и эксплуатации нагорных плотин, обеспечивающих

водоснабжение мелиоративных систем и сельскохозяйственных территорий в сейсмоопасных регионах. Современные методы математического моделирования значительно повышают точность инженерных расчетов и обеспечивают надежность гидротехнических сооружений, что особенно важно для обеспечения аграрной безопасности. Оценка напряженно-деформированного состояния сооружений служит основой для прогнозирования их поведения под различными нагрузками и принятия эффективных мер по поддержанию устойчивости. Практическая ценность выполненной работы заключается в использовании результатов проектными и инженерно-изыскательскими организациями при проектировании и строительстве нагорных плотин, позволяя проектировщикам точно прогнозировать поведение гидротехнических объектов в различных эксплуатационных условиях, обеспечивающих надежное и устойчивое водоснабжение в сельском хозяйстве, особенно в районах с повышенной сейсмической активностью и сложными инженерно-геологическими условиями

**Ключевые слова:** сила гравитации; конформное отображение; начальное напряженное состояние; граничные условия; моделирование плотин; гидростатическое давление; фильтрационные процессы

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# Legal regulation of agricultural technologies in the context of digital transformation: A comparative analysis of the EAEU countries

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**Abstract.** The digitalisation of the agricultural sector is accompanied by the introduction of innovative technologies, creating new challenges for legal regulation. Within the Eurasian Economic Union, there is a growing need for coordinated approaches to ensuring sustainable development and food security. The article presented a comprehensive analysis of digitalisation processes in the agricultural sector of the Eurasian Economic Union member states, based on a comparative study of the legal framework and practices of digital technology implementation. The authors highlighted different models of digital transformation. Russia is implementing a large-scale federal project "Digital Agriculture", Kazakhstan is focusing on creating model digital farms and full digitalisation of agricultural land, while Belarus has made significant progress in automating accounting and implementing an electronic system of veterinary certification. Kyrgyzstan and Armenia, despite the adoption of appropriate policy frameworks, faced serious challenges, including inadequate infrastructure, limited funding, and low levels of digital literacy. The main findings indicated common problems in the Eurasian Economic Union countries: a digital divide between large and small farms, poorly developed digital infrastructure in rural areas, and a shortage of qualified specialists. As promising areas, the authors proposed harmonisation of legislation, the creation of a single Eurasian digital agricultural platform and the development of joint educational programs, while emphasising the need to take into account the national characteristics of each participating country when coordinating the digital transformation of agriculture within the Eurasian Economic Union. The results of the research can be used both in the scientific community and in the development of digitalisation strategies, improving legislation and developing coordinated approaches to regulating agricultural technologies in the Eurasian Union

**Keywords:** digitalisation; Eurasian Economic Union; agricultural cooperation; cybersecurity; agricultural data; harmonisation of norms

## Introduction

Modern agriculture faces many challenges, including the need to increase production volumes for a growing population and adapt to climate change. In this context, digitalisation, understood as the process of introducing digital technologies into traditional operations, offers new opportunities to improve the efficiency and

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sustainability of the agricultural sector (Katrin, 2022). Of particular interest is a comparative analysis of the regulatory framework for this process in the countries of the Eurasian Economic Union (EAEU), as the rapid development of digital technologies is making the agricultural sector one of the key industries most receptive to innovation. The introduction of agricultural technology, including elements of precision farming and remote monitoring systems based on artificial intelligence, can significantly increase the productivity, sustainability and environmental safety of agricultural production. At the same time, the digitalisation of agriculture requires adequate regulatory and legal regulation, as the use of innovative solutions affects a wide range of legal aspects: from the protection of personal and production data to the regulation of intellectual property and cybersecurity. Research on this topic is particularly relevant in the context of the Eurasian Economic Union, where there are both common trends and significant differences in the pace and mechanisms of legal regulation of agricultural technologies. Despite the existence of supranational institutions such as the Eurasian Economic Commission (EEC) and the desire to harmonise legislation, the EAEU member states (Russia, Belarus, Kazakhstan, Armenia, Kyrgyzstan) demonstrate varying levels of digital maturity and approaches to the legal support of agrotechnological transformation. A corporate analysis of national strategies and regulatory acts in the field of digital agriculture allows for identifying institutional barriers, best practices and growth points, as well as formulating proposals for harmonising legal regulation within the EAEU. This is particularly important in the context of integration processes that offer the free movement of goods, services and technologies within the union. The lack of a unified approach can create obstacles to the cross-border introduction of agricultural technologies and slow down the digital transformation of the entire agricultural sector in the region.

An analysis of recent scientific research has revealed a growing interest in issues related to regulatory legal regulation, agricultural technology, and digital transformation of the agricultural sector in EAEU countries. Contemporary research touches upon both strategic and applied aspects of digitalisation, emphasising the need for a comprehensive approach to the legal support of the agricultural digital agenda. The work by M. Mustafayev *et al.* (2024) examined the legal support for the integration of the EAEU digital space, focusing on the need to synchronise national legal systems for the effective implementation of digital technologies, including in the agricultural sector. The authors pointed to a lack of legal instruments regulating cross-border interaction within the digital economy. N. Voronina (2024) emphasised the importance of digitalisation for the cooperative movement in agriculture. The author argued that digital tools help strengthen ties between small agricultural producers and markets, but that legal regulation does not yet meet these challenges. A. Makrushin (2023) examined the impact of digitalisation on the labour market in the EAEU, including the agricultural sector. The author emphasised that the sustainable development of digital agricultural technologies requires the adaptation of labour legislation and the strengthening of digital literacy in rural areas. The work of S. Kamolov & S. Glazyeva (2023) presented a critical review of the current state of implementation of the digital agenda. The authors noted that the agricultural sector is characterised by a fragmented approach, insufficient regulation of data collection and exchange, and gaps in the legal protection of intellectual property in agricultural technologies. The study by Ch. Adamkulova *et al.* (2025) emphasised that digital agricultural platforms improve logistics, increase management efficiency and promote international cooperation, while the introduction of technologies such as the Internet of Things, AI and blockchain, minimises costs and improves supply chains. This indicates that the digitalisation of the agricultural sector has the potential to significantly increase its competitiveness. Finally, G. Barseghyan, representative of the EEC at the Digital Almaty forum in 2025, noted that the digitalisation of the agro-industrial complex was identified as a key area for improving the competitiveness of the industry within the EAEU, which once again emphasises the importance of legal support for technological progress in the agricultural sector (Goar Barseghyan..., 2025).

The aim of the study was to conduct a comparative analysis of the regulatory framework for agricultural technologies in the context of digital transformation in the countries of the Eurasian Economic Union in order to identify institutional barriers, effective practices and areas for harmonisation of legal support that would contribute to the sustainable innovative development of the agricultural sector within the Union's integration space.

## Materials and Methods

The methodology of this study was based on a systematic, comparative legal, interdisciplinary and analytical approach. The study combined theoretical and applied aspects of jurisprudence, with an emphasis on comparative analysis and integration potential, which helped to identify current problems and propose recommendations for legal modernisation and convergence of digital agrotechnology regulation in the EAEU countries. The methodological basis of this study was a comprehensive approach, including both an analysis of the regulatory and legal documents of the member countries of the Eurasian Economic Union and an assessment of the practical implementation of agricultural technology in the context of digital transformation. The main object of the study was the legal regulation systems in the agricultural sector in the

Russian Federation, the Republic of Belarus, the Republic of Kazakhstan, the Kyrgyz Republic and the Republic of Armenia. The main empirical material used was official legal acts of strategies and concepts regulating the digitalisation of agriculture in these countries. To analyse the actual level of digitalisation and the introduction of agricultural technologies, the websites of relevant ministries and agencies and official documents were used, such as: Order of the Government of the Russian Federation No. 151-r (2015), Law of the Kyrgyz Republic No. 127 (2017), Resolution of the Government of the Republic of Kazakhstan No. 827 (2017), Resolution of the Government of the Republic of Armenia No. 1886-I (2019), Cabinet of Ministers of the Kyrgyz Republic (2021), Concept of Cluster Policy… (2021), FAO & ITU (2023), Concept of Digital Transformation… (2024), Ministry of Agriculture and Food of the Republic of Belarus (n.d.), etc. The study also used publicly available analytical materials and articles, which made it possible to track scientific and practical interest in the topic. To ensure the comparability of approaches and assess differences in regulation, a comparative legal method was used to conduct a parallel characterisation of regulatory acts, programmes and strategies for digital agricultural development in the EAEU countries. This approach made it possible to identify both common vectors of digital transformation and unique national features. In addition, structural-functional analysis methods were used to assess the effectiveness of existing legal regulation mechanisms, as well as a formal-legal method to study the original legal texts.

## Results and Discussion

### Legal and institutional foundations for the digitalisation of agriculture in the Kyrgyz Republic

Kyrgyzstan, where, according to the Cabinet of Ministers of the Kyrgyz Republic (2021), agriculture remains the backbone of the economy and a source of livelihood for 66% of the rural population, faces challenges of digital transformation that are characteristic of the region. As noted by S. Kurbatova & L. Ajsner (2019), the process of digitalisation requires special legal regulation that takes into account the specificities of the agricultural sector. With a poverty rate of 23.2% in rural areas, according to the Cabinet of Ministers of the Kyrgyz Republic (2021), the country is in particular need of modern solutions, but faces problems typical for the region: lack of funding, weak internet infrastructure and low digital literacy.

In 2017, the Kyrgyz Republic adopted Law of the Kyrgyz Republic No. 127 "On Electronic Management" (2017), which laid the foundation for building a modern e-government system in the country, ensuring transparency, efficiency and accessibility of public services. Its provisions create the necessary legal conditions for the further development of the country's digital economy, including the digitisation of key sectors such as agriculture. The document provides for the development of information systems, the integration of various departmental databases, and the use of modern technologies in control and supervisory activities. The Concept of Agricultural Development of the Kyrgyz Republic until 2025 (Cabinet of Ministers of the Kyrgyz Republic, 2021) defined the strategic directions for the modernisation of the country's agro-industrial complex for a five-year period. The main objective of the act was to radically increase the efficiency of the agro-industrial complex through the comprehensive modernisation of all its sectors. The concept paid particular attention to the introduction of innovative technologies, including large-scale digitalisation of agriculture. As part of the implementation of these tasks, it was planned to create a modern system for tracking agricultural products at all stages, from production to the end consumer, which was to ensure improved food quality and safety. In the area of digital infrastructure development for the agro-industrial complex, the concept envisaged the creation and development of the Ayylmalyimat information system, designed to organise effective online document management in the agricultural sector (Dzhumagulov & Mistriukova, 2025).

At the same time, the Concept of Cluster Policy for Agricultural Development of the Kyrgyz Republic Based on Specialisation by Regions for 2021-2025 (2021) was developed, which aimed to create conditions for sustainable economic growth through the development of cluster initiatives bringing together business, science and the state. The main focus was on the agro-industrial complex, where clustering would increase the competitiveness of products through cooperation between small and medium-sized producers, the introduction of innovative technologies and improved access to markets. The document provided for the formation of territorial and sectoral clusters (e.g., fruit and vegetable, textile, tourism), infrastructure development (logistics, processing), and support for export potential. The Concept paid particular attention to the digitalisation of processes, staff training and attracting investment. The implementation of the concept was intended to contribute to the diversification of the economy, the creation of new jobs and an increase in Kyrgyzstan's share in regional value chains. The next regulatory legal act governing digitalisation in the Kyrgyz Republic was the Concept of Digital Transformation of the Kyrgyz Republic for 2024-2028 (2024). This concept defines the priority areas for digitalisation in all sectors of the country's economy, including agriculture. The document focuses on the creation of geographic information systems (GIS) for precision farming, the introduction of satellite monitoring of agricultural land, and the use of unmanned aerial vehicles (drones) to monitor the condition of crops and pastures. Particular importance is attached to the creation of unified digital registers of agricultural land and livestock in order to establish a

system for accounting and managing the country's agricultural resources.

Thus, despite the existence of key strategies and regulatory documents governing the digitalisation of Kyrgyzstan's agro-industrial complex, the implementation of these initiatives remains limited and largely fragmented. The adopted concepts, programmes and laws form the necessary legal framework, but the lack of a consistent implementation mechanism, insufficient inter-agency coordination and poorly developed regulatory details reduce their practical effectiveness. Disparate initiatives often duplicate functions, lack sustainable funding and are not based on a unified digital infrastructure. In addition, systemic problems of an infrastructural and personnel nature are a serious constraint: poor internet coverage in rural areas, low levels of digital literacy among farmers, and an acute shortage of specialists in the field of agricultural technology. These barriers turn strategic priorities into declarative intentions that have no lasting impact on the development of the industry. However, with the political will to develop mechanisms for interdepartmental cooperation, attract investment in infrastructure, and implement comprehensive educational programmes, Kyrgyzstan has great potential to move from local digital solutions to systemic transformation of the agricultural sector. Given the importance of agriculture for the country's economy and the standard of living of the majority of the population, effective digitalisation could become not only a driver of modernisation, but also a key tool for combating poverty and improving food security.

**Comparative analysis of the digital transformation of agriculture in the EAEU countries**

Kazakhstan demonstrates a systematic approach to the digitalisation of its agro-industrial complex. As noted in a review by A. Nazarbekov (2023), the country is implementing a comprehensive programme that includes precision farming, digital farms, satellite monitoring and automated accounting. These initiatives are backed by a robust regulatory framework. In 2017, the state programme Digital Kazakhstan (n.d.) was adopted, with a separate section devoted to agriculture (Resolution of the Government of the Republic of Kazakhstan No. 827, 2017). A key result of the programme was the creation of digital model farms. Kazakhstan has completely digitised its agricultural land (222 million hectares) by introducing a unified GIS system with electronic land passports containing data on soil, usage history and cadastral value (100% of farmland…, 2025). This project aims to combat illegal land trafficking, increase the transparency of state support, and provide farmers with yield analytics. Although the system already monitors the condition of fields and simplifies land transactions, there are also issues with data accuracy in some areas and limited internet access in rural areas.

A comparative analysis shows that Kazakhstan, as one of the largest agricultural countries in the EAEU, demonstrates a more advanced approach to the digitalisation of agriculture. The state programme Digital Kazakhstan (n.d.) includes comprehensive projects in the areas of precision farming, digital livestock farming and agricultural holding management. According to B. Irmulatov *et al*. (2021), the introduction of precision farming has increased grain yields. However, as in Kyrgyzstan, the process faces problems of internet access in remote areas and a shortage of qualified specialists (Kurbatova & Ajsner, 2019).

Legal regulation in the EAEU countries is developing along similar lines. For example, Kyrgyzstan has adopted the Concept of Agricultural Development of the Kyrgyz Republic until 2025 (Cabinet of Ministers of the Kyrgyz Republic, 2021) and the Concept of Digital Transformation of the Kyrgyz Republic for 2024-2028 (2024), and in Kazakhstan, the Digital Kazakhstan (n.d.) programme. The precision farming project covers the introduction of satellite navigation and remote sensing technologies, automatic agricultural machinery control systems, and irrigation and fertiliser application control systems. This can optimise fertiliser and water costs, increase crop yields and product quality, and reduce the environmental impact of agricultural production. According to reports, the introduction of precision farming has contributed to a 15-20% increase in grain crop yields (Nazarbekov, 2023).

The FAO (2020) and FAO & ITU (2023) note that digital technologies should be accessible to all categories of farmers, which is especially important for countries with a predominance of small farms, such as Kyrgyzstan. The technological solutions offered by digitalisation – artificial intelligence, remote sensing, the Internet of Things – need to be adapted to the conditions of each EAEU country. Educational programmes play a key role in the digital transformation of all EAEU countries; without trained specialists, the introduction of new technologies will be limited (Godin *et al*., 2020). In Kazakhstan, special attention is paid to this through training and educational programmes, while in Kyrgyzstan this aspect is still underdeveloped.

Russia's experience in digitising the agro-industrial complex, including the federal project "Digital Agriculture" and the industry programme "Digitisation of the Agro-Industrial Complex 2024", demonstrates the most developed regulatory framework among the EAEU countries (Dobrovlyanin & Antineskul, 2022). At the same time, as noted by V. Belsky (2019), the Russian Federation also faces characteristic problems – the gap between large holdings and small farms, insufficient internet coverage in rural areas, and a shortage of qualified personnel. The digitalisation process is hampered by uneven technology adoption (25% of large farms use precision farming techniques, compared to 5% of small farms), a shortage of skilled personnel, and poor

internet coverage in rural areas (Gasanov *et al*., 2021). Despite the creation of a unified digital platform for the agro-industrial complex and the introduction of satellite monitoring (covering 30% of large enterprises), the main barriers remain insufficient funding for small farms and a fragmented regulatory framework. The Russian Federation Government approved the Strategy for Sustainable Development of Rural Areas… (2015). The strategy set out long-term development goals for rural areas in Russia. The regulatory act considers the socio-economic development of rural areas as a key factor in ensuring the country's food security and improving the quality of life of the rural population. The strategy provides for measures to develop infrastructure, create modern jobs, improve housing conditions and access to social services in rural areas. Although the text of the document does not directly refer to digitalisation as a separate area, it implies the use of modern technologies in agriculture. In particular, the strategy creates the conditions for the introduction of innovative solutions, such as the use of quadcopters to monitor the condition of fields, the use of precision farming systems and other digital tools that contribute to improving the efficiency of agricultural production.

The Belarusian agro-industrial complex is actively introducing digital technologies, as confirmed by materials from the official portal of the Ministry of Agriculture and Food of the Republic of Belarus (n.d.). The country is implementing a comprehensive approach to the digitalisation of the industry, combining technological modernisation with the creation of an appropriate regulatory framework. Particular attention is paid to the automation of key agricultural production processes. A significant achievement was the introduction of the "Electronic Veterinary Certificate" system, which radically changed approaches to quality control of livestock products. Digital support for the entire chain of goods movement has significantly reduced the time required for paperwork and increased the transparency of control. This aspect is particularly important for simplifying export and import operations and complying with international standards. In crop production in Belarus, there has been active implementation of precision farming technologies. According to the Ministry of Agriculture and Food of the Republic of Belarus (n.d.), modern GPS-based systems optimise soil cultivation processes, significantly reducing overlap and increasing the efficiency of equipment use. Automated irrigation systems demonstrate impressive results in terms of water conservation, which is particularly relevant in the context of climate change. Satellite monitoring of fields and differentiated fertiliser application make it possible to increase yields and reduce the anthropogenic impact on the environment. Digital transformation has also affected the field of accounting and reporting. The transition to electronic document management has significantly reduced the time spent on preparing reports and minimised the number of errors, which in turn has created conditions for rapid access to data and increased the transparency of budget spending. The strategy for further digitalisation of the industry includes the creation of a unified digital platform for the agro-industrial complex, the development of precision farming infrastructure and the introduction of intelligent data analysis systems (Zhuravlev, 2024). Particular attention is paid to the training of qualified personnel and the development of a regulatory framework for the use of new technologies. The prospects for the development of digital agriculture in Belarus are linked to the introduction of advanced technologies, including artificial intelligence for yield forecasting, smart greenhouse systems with automatic climate control, and the creation of digital twins of agricultural enterprises (Karniciy, 2021). The integration of blockchain solutions into supply chain tracking systems creates an immutable digital chain of product data, which dramatically improves quality control efficiency.

The Eurasian Economic Union's agricultural development strategy opens up new horizons for Armenia to modernise its agricultural sector through digitalisation. For a mountainous country with a predominance of small farms, this document serves as a roadmap for the technological transformation of traditional agriculture. The Strategy for the Development of Agriculture in the Republic of Armenia until 2030 takes into account the importance of introducing digital technologies to modernise the agro-industrial complex (Resolution of the Government of the Republic of Armenia No. 1886-I, 2019). The strategy envisages the creation of digital platforms for farmers and the digitisation of public services in the agricultural sector, including the automation of subsidy and reporting processes. Armenia also has a State programme for the development of "smart" livestock farms, which provides financial support for the construction and modernisation of farms with the introduction of modern technologies (State support for…, 2019). The programme offers three farm models: small (130-280 $m^2$ for 10-15 head with compensation of 5.5 million drams), medium (281-450 $m^2$ for 20-25 head – 11.5 million drams) and large (451+ $m^2$ for 40-45 head – 17.5 million drams). The programme is being implemented by the Ministry of Agriculture and provides for standard farm designs using various materials and automated animal husbandry systems.

Armenia, with its unique agroclimatic conditions, can benefit particularly from the strategy's provisions on adapting modern technologies to complex terrain and limited water resources. The introduction of precision farming systems tailored to the specific characteristics of mountain slopes will enable Armenian farmers to optimise the use of scarce resources and increase land productivity (Resolution of the Government of the Republic of Armenia No. 1886-I, 2019). The use of smart drip irrigation technologies, which can radically

solve the problem of water shortages in arid regions of the country, looks particularly promising. For Armenian agricultural exports, the EAEU strategy creates fundamentally new opportunities through the formation of a unified traceability system for agricultural products. All this is particularly significant for Armenia's traditional export goods – fruit, vegetables and wine products – the quality of which can now be documented all the way from the field to the shop shelf. The provisions of the strategy aimed at supporting small and medium-sized farms are of particular value to Armenia. The creation of regional centres of excellence and the development of special programmes for preferential access to digital services will allow even small family farms to take advantage of technological modernisation (Resolution of the Government of the Republic of Armenia No. 1886-I, 2019). In the context of mass rural exodus, digitalisation is becoming particularly important as a means of preserving and adapting the traditional rural way of life to modern conditions. The implementation of educational programmes within the framework of the strategy gives Armenia a chance to train a new generation of farmers who combine centuries-old traditions of agriculture with mastery of modern digital technologies. Participation in the creation of joint EAEU research centres gives Armenian specialists the opportunity to contribute their unique experience in viticulture, soil erosion control and water resource management. The digital transformation of agriculture within the framework of the Eurasian strategy provides Armenia with an opportunity to overcome key constraints, such as a shortage of arable land, water scarcity, fragmented land plots and difficulties in accessing external markets. The successful implementation of this project will require careful adaptation of the union-wide provisions to national conditions, the development of rural digital infrastructure, and the creation of an effective training system (Resolution of the Government of the Republic of Armenia No. 1886-I, 2019).

A comparative analysis of the digital transformation of agriculture in the countries of the Eurasian Economic Union shows that, despite common directions and goals, each country is implementing the digitalisation of the agricultural sector taking into account its national characteristics and priorities. Kazakhstan and Russia demonstrate the most systematic and comprehensive approach, supported by government programmes, regulatory frameworks and technical infrastructure. Belarus focuses on process automation and transparency, including electronic document management and product tracking systems. Armenia, in turn, is adapting digital technologies to its geographical and water conditions, focusing on supporting small farms and developing export potential. Kyrgyzstan is in the process of establishing a regulatory and technological framework, facing a shortage of personnel and infrastructure. Thus, the main challenges for all EAEU countries are similar: a shortage of qualified specialists and limited access to digital technologies for small farms. At the same time, there is a common desire to digitise the agricultural sector, supported by EAEU strategies and national programmes, which creates potential for sustainable growth, increased productivity and improved quality of agricultural production.

**Prospects and priority areas for the digitalisation of the agricultural sector within the EAEU**

The prospects for the further development of digitalisation of the agro-industrial complex within the EAEU are presented in several key areas. Technologically, this involves the development of platform solutions for small farms, the creation of regional centres of excellence and the development of adaptive technologies for different climatic zones. In the regulatory sphere, there is a need to harmonise standards within the EAEU, create an intergovernmental certification system and simplify procedures for introducing innovations. Organisational measures should include the development of a grant support system, the creation of a network of demonstration farms, and the implementation of educational programmes. Of particular importance is the development of uniform EAEU standards for the collection and processing of agricultural data, the use of unmanned aerial vehicles (UAVs), and precision farming systems. The creation of mechanisms for technology transfer between the countries of the Union, the development of joint educational programmes and the coordination of research activities could significantly accelerate the digital transformation of the agro-industrial complex throughout the region.

It should be noted that the most promising direction appears to be the creation of a Eurasian digital agricultural platform that would combine databases and analytical systems, forecasting mechanisms, monitoring systems and educational resources. Such an approach would preserve the national characteristics of each country's agricultural sector development, while ensuring the synergistic effect of combining efforts and resources. Russia's experience, particularly in terms of regulatory control and the creation of a comprehensive system for technology implementation, would form the basis for such a platform, adapted to the specific characteristics of other EAEU countries. The implementation of these measures requires coordinated action at the intergovernmental level, including the harmonisation of legislation, the creation of mechanisms for financing joint projects, and the development of infrastructure for the exchange of knowledge and technologies. Only such a comprehensive approach will enable EAEU countries to fully realise the potential of digital transformation in agriculture, ensuring its sustainable development in the face of modern challenges.

## Conclusions

The digital transformation of the agro-industrial complex in the countries of the Eurasian Economic Union

is developing at different rates, reflecting both common strategic guidelines and the national specifics of each state. An assessment of the state and prospects of digital transformation demonstrates both similar directions of development and marked differences in the national approaches of the participating countries. Russia demonstrates the most systematic and large-scale approach to the digitalisation of the agro-industrial complex, which corresponds to the size of its agro-industrial sector. The country has created a comprehensive regulatory framework, including the Digital Agriculture project and an industry-specific digitalisation programme. Russian agricultural holdings are actively introducing precision farming technologies and satellite monitoring. However, there remains a significant gap between large enterprises that have achieved a high level of digitalisation and small farms that face difficulties in introducing new technologies.

Kazakhstan occupies an intermediate position in the process of digital transformation of the agro-industrial sector, focusing on the creation of "digital farms" as pilot projects for subsequent scaling up of experience. Kazakhstan's strategy for the digitalisation of agriculture is characterised by a pragmatic approach that combines the borrowing of international experience with adaptation to local conditions. Particular attention is paid to the development of digital infrastructure in rural areas and personnel training, although the pace of technology adoption lags somewhat behind Russian indicators. Belarus is demonstrating a cautious but consistent approach to the digitalisation of the agro-industrial complex, taking its first steps in the automation of accounting and reporting. The Belarusian model is characterised by a high degree of centralisation of digital transformation processes with an active role for the state. The introduction of electronic veterinary certification and certain elements of precision farming demonstrates potential for further development, although the overall level of technological equipment in agricultural enterprises remains low.

Armenia, which has the smallest agro-industrial sector among the EAEU countries, demonstrates a special approach to digitalisation, focused on the needs of small farms and the specifics of mountain farming. The Armenian model emphasises the adaptation of technologies to complex terrain and water scarcity, as well as the development of traceability systems for traditional export goods such as fruit, vegetables and wine products. The level of digitalisation remains low, but the strategic guidelines are clearly defined. Kyrgyzstan, on the other hand, is in the early stages of digital transformation of its agro-industrial sector, facing the most serious challenges related to limited resources and weak infrastructure. Particular attention is paid to the digital literacy of the rural population and the creation of simple, accessible technological solutions.

Despite differences in the pace and scale of digitalisation, all EAEU countries face a number of common challenges. These include digital inequality between large and small farms, underdeveloped rural digital infrastructure, a shortage of skilled personnel and the need to adapt the regulatory framework. At the same time, each country is developing its own approaches to solving these problems, based on the specifics of its agro-industrial complex. The prospects for the further development of digitalisation of the agro-industrial complex within the EAEU are linked to deeper coordination between the participating countries. The creation of a single digital space for agriculture, the harmonisation of standards and the exchange of best practices could become a powerful catalyst for technological modernisation across the entire region. The development of joint research projects and educational programmes that will allow for the pooling of efforts in training personnel for digital agriculture appears to be particularly important.

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## Санариптик трансформация шартында агротехнологияларды укуктук жөнгө салуу: ЕАЭБ өлкөлөрүнүн салыштырма анализи

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**Аннотация.** Агрардык сектордун цифралашуусу жаңы технологияларды киргизүү менен коштолуп, укуктук жөнгө салуу үчүн жаңы чакырыктарды жаратат. Евразиялык экономикалык союздун алкагында туруктуу өнүгүүнү жана азык-түлүк коопсуздугун камсыз кылуу боюнча макулдашылган ыкмаларга муктаждык өсүп жатат. Макалада санариптик технологияларды ишке ашыруунун укуктук базасын жана практикасын салыштырып изилдөөнүн негизинде Евразия экономикалык биримдигине мүчө мамлекеттердин агрардык секторундагы санариптештирүү процесстерине комплекстүү талдоо берилген. Авторлор санариптик трансформациянын ар кандай моделдерин белгилешет. Россия "Санариптик айыл чарба" масштабдуу федералдык долбоорун ишке ашырууда, Казакстан моделдик санариптик чарбаларды түзүүгө жана айыл чарба жерлерин толук санариптештирүүгө басым жасаса, Беларусь бухгалтердик эсепти автоматташтырууда жана ветеринардык сертификациянын электрондук системасын киргизүүдө олуттуу ийгиликтерге жетишти. Кыргызстан менен Армения тийиштүү саясат алкактары кабыл алынганына карабастан олуттуу көйгөйлөргө туш болууда, анын ичинде инфраструктуранын жетишсиздиги, чектелген каржылоо жана санариптик сабаттуулуктун төмөн деңгээли. Негизги жыйынтыктар Евразия экономикалык биримдигинин өлкөлөрүндөгү жалпы көйгөйлөрдү көрсөтөт: чоң жана майда чарбалардын ортосундагы санариптик ажырым, айыл жеринде санариптик инфраструктура начар өнүккөн жана квалификациялуу адистердин жетишсиздиги. Перспективдүү багыттар катары авторлор Евразия экономикалык биримдигине алкагында айыл чарбасын санариптик трансформациялоону координациялоодо ар бир катышуучу өлкөнүн улуттук өзгөчөлүктөрүн эске алуу зарылдыгын баса белгилеп, мыйзамдарды шайкеш келтирүүнү, бирдиктүү евразиялык санариптик агрардык платформаны түзүүнү жана биргелешкен билим берүү программаларын иштеп чыгууну сунушташат. Изилдөөнүн жыйынтыктары илимий чөйрөдө, ошондой эле санариптештирүү стратегиясын иштеп чыгууда, мыйзамдарды өркүндөтүүдө жана Евразия мейкиндигинде агротехнологияларды жөнгө салууга макулдашылган мамилелерди иштеп чыгууда колдонулушу мүмкүн

**Негизги сөздөр:** санариптештирүү; Евразия экономикалык биримдиги; айыл чарба кооперациясы; киберкоопсуздук; айыл чарба маалыматтары; стандарттарды унификациялоо

# Нормативно-правовое регулирование агротехнологий в условиях цифровой трансформации: сравнительный анализ стран ЕАЭС

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**Аннотация.** Цифровизация аграрного сектора сопровождается внедрением инновационных технологий, что формирует новые вызовы для правового регулирования. В рамках Евразийского экономического союза возрастает потребность в согласованных подходах к обеспечению устойчивого развития и продовольственной безопасности. В статье представлен всесторонний анализ процессов цифровизации в аграрном секторе государств-членов Евразийского экономического союза, основанный на сравнительном изучении нормативно-правовой базы и практики внедрения цифровых технологий. Авторы выделили различные модели цифровой трансформации. Россия реализует масштабный федеральный проект «Цифровое сельское хозяйство», Казахстан фокусируется на создании образцовых цифровых ферм и полной оцифровке сельскохозяйственных угодий, в то время как Беларусь добилась значительного прогресса в автоматизации учета и внедрении электронной системы ветеринарной сертификации. Кыргызстан и Армения, несмотря на принятие соответствующих политических рамок, сталкиваются с серьезными проблемами, включая неадекватную инфраструктуру, ограниченное финансирование и низкий уровень цифровой грамотности. Основные выводы свидетельствуют об общих проблемах в странах Евразийского экономического союза: цифровой разрыв между крупными и мелкими фермерскими хозяйствами, слаборазвитая цифровая инфраструктура в сельской местности и нехватка квалифицированных специалистов. В качестве перспективных направлений авторы предложили гармонизацию законодательства, создание единой евразийской цифровой агроплатформы и разработку совместных образовательных программ, подчеркивая при этом необходимость учета национальных особенностей каждой страны-участницы при осуществлении координации цифровой трансформации сельского хозяйства в рамках Евразийского экономического союза. Результаты исследования могут быть использованы как в научной среде, так и при разработке стратегий цифровизации, совершенствовании законодательства и выработке согласованных подходов к регулированию агротехнологий на евразийском пространстве

**Ключевые слова:** цифровизация; Евразийский экономический союз; сельхозкооперация; кибербезопасность; агроданные; унификация норм

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# Neural network models for statistical analysis and tax planning in agrarian economy

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**Abstract.** Modern agricultural economy faces a number of challenges, including climate change, market volatility and the need to improve management efficiency. In the context of digitalisation, the introduction of intelligent tools, in particular neural network models for statistical analysis and tax planning, is of particular importance. This study provided an overview of current approaches to the application of artificial neural networks (ANNs) in the agricultural sector. MLP, CNN, RNN, RNN, LSTM architectures and their hybrid variants used for yield forecasting, tax burden estimation, subsidy planning and financial risk analysis were considered. The aim of this study was to identify the potential of neural network models to improve the efficiency of statistical analysis and tax planning in the agricultural economy, as well as to determine their role in the formation of digital management decision support systems. The paper systematised the main areas of application of neural networks in agrarian economy, gave examples of effective solutions and substantiated the practical significance of ANNs for decision support under uncertainty. Special attention was paid to the integration of ANNs into digital platforms of the agrarian sector and the formation of intelligent systems to support fiscal management. The

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analysis confirmed the high adaptability and forecasting accuracy of neural networks and emphasised the need to develop digital infrastructure and regulatory framework for their widespread implementation. The results of the study can be used in developing strategies for sustainable agricultural development and improving the economic sustainability of agricultural enterprises. The work is of interest to researchers, developers of digital solutions and specialists in the field of agricultural policy

**Keywords:** artificial intelligence; predictive modelling; fiscal policy; digital agriculture; sustainable development; yield prediction; intelligent decision support systems

## Introduction

In the context of accelerating digitalisation of the economy, the agricultural sector is also undergoing a significant transformation due to the need to adapt to new challenges: climate change, growing global competition, fluctuations in prices for products and resources, increasing requirements for efficiency and transparency of management. One of the key tasks of modern agricultural economy is to ensure sustainable development of agricultural enterprises by optimising production, financial and tax processes on the basis of objective data and modern analytical tools. In this context, intelligent methods of data analysis, including artificial intelligence technologies and, in particular, neural networks, are becoming increasingly relevant (Bassine *et al.*, 2023). As noted by M. Al-Adhaileh & T. Aldhyani (2022), the agricultural economy is inherently characterised by a high degree of uncertainty and seasonality, which makes traditional economic modelling and forecasting difficult. Parameters such as crop yields, subsidy levels, tax burden, market prices and logistics costs are subject to numerous fluctuations and depend on a variety of factors, from weather conditions to public policy decisions. In this situation, neural network models become a reliable decision support tool both at the individual farm level and in public fiscal policy formulation (Mansoor *et al.*, 2025). As pointed out by Y. Adhitya *et al.* (2023), the use of neural network models that can identify hidden non-linear dependencies in data and learn from historical information is becoming a powerful tool for analysing and making management decisions.

Effective tax planning is of particular importance in the management of agricultural enterprises. According to A. Berguiga *et al.* (2023), with limited access to financial resources and instability of tax laws, agricultural producers need a reliable mechanism for estimating current and future tax liabilities. Traditional tax calculation methods often fail to account for industry specificity, seasonality and subsidies, leading to unreliable forecasts and risks of fiscal instability (Garg *et al.*, 2021). Neural networks allow to form individualised forecasts of tax burden taking into account multidimensional parameters: profitability level, asset structure, volume of benefits, regional coefficients, price fluctuations, etc. As pointed out in their work F. Huber *et al.* (2022), the application of artificial neural networks (ANN) in agricultural economics opens new opportunities for processing a large amount of statistical information. Unlike classical econometric models, which are limited by linear dependencies and require prior assumptions, ANNs are able to learn from incomplete and noisy data, identify complex relationships and adapt to new input conditions (Islam *et al.*, 2024). According to J. Logeshwaran *et al.* (2024), this is particularly important for analysing economic indicators from various sources – accounting records, tax returns, agricultural statistics, subsidy and credit programmes.

In recent years, there has been a growing interest in the use of artificial intelligence in the agribusiness sector. Pilot projects are being implemented in many countries to introduce digital solutions in agribusiness: from monitoring crop yields using drones to managing finances using intelligent systems. An important area of digitalisation is the automation of accounting processes, which is confirmed by the successful experience of implementing modern information systems in the public sector in Albania, where automation has significantly improved the efficiency of financial information processing (Hoxha *et al.*, 2025). However, as noted by Z. Sbai (2025), most of such projects in the agricultural sector focus on technological aspects – field automation, precision farming and crop health monitoring. At the same time, financial and economic instruments, including tax planning models, remain underdeveloped.

Thus, the generalised analysis confirms that the use of neural network models (MLP, CNN, as well as LSTM) in agrarian economics contributes to improving the quality of forecasts and forming more informed decisions in the field of tax planning and financial flow management. The aim of this paper was to conduct an analytical review and systematisation of existing approaches to the application of neural network models for statistical analysis and tax planning in agrarian economy. The objectives of the study were: to systematise the main areas of application of neural network models in the agricultural sector, including yield forecasting, tax burden estimation and subsidy planning; to describe and classify the most common neural network architectures (MLP, CNN, RNN, LSTM) and their hybrid variants used in agricultural economics; to analyse the key advantages of neural network models, such as improved forecast accuracy, ability to detect non-linear dependencies and adaptability to regional conditions; to justify the use of

neural network models in statistical analysis and tax planning in the agricultural economy; to analyse the key advantages of neural network models, such as improved forecasting accuracy, ability to detect non-linear dependencies and adaptability to regional conditions.

## Materials and Methods

The present study is an analytical review of modern approaches to the application of neural network models in the tasks of statistical analysis and tax planning in agrarian economy. The methodological basis of the work included system and comparative analysis, as well as a substantial review of publications in the leading scientific databases Scopus, Web of Science and Google Scholar. The following keywords were used for the search: "neural networks in agriculture", "tax planning using AI", "crop yield prediction with deep learning", "agricultural economics and machine learning". The criteria for selecting sources were: publication in peer-reviewed journals in the last 5-10 years, availability of practical examples or empirical validation of models, as well as the relationship of the work to tax planning, financial analysis or risk management in agriculture. Special attention was paid to publications containing the results of applying neural network architectures to solve applied problems in the agricultural sector. Comparative analysis was carried out in the following areas: yield forecasting – models for analysing data on climate, soil, agrotechnics; tax planning – use of neural network algorithms for modelling tax burden and subsidies; financial analysis – profitability assessment, forecasting revenues and expenses; risk management – identification of uncertainty factors and reduction of fiscal instability. When systematising the publications, the type of neural network architecture was taken into account:

- MLP (Multi-Layer Perceptron) – most effective for analysing tabular economic data, including income, expenditure and tax payment indicators;
- CNN (Convolutional Neural Networks) – applicable for processing spatial and visual data, such as satellite images of fields for yield estimation;
- RNN and LSTM (Recurrent Neural Networks, Long Short-Term Memory) – allow to work with time series, which is important for forecasting price dynamics, seasonality of crops and tax revenues;
- hybrid models – combine the advantages of neural networks (NN) and traditional methods (regression, decision trees), increasing the accuracy of forecasts and interpretability of results, especially in models of complex analysis of taxes and subsidies.

In addition, the study took into account the criteria of applicability of the models at different levels of management – from individual farms to state structures. Both experimental prototypes and tested solutions already implemented in digital agribusiness platforms were analysed. The work also considered the integration of neural network algorithms with accounting, financial forecasting and tax administration systems, which allowed for assessing their potential not only in the technological but also in the institutional context. Thus, the methodological approach of the study was based on the integration of modern scientific data, systematic comparison of different architectures and their applicability to the key tasks of agrarian economy.

## Results and Discussion

The analysis of publications devoted to the application of neural network models in agrarian economics allows for identifying several key areas of their use that have the greatest potential for statistical analysis and tax planning. First of all, neural network models are successfully used for forecasting financial indicators of agricultural enterprises, including revenue, profit, cost structure and tax burden. The most popular in this area are multilayer perseptrons (MLP) and convolutional neural networks (CNN), which are able to efficiently process multivariate data and identify complex relationships between economic variables. For example, R. Manogna *et al.* (2025) proved the effectiveness of MLPs in predicting agricultural commodity prices, while the study of I. Attri *et al.* (2023) showed many examples of successful application of CNNs and RNNs to accelerate economic growth. At the same time, the study by T. Saranya *et al.* (2020) and M. Bhavana & K. Rao (2025) confirm that the application of neural network architectures improves the accuracy of forecasting yields and financial outcomes in highly variable environments.

Comparison with classical econometric models also demonstrates the advantages of neural networks. A. Chlingaryan *et al.* (2018) and A. Mahin (2025) note that the prediction accuracy of neural network algorithms is higher when working with non-linear dependencies and incomplete data. This is especially true in highly variable agricultural markets and climatic factors, where linear models are often not sufficiently reliable. In addition, the use of neural networks in management decision support systems (MDSS) is an important trend (Albanese *et al.,* 2021). Such systems allow to automate the assessment of tax risks, analyse the consequences of different tax policy options and form recommendations on tax optimisation in agrarian farms. Integration of neural network models into management decision support systems provides adaptation to regional conditions, tax incentives, asset structure and seasonal features of agricultural production (Adkisson *et al.,* 2021). This makes it possible to form individualised forecasts and improve the accuracy of economic calculations taking into account territorial specifics.

A separate group consists of studies that use neural network algorithms to assess the impact of climate and weather factors on the economic performance of agribusinesses. I. Malashin (2024) demonstrated the potential of deep learning for predicting crop yields under climate variability, which is directly related to the

estimation of future income and tax base of enterprises. Similarly, A. Chlingaryan *et al.* (2018) showed that the use of machine learning to analyse agro-climatic data can significantly improve the accuracy of yield forecasts compared to classical models. Moreover, the studies of G. Kamilaris & F. Prenafeta-Boldú (2018) confirmed that the application of convolutional and recurrent neural networks is effective when dealing with spatial and temporal data (e.g., satellite images and meteorological series), which makes it possible to take into account seasonal and climatic risks when developing agroeconomic strategies. In turn, R. de Oliveira & R. de Souza e Silva (2023) addressed crop management and forecasting, as well as disease and pest management.

Neural network models not only improve forecasting of economic indicators, but also contribute to the comprehensive consideration of climate risks, making tax planning more accurate and resilient to external fluctuations. This approach is particularly relevant for calculating taxes that depend on production, yields or natural conditions, and can be used to justify the application of tax exemptions in times of force majeure (Pérez-Pérez *et al.,* 2024). The review showed that one of the most promising tasks is the modelling of tax burden taking into account subsidies and state support, especially in countries with a developed system of agricultural regulation. Thus, M. Yakubov *et al.* (2023) proposed to use neural networks to forecast regional tax revenues in the agricultural sector, emphasising the importance of including the parameters of subsidies and benefits in the model. In turn, P. Adekemi (2025) showed that artificial intelligence methods can identify tax risks and prevent unfair practices. The practical effectiveness of digital innovations in the financial accounting of agricultural enterprises is confirmed by concrete results: the introduction of automated systems for processing financial data and the use of machine learning technologies allow not only to increase the accuracy of accounting operations, but also significantly improve economic performance (Hnatyshyn *et al.,* 2025). Additionally, A. Alawode *et al.* (2024) point out that the integration of artificial intelligence (AI) in agricultural economic forecasting allows regional subsidies, price fluctuations and institutional regulatory mechanisms to be taken into account, making tax models more adaptive and practically meaningful. Thus, modelling tax burden using neural network algorithms opens new perspectives for the development of financial planning tools capable of taking into account the impact of public policies, subsidies and benefits on the sustainability of the agricultural sector. Under these conditions, neural networks allow taking into account not only direct tax payments, but also indirect fiscal impacts associated with subsidy mechanisms, compensations, as well as tax deductions and deferrals (Chlingaryan *et al.,* 2018). It has also been established that the efficiency of neural network models significantly depends on the quality and volume of available data, which makes relevant issues of information preprocessing, feature normalisation, handling missing values and class imbalance. Thus, K. Liakos *et al.* (2018) in their review emphasise that the correct processing of raw data and their harmonisation to common formats is a key condition for the successful application of machine learning in agriculture.

The problem of dealing with missing values and limited datasets is analysed in detail in the study by A. Chlingaryan *et al.* (2018), where it is shown that the use of data reconstruction techniques and hybrid algorithms can improve the reliability of predictions under agrarian uncertainty. In addition, G. Kamilaris & F. Prenafeta-Boldú (2018) emphasise the need for class balancing in agricultural object classification tasks (e.g. soil types or crop classes), as sampling imbalance can distort the training results of neural networks. Scientific works confirm that data preprocessing and preparation play no less important role than the model architecture itself and largely determine its accuracy and stability. The use of modern approaches to data preparation (feature engineering) and regularisation methods makes it possible to increase the models' resistance to overtraining and improve the interpretability of the results. Comparative analysis has shown that hybrid models combining neural network architecture with traditional analytical tools such as linear regression, principal component methods and decision trees provide maximum accuracy of tax burden forecasting. M. Abedin *et al.* (2022) in their review note that the combination of machine learning methods and classical statistical tools allows for more accurate modelling of tax planning and consideration of state support factors. Similar results are obtained in the study of P. Sharma *et al.* (2023), where the integration of deep learning and regression methods demonstrated high efficiency in the development of models of agrarian economy management.

R. de Oliveira & R. de Souza e Silva (2023) emphasise that the integration of neural network algorithms with decision trees and factor analysis methods significantly increases the interpretability of results and the adaptability of models to regional conditions, which is especially important in the tasks of financial forecasting and tax planning. In addition, the review of K. Liakos *et al.* (2018) confirms that hybrid approaches in the agricultural sector have an advantage by combining the ability of neural networks to detect non-linear dependencies and the robustness of traditional econometric methods to noise and omissions in the data. This confirms the effectiveness of a combined approach that combines the capabilities of artificial intelligence and economic logic.

The results of the review show that neural network models are an effective tool for analysing and forecasting economic and fiscal processes in the agrarian economy. They are highly adaptive, robust to noise in the data and capable of modelling complex relationships,

which makes them particularly valuable in the uncertainty characteristic of agriculture (Kamilaris & Prenafeta-Boldú, 2018). However, the full integration of such models into practice requires further development of digital infrastructure, improvement of data quality and the formation of normative approaches to the use of AI in the management of agricultural systems. Table 1 summarises the main neural network architectures and their functions to illustrate their potential in agricultural economics and tax planning tasks.

**Table 1.** Overview of neural network models and their application in agricultural economics

| Type of model | Functions | Application in agrarian economy |
|---|---|---|
| MLN (Multilayer Perseptron) | Suitable for forecasting based on structured tabular data, easy to implement | Forecasting of revenues, expenditures, tax burden |
| CNN (Convolutional Neural Networks) | Effective for analysing spatial and visual data (e.g. satellite images, yield maps) | Crop image analysis, biomass estimation |
| RNN (Recurrent Neural Networks) | Applied to sequential data, modelling temporal dependencies | Prediction of prices, resource consumption, yields by seasons |
| LSTM (Long Short-Term Memory) | Improved version of RNN, stores information over long time intervals | Modelling the impact of climate cycles on production |
| Hybrid models (NN + decision tree, etc.) | Combining neural networks with other algorithms to improve accuracy and interpretability | Integrated modelling of taxes, subsidies, production decisions |

**Source:** compiled by the authors based on the analysis of scientific publications

Table 1 is a classification of the main types of neural network models used in agricultural economics, indicating their key features and areas of practical use. The table includes both basic architectures (multilayer perseptron – MLP, convolutional neural networks – CNN, recurrent neural networks – RNN, modifications of LSTM type) and hybrid models that combine the capabilities of neural networks with other machine learning algorithms. The peculiarities of each architecture in terms of structure and analytical capabilities are considered, as well as examples of tasks in which these models have shown high efficiency. These include tax forecasting, satellite image analysis, modelling of seasonal and climatic factors, integrated planning based on production and fiscal data. The presented review demonstrates the broad potential of neural network approaches within the digital transformation of the agricultural sector, especially in the context of developing decision support systems and tax modelling. As an illustration, Figure 1 presents the structure of a neural network model applicable to statistical analysis and tax planning in the agrarian economy.

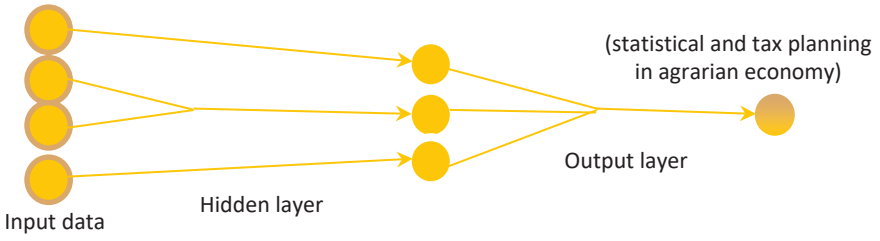


**Figure 1.** Structure of neural network model for statistical analysis and tax planning in agrarian economy
**Source:** compiled by the authors

Figure 1 shows the basic architecture of a feed forward neural network model consisting of three layers: input layer, hidden layer and output layer. The input layer accepts input data such as economic indicators, taxes, subsidies, climate and agricultural resources. The latent layer processes the input information using internal weights and activation functions, revealing non-linear relationships between variables. The output layer generates predicted values that are interpreted as results of statistical analyses and fiscal planning in the agricultural economy. The framework is used for decision support, tax burden modelling, subsidy optimisation and economic efficiency assessment of agricultural production. The presented review demonstrates the broad possibilities of applying neural network approaches within the digital transformation of the agricultural sector, especially in the context of developing decision support systems and tax modelling. As can be seen in Figure 1, the structure of the neural network model reflects the main stages of data processing, and Table 2 summarises the directions of practical application of neural networks in the agricultural economy.

**Table 2.** Applications of neural networks in agrarian economics

| Field from application | Type of model | Problem description |
|---|---|---|
| Yield forecast | RNN / LSTM | Forecasting of yields by season, taking into account weather conditions |
| Tax burden estimation | MLP / Decision Tree | Calculation of taxes and levies based on historical financial data |
| Subsidy planning | CNN + MLP | Determining optimal allocation of government support |
| Cost management | MLP | Forecasting resource costs (seeds, fuel, machinery, etc.) |
| Climate risk modelling | RNN LSTM + | Analysing the impact of droughts, rainfall and temperature on crop yields |
| Assessment of agribusiness performance | Hybrid modelling (NN + econometrics) | Profitability and efficiency analytics based on AI algorithms |

**Source:** compiled by the authors based on analytical synthesis of scientific publications

Table 2 presents a summarised list of key benefits of using neural network models in agricultural economics. Six main areas in which neural networks demonstrate their effectiveness are presented: improvement of forecasting accuracy, processing of complex and hidden dependencies between data, adaptation to regional conditions of agricultural production, automation of analytical processes and reporting, the possibility of integration into digital agricultural platforms, as well as support for strategic planning and management of tax and investment decisions. Each benefit is accompanied by a brief description of its relevance for digitalisation and sustainability of the agricultural sector. The presented characteristics emphasise the relevance of implementing artificial intelligence in the management of agricultural systems and the development of intelligent decision support tools.

The review confirms that neural networks have significant advantages for the agricultural economy: they allow more accurate forecasting of crop yields and tax burden, identify hidden dependencies in data, take into account regional peculiarities and integrate into the digital infrastructure of "smart agriculture". The main benefits of using neural network models are summarised in Table 3.

**Table 3.** Advantages of using neural networks in the agricultural economy

| Advantage | Description |
|---|---|
| Increase in the accuracy of forecasts | Neural networks provide more accurate predictions than classical models, especially in the case of complex dependencies between parameters |
| Processing of non-linear and hidden dependencies | Ability to identify hidden patterns in economic and climate data |
| Adaptation to regional conditions | Models take into account local agricultural specificities and can be trained on regional data |
| Automate analytics and reporting | Reduce reporting time and human error in analyses |
| Integration into digital platforms | Compatible with smart agriculture platforms and AI infrastructure |
| Support strategic planning | Support tax, investment and risk management solutions |

**Source:** compiled by the authors based on an analysis of the academic literature

Table 3 summarises the key benefits of implementing neural network technologies in the practice of agricultural management and economic analysis. The most significant areas in which artificial neural networks provide added value are presented: from improving the accuracy of forecast calculations to adapting models to local conditions and automating reporting procedures. Each benefit is accompanied by an explanation of its practical significance – whether it is the processing of complex multivariate dependencies, reducing the burden on economic specialists or extending the functionality of digital platforms in the agro-industrial complex. The systematisation of these advantages highlights the relevance and prospects of using neural networks as a tool for digital transformation of the agrarian economy, aimed at improving the efficiency and sustainability of management in changing conditions.

Neural network models such as MLP, CNN, RNN, LSTM and their hybrid combinations with econometric algorithms have been effectively applied for yield forecasting, calculating tax burden, modelling the impact of climate risks and assessing agribusiness performance (Khan & Yairi, 2018). These models are able to account for non-linear and hidden dependencies between economic, climatic and fiscal indicators, making them more accurate and adaptive than traditional analytical tools. Thus, neural network technologies can significantly improve the quality of management decisions in the agricultural economy, provide adaptation to regional conditions, increase the transparency of tax planning and the sustainability of agricultural enterprises. However, for the successful integration of AI in the agricultural sector, further efforts are needed to develop digital infrastructure, improve the quality of source data and form a regulatory and legal framework governing the application of intelligent technologies in the agricultural sector.

The results of the review confirm the growing interest of the scientific community in the application of neural network models in the agricultural economy,

especially in the context of statistical forecasting and tax planning. However, despite the obvious effectiveness of such approaches, there are a number of theoretical and practical issues that require more in-depth study. Firstly, neural network models demonstrate high accuracy in the presence of large datasets, but the agricultural sector in a number of regions, especially in developing countries, suffers from a lack of quality and structured data. This limits the ability to train models and requires the implementation of better data processing techniques, including mechanisms for missing value immunisation, normalisation and class balancing.

Secondly, there is a significant difference in the performance of neural networks depending on the choice of architecture and training parameters. A number of studies emphasise that MLP and RNN models are susceptible to overtraining, especially when the amount of data is small and the number of training samples is limited. For example, A. Chlingaryan *et al.* (2018) note that simple neural network architectures can lose generalisability when analysing agrarian data with high variability. Similar conclusions are drawn in a study by G. Kamilaris & F. Prenafeta-Boldú (2018), where it is stated that when dealing with small volume agricultural datasets, MLP and RNN networks show a decrease in accuracy and the need for regularisation techniques. In a study by K. Liakos *et al.* (2018) also emphasises that the choice of architecture and training parameters has a critical impact on the accuracy of predictions, and the use of LSTMs and hybrid models capable of accounting for complex temporal dependencies is recommended to reduce the risk of overtraining. At the same time, hybrid approaches combining neural networks with econometric methods produce more stable and interpretable results. This raises the question of the need for further development of explainable AI, which is particularly important for fiscal and tax decisions, where validity and transparency of models are required.

A third important aspect is the integration of neural networks into real-world decision support systems in agricultural policy and economic management. Despite the development of prototypes and conceptual solutions, their practical application is hampered by the lack of a regulatory framework, IT infrastructure limitations and a shortage of qualified specialists in the field of agricultural digitalisation. This is especially true for tax modelling tasks, where it is necessary to take into account dynamic changes in the regulatory framework, subsidy system and economic specifics of regions. In addition, an ethical and legal aspect arises when discussing the implementation of AI in tax planning. The use of models that make decisions based on historical data may lead to implicit discrimination of certain categories of households. Consequently, when building neural network systems, it is necessary to take into account the principles of fairness, transparency and accountability, which requires the participation of not only technical specialists, but also lawyers, economists and representatives of government agencies. Thus, despite the obvious prospects, the application of neural network models in agrarian economics requires an interdisciplinary approach that combines technical accuracy with economic logic and regulatory expediency.

## Conclusions

This review has shown that neural network models have significant potential in the tasks of statistical analysis and tax planning in agrarian economy. Their ability to process large volumes of multidimensional data, to identify hidden and non-linear relationships between economic, climatic and fiscal parameters makes them an effective tool in conditions of uncertainty characteristic of agricultural production. The analysis of publications has confirmed that the use of neural networks can significantly improve the accuracy of forecasting yields, tax burden and financial indicators compared to classical econometric methods. The most promising for the agricultural sector are MLP, RNN, LSTM architectures, as well as hybrid models, which combine the capabilities of neural networks with classical methods of analysis (regression, decision trees, principal component methods). These approaches have been successfully applied to solve problems of yield forecasting, tax burden assessment, optimisation of subsidy allocation and strategic planning in agriculture. Special attention in the analysed studies is paid to the problems of quality of initial data. It is revealed that correct preprocessing, normalisation of attributes and dealing with missing values have a decisive influence on the accuracy of models. The development of digital infrastructure, the creation of specialised databases for agriculture and the formation of a regulatory framework for the application of AI in the agricultural sector are also important areas. It is necessary to take into account the issues of interpretability, transparency and reliability of AI systems, especially in the context of fiscal decision-making and public resource management.

Prospects for further research are related to the development of more interpretable hybrid models, the integration of neural network algorithms into “smart agriculture” platforms, as well as the creation of tools to take into account climate risks and regional specifics. An important direction will be the development of intelligent decision support systems capable not only of forecasting economic indicators, but also of offering optimal scenarios for tax planning, subsidy distribution and risk management. Of additional interest is the integration of neural network models with big data, blockchain and Internet of Things technologies, which will enable the formation of more sustainable and transparent value chains in the agricultural sector.

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## Conflict of Interest
The authors declare no conflict of interest.

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# Агрардык экономикадагы статистикалык талдоо жана салыктык пландаштыруу үчүн нейротармактык моделдер

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**Аннотация.** Азыркы агрардык экономика климаттын өзгөрүшү, рыноктун туруксуздугу жана башкаруунун эффективдүүлүгүн жогорулатуу зарылчылыгы сыяктуу бир катар чакырыктарга туш болууда. Санариптештирүү шартында интеллектуалдык куралдарды, айрыкча статистикалык талдоо жана салыктык пландаштыруу үчүн нейротармактык моделдерди киргизүүнүн мааниси өзгөчө чоң. Бул изилдөөдө агрардык сектордо жасалма нейрондук тармактарды (ЖНТ) колдонуу боюнча заманбап ыкмаларга сереп берилет. MLP, CNN, RNN, LSTM архитектуралары жана алардын гибриддик варианттары түшүмдүүлүктү божомолдоодо, салыктык жүктү баалоодо, субсидияларды пландаштырууда жана каржылык тобокелчиликтерди талдоодо колдонулушу каралат. Изилдөөнүн максаты – агрардык экономикадагы статистикалык талдоону жана салыктык пландаштырууну натыйжалуу жүргүзүүдө нейротармактык моделдердин потенциалын аныктоо жана башкаруу чечимдерин колдогон санариптик системаларды түзүүдөгү алардын ролун белгилөө. Иште агрардык экономикада нейрондук тармактарды колдонуу негизги багыттары системалаштырылган, натыйжалуу чечимдердин мисалдары келтирилген жана белгисиздик шартында чечим кабыл алууну колдоо үчүн ЖНТнын практикалык мааниси негизделген. Айрыкча ЖНТны агрардык сектордун санариптик платформаларына интеграциялоо жана фискалдык башкарууну колдогон интеллектуалдык системаларды түзүү маселесине көңүл бурулган. Жүргүзүлгөн талдоо нейрондук тармактардын жогорку адаптивдүүлүгүн жана божомолдорунун тактыгын ырастап, аларды кеңири колдонуу үчүн санариптик инфраструктураны жана нормативдик-укуктук базаны өнүктүрүүнүн зарылдыгын баса белгилейт. Изилдөөнүн жыйынтыктары айыл чарбасын туруктуу өнүктүрүү стратегияларын иштеп чыгууда жана айыл чарба ишканаларынын экономикалык туруктуулугун жогорулатууда пайдаланылышы мүмкүн. Иш изилдөөчүлөр, санариптик чечимдерди иштеп чыгуучулар жана агрардык саясат чөйрөсүндөгү адистер үчүн кызыктуу болуп саналат

**Негизги сөздөр:** жасалма интеллект; предиктивдик моделдөө; фискалдык саясат; санариптик айыл чарба; туруктуу өнүгүү; түшүмдүүлүктү божомолдоо; чечим кабыл алууну колдогон интеллектуалдык системалар

# Нейросетевые модели для статистического анализа и налогового планирования в аграрной экономике

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**Аннотация.** Современная аграрная экономика сталкивается с рядом вызовов, включая изменение климата, волатильность рынка и необходимость повышения эффективности управления. В условиях цифровизации особое значение приобретает внедрение интеллектуальных инструментов, в частности нейросетевых моделей для статистического анализа и налогового планирования. В данном исследовании представлен обзор современных подходов к применению искусственных нейронных сетей (ИНС) в аграрном секторе. Рассматривались архитектуры MLP, CNN, RNN, LSTM, а также их гибридные варианты, используемые для прогнозирования урожайности, оценки налоговой нагрузки, планирования субсидий и анализа финансовых рисков. Целью данного исследования было выявление потенциала нейросетевых моделей для повышения эффективности статистического анализа и налогового планирования в аграрной экономике, а также определение их роли в формировании цифровых систем поддержки управленческих решений. В работе систематизированы основные области применения нейронных сетей в аграрной экономике, приведены примеры эффективных решений и обоснована практическая значимость ИНС для поддержки принятия решений в условиях неопределенности. Особое внимание уделено интеграции ИНС в цифровые платформы аграрного сектора и формированию интеллектуальных систем поддержки фискального управления. Проведенный анализ подтвердил высокую адаптивность и точность прогнозирования нейронных сетей и подчеркнул необходимость развития цифровой инфраструктуры и нормативно-правовой базы для их повсеместного внедрения. Результаты исследования могут быть использованы при разработке стратегий устойчивого развития сельского хозяйства и повышения экономической устойчивости сельскохозяйственных предприятий. Работа представляет интерес для исследователей, разработчиков цифровых решений и специалистов в области аграрной политики

**Ключевые слова:** искусственный интеллект; предиктивное моделирование; фискальная политика; цифровое сельское хозяйство; устойчивое развитие; прогнозирование урожайности; интеллектуальные системы поддержки решений

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# Innovations in food production

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**Abstract.** With growing demands for food quality and increased interest in healthy foods, the development of innovative technologies and functional products is becoming particularly relevant. This study aimed to analyse the current scientific foundations and approaches underlying the creation of innovative food products. A systematic analysis of contemporary scientific and practical research devoted to the development of innovative food products was carried out in the following databases: Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, eLIBRARY, and others. Key areas of research were analysed, including the search for alternative sources of protein, the use of functional ingredients, biotechnological methods (precision fermentation, mycoproteins, muscle cell cultivation in bioreactors), the use of artificial intelligence, and the digitisation of development and quality control processes. The use of high pressure for the pasteurisation or sterilisation of food products was also considered a promising technology. The review showed that there are many developments in the field of food packaging; innovative packaging can be biodegradable, active, smart, or reusable. The processing of raw material by-products (oil cake, whey, peel, etc.) for the production of flour, fibre, and polyphenol concentrates is a trend at the intersection of sustainability and functionality. This article paid particular attention to the development of new functional products. It highlighted the role of interdisciplinary research in forming the scientific basis for innovation in the food industry. The analysis conducted allowed for identifying promising avenues for development and determine strategic guidelines for further research and the introduction of innovations into production

**Keywords:** innovative food products; alternative proteins; mycrobic meat; functional ingredients; technologies; raw materials; platforms of innovation

## Introduction

The dynamic development of the food industry in the 21st century is driven by the need to address a range of interrelated challenges: ensuring food security, meeting growing consumer demands for food quality and functionality, and introducing environmentally sustainable production technologies. As noted by K. Topolska *et al.* (2021), the food industry worldwide is undergoing a number of changes, mainly driven by consumer demand for safe and healthy foods with pleasant organoleptic properties. The Global Food Innovation Index compared factors contributing to innovation in the food, agribusiness and beverage industries in 10 countries. The ranking of these countries, based on their innovation environment for the food industry, is as follows: 1st place – United Kingdom, 2nd – United States, 3rd – Germany, 4th – Australia, 5th – Canada, 6th – Netherlands, 7th – Japan, 8th – Mexico, 9th – France, 10th – Italy (Charlebois, 2020). In particular, according to the German Innovation Report Food (2023), around 30,000 new food products are developed in Germany every year, of which more than 90% do not remain on the market, meaning that only 10% of products are successful. Of these, 94% of new developments are modifications of existing products, and only 3% are innovative products. In 2002, only 350 innovative food and beverage products were developed and successfully introduced into production in Germany.

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A "novel food" is a newly developed, innovative food product; a food product produced using new technologies and production processes; or a food product that is traditionally consumed or has been consumed outside the European Union and has not been consumed to a significant extent in the EU (Regulation (EU), 2015; European Commission, 2025). The word "innovation" can be defined in many ways. Innovation is "the process of transforming a discovery (i.e., an idea, invention) into a product(s) or service(s) that consumers/customers are willing to buy". Innovation encompasses many aspects, such as science, technology, marketing and organisation, partnership, risk management and social responsibility (Burke, 2024; Wei *et al*., 2025). However, as noted by J. Prates (2025), discoveries must be translated into products, services, or processes that are disseminated and integrated into the economy so that society can benefit from these discoveries. For an idea to be called an innovation, it must be reproducible at an economical price and satisfy a specific need. Thus, not all ideas are innovations, but only those that are suitable for implementation. Innovations are necessary to gain a competitive advantage and create value, and their results can be both tangible (e.g., new products, projects) and intangible (e.g., new processes and ways of doing business, expert knowledge) (D'Almeida & de Albuquerque, 2024). An innovative product can be a key factor for success in aggressive and competitive food markets. Thus, an innovative product is a new product that did not exist on the market before, while adaptation is the process of giving an old product new properties or adapting a product to new conditions. However, imitation of a new successful product is more common on the market.

The aim of this work was to analyse contemporary scientific and practical research devoted to the development of innovative food products. A systematic analysis was carried out in the following databases: Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, eLIBRARY, etc. The following keywords were used in the selection: "innovative food products", "functional foods", "biotechnology in food industry", "digitalisation of food production", "innovations in the food industry". The criteria for including sources in the analysis were: relevance to the topic of innovative food products, the availability of experimental data or scientifically substantiated theoretical propositions, publication in peer-reviewed journals and conference proceedings. Particular attention was paid to works describing the practical application of new technologies in the food industry, as well as research on consumer preferences and market trends in the field of functional foods.

**Innovative processing technologies and alternative sources of dietary protein**

The considerable popularity of vegetarianism in recent years has led many to seek alternative sources of animal products. Plant-based meat and milk substitutes are carving out their niche in the food market. The active promotion of these products is based not only on promises of personal comfort for consumers, but also on the obligation of every inhabitant of the planet to care for the environment. Refusing to consume animal meat is presented as one way to reduce the harmful impact of livestock farming and the meat processing industry on the climate. One of the newest areas of research into alternative sources of protein is microbial proteins. Microbial proteins are produced by precision fermentation using microorganisms (yeast/mould/bacteria) that are programmed to produce milk proteins (casein, whey proteins), egg albumin, collagen, haem, etc. (Le Mouël & Forslund, 2017). Targeted enzyme hydrolysis is a tool for texturing and creating bioactive peptides. At the same time, as described in the work of S. Wei *et al*. (2025), bacteria are also used to produce specific ingredients. This method gives functional properties to microbial proteins, reducing humanity's dependence on agriculture and weather risks. Active research is underway in this area – the selection of strains and regimes, as well as the development of regulatory documents and scaling (Eastham & Leman, 2024; Knychala *et al*., 2024).

The next relevant area is the production of cultured meat. The cultivation of muscle/fat cells in bioreactors is progressing from minced meat to whole muscle structures. In 2025, Australia authorised the limited sale of cultivated quail meat, demonstrating the transition of this field into the "real world" (Southey, 2025). At the same time, meat analogues based on plant proteins (stretch textures, extrusion/shear, fat binding) are being actively researched (Berners-Lee *et al.,* 2018; Spiro *et al*., 2024). A successful example of the practical implementation of such developments is the technology of plant-based minced semi-finished products using protein-wheat texturate, which are characterised by a balanced amino acid composition and a significant content of valine, methionine and phenylalanine, making them a complete alternative to meat products for vegetarians (Filin *et al.,* 2023). The production of flour from crickets, yellow mealworms, etc. is carried out in accordance with the EU Regulation on novel foods; a single list is maintained, which specifies the conditions of use and labelling (European Commission, 2025).

The following developments relate to microalgae (e.g., *Nannochloropsis*). They are sources of unsaturated fatty acids and pigments (astaxanthin). There is a growing number of applications for microalgae in the food industry and clinical observations on their effect on the human lipid profile (Prates, 2025). Microalgae have a number of promising applications in the field of functional foods, both in the form of natural biomass (microstructural powders or syrups) and as a source of biologically active ingredients (Kaledina *et al*., 2020). Most alternative protein sources have advantages:

they are easily digestible, rich in vitamins, minerals and fibre, and suitable for various diets, including vegetarian ones. Another aspect of the use of alternative protein sources is that not all consumers are willing to eat products made with new ingredients. Therefore, consumer opinion should be taken into account when developing food innovations.

In parallel with the search for new sources of protein, modern food processing technologies are actively developing, aimed at improving the quality and functionality of products. Over the past decades, fast and efficient production methods have emerged that improve the quality and shelf life of food products, and suitable alternative processing technologies have been found, such as high hydrostatic pressure, pulsed electric fields, ultrasound, and microwaves (Ozaybi, 2024). Non-thermal pasteurisation of food raw materials, including dairy products at high pressure (400-600 MPa), preserves nutrients, controls protein structures and texture, and improves the safety and organoleptic properties of finished products. Updated reviews for 2023-2025 detail the effect of extrusion on the secondary structure of protein, bioactive components, and aggregation (Ozaybi, 2024; Siddiqui *et al.,* 2024). 3D food printing is used for shaping/texturing, targeted fortification, and "digital gastronomy". Limitations include speed/throughput and the stability of "food ink", as highlighted in reviews by R. Burke (2024) and S. Xiao *et al.* (2025).

Innovative food packaging should be biodegradable, active, smart or reusable. Smart/active packaging is equipped with sensors to monitor the freshness, pH, amines, sulphur compounds of food products, as well as the release of antioxidants/antimicrobial agents to extend shelf life (Chiu *et al.,* 2024; Palanisamy *et al.,* 2025). Algae are used to produce packaging, edible capsules and coatings for compostable containers, which are already being used by large retail chains (Oughton, 2023). A. D'Almeida & T. de Albuquerque (2024) describe developments in biomaterials, such as starch or cellulose films incorporating active ingredients (antioxidants, freshness sensors). Stora Enso (2024) uses FiberLight Tec™ technology to produce lightweight, high-quality cellulose packaging, reducing the carbon footprint and weight of the packaging. Waste-free disposal or use of raw material processing by-products (oil cake, whey, peel, etc.) for the production of flour, fibre, and polyphenol concentrates remains a relevant area, combining production sustainability and product functionality (Lu *et al.,* 2024). Systematic reviews highlight the contribution of waste-free technologies to "triple" sustainability: ecology, economy, and society.

**Functional and personalised nutrition and artificial intelligence**

Artificial intelligence (AI) accelerates the development of product formulations that take into account consumer requirements (metabolomics, allergies, taste preferences), as well as the optimisation of formulations/sensory properties. Reviews are emerging on the integration of AI into personalised nutrition and the development of new products, such as NotMilk®, NotChicken® (Zatsu *et al.,* 2024; Kuhl, 2025). The integration of more sophisticated AI tools, such as deep learning and advanced robotics, can significantly improve the safety, quality, and efficiency of food products at all stages of the supply chain. P. Detopoulou *et al.* (2023) expect AI to play a key role in improving personalised nutrition in the future by providing real-time dietary recommendations based on an individual's genetic characteristics, lifestyle and health data, thereby transforming public health strategies. I. Kiselev *et al.* (2018) argue that the development of AI-based sensory technologies, such as more accurate electronic noses and tongues, will further improve the accuracy of food quality assessment by enabling non-destructive testing of food products. Innovations in AI-based smart packaging, capable of autonomously monitoring and maintaining optimal food storage conditions, will also contribute to increasing shelf life and reducing food waste on a global scale. Another promising area is the use of AI in sustainable food production. Precision agriculture based on AI, combined with big data analytics, will optimise resource use, reduce environmental impact and increase crop yields (Kutyauripo *et al.,* 2023; Zatsu *et al.,* 2024).

Of all the innovative trends in food production listed above, functional and personalised products stand out. The Food and Agriculture Organization (FAO) (n.d.) uses the following definition: "…functional foods are foods that contain additional beneficial components beyond basic nutrients, offering health advantages for the prevention and management of disease". In other words, functional food is produced by adding or concentrating a beneficial ingredient or replacing an ineffective or harmful ingredient, and has (in addition to its traditional nutritional value) additional health benefits or acts as a remedy for certain diseases (Kaur & Das, 2011). The increase in environmental and social problems is the main driving force behind the development of functional products worldwide. According to C. Karelakis *et al.* (2020), the main consumer motive for purchasing functional foods is a growing desire to use products to prevent chronic diseases such as cardiovascular disease, Alzheimer's disease and osteoporosis, as well as to improve health, for example by strengthening the immune system and promoting well-being. Functional foods are officially recognised by the Japanese government as an alternative to drug therapy and are defined as "Food for Specified Health Use" (FOSHU) (Iwatani & Yamamoto, 2019). According to GOST 52349-2005 (2005), there are seven main types of functional ingredients that give foods functional properties (Table 1).

**Table 1.** Main types of functional ingredients

| No. | Ingredient class | Examples | Main functional effects |
|---|---|---|---|
| 1 | Probiotics, prebiotics and synbiotics | Probiotics: *Lactobacillus*, *Bifidobacterium*; Prebiotics: lactulose, gluco-oligosaccharides, fructo-oligosaccharides, xylo-oligosaccharides; Synbiotics: combinations | Maintaining healthy gut microbiota, immunomodulation, improving mineral absorption |
| 2 | Antioxidants | Polyphenols (flavonoids, phenolic acids, stilbenes), carotenoids (β-carotene, lutein), terpenoids, tocopherols and tocotrienols | Protecting cells from oxidative stress, preventing chronic diseases, cardioprotective and neuroprotective effects |
| 3 | Polyunsaturated fatty acids (PUFAs) | Omega-3 fatty acids (eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), alpha-linolenic acid (ALA), omega-6 (linoleic acid, arachidonic acid) | Normalisation of lipid metabolism, anti-inflammatory effect, support for the brain, heart and vision |
| 4 | Dietary fibre | β-glucan, inulin, pectin, cellulose | Lowering cholesterol levels, regulating blood sugar levels, promoting beneficial microflora growth, improving gastrointestinal motility |
| 5 | Vitamins | Vitamins A, D, E, K, C, B group | Supports metabolism, antioxidant properties, participates in immune responses, prevents vitamin deficiency |
| 6 | Minerals | Calcium, iron, zinc, magnesium, selenium, iodine | Bone and tooth formation, regulation of enzymatic processes, antioxidant protection, support of blood formation |
| 7 | Proteins and their structural components | Casein, whey proteins, soy proteins, peptides | Muscle tissue formation, pressure regulation (bioactive peptides), antioxidant and immunomodulatory effects |

**Source:** GOST 52349-2005 (2005)

The functional food market in the United States, Japan, the Asia-Pacific region and the European Union is a profitable niche in food production and is forecast to grow worldwide (Bigliardi & Galati, 2013). The existing literature offers various options for classifying functional foods. Functional foods are classified according to their purpose as follows (Bigliardi & Galati, 2013; Mudgil & Barak, 2019): functional foods that are beneficial or improve the lives of children (prebiotics and probiotics); functional products that reduce existing health risks (high cholesterol or high blood pressure); functional products that make life easier (lactose-free or gluten-free products). By product type, B. Bigliardi & F. Galati (2013) propose the following classification of functional products:

- products enriched with additional nutrients, labelled as "fortified foods" (fruit juices enriched with vitamins C and E, zinc and calcium);
- products enriched with new nutrients or components that are not normally found in a given food, labelled as "enriched foods" (probiotics or prebiotics);
- products from which a harmful component has been removed, reduced or replaced with another with beneficial effects, labelled as "altered foods" (adding dietary fibre to reduce the amount of fat in meat products or ice cream);
- products in which one of the components has been naturally enhanced, labelled as "enhanced commodities" (eggs with increased omega-3 content).

According to this classification, the methods used to develop potentially functional foods are presented in Figure 1. The development of successful functional foods is a complex process that differs somewhat from the traditional development of new foods. The work of A. Rudder *et al.* (2001) presents various models of new product development (NPD) with different stages and success factors. However, there is no consensus on which NPD method in the food industry is right or wrong. There are four main critical stages of NPD: product strategy development based on the results of technological and marketing research, product design and production, product commercialisation (product launch) and post-launch, which are common to all these models (Earle, 1997). In accordance with modern scientific concepts, the process of creating a functional food product consists of the following stages: monitoring the nutrition of the population; developing medical and biological requirements for a functional product; selecting and justifying a food matrix; selecting and justifying a functional component; modifying a food product into a functional one; confirming the positive effect.

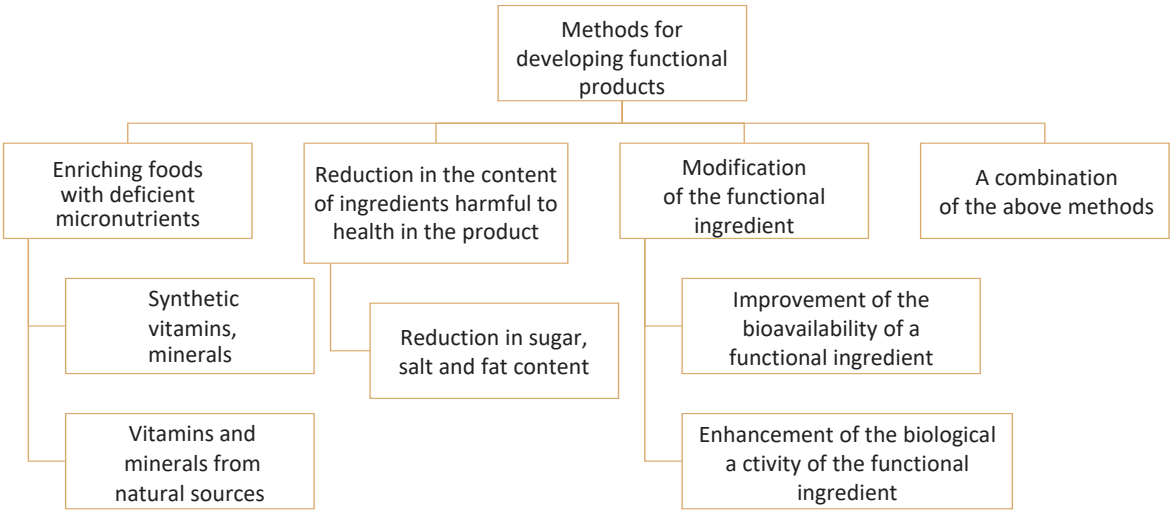


**Figure 1.** Methods for developing functional foods
**Source:** developed by the author based on M. Roberfroid (2002), B. Bigliardi & F. Galati (2013)

The dynamics of functional food development are quite intensively discussed in the literature, but the successful process of functional product development remains unresolved for both food manufacturers and scientists and researchers. A study conducted by C. Mark-Herbert (2004) proposed "business reunification" as a method for developing new functional foods. This involves the joint development of products by pharmaceutical companies and food manufacturers with the exchange of resources and skills. One such example was the launch of a probiotic product on the US market through the joint efforts of CAG Functional Foods and a Swedish biotechnology company. However, the partners encountered serious difficulties due to intellectual property rights and brand ownership issues.

Technological and marketing research are crucial stages in the development of a new food product. In addition, one of the key concepts is that NPD is, to a large extent, a team activity. The team should consist not only of technologists, but also marketers, engineers and scientists from various fields. Comprehensive knowledge of the basic concepts of nutrition, the design and implementation of new packaging technology, the product quality assessment process (shelf life testing, sensory evaluation), etc. is required (Brody, 1999). Thus, NPD requires comprehensive scientific and practical knowledge, and intuition plays an important role in this process.

**New product development platforms**

Successful new product launches require the development of a truly innovative product. Scientific and industry literature often identifies four key platforms on which the development of innovative food products is based. Table 2 presents the four main platforms for innovative product development.

**Table 2.** Main platforms for the development of innovative products

| No. | Platform | Essence | Examples of application |
|---|---|---|---|
| 1 | Functional ingredients and nutraceuticals | Use of bioactive substances (probiotics, prebiotics, omega-3 fatty acids (FA), polyphenols, vitamins and minerals) to give products additional physiological properties | Yoghurts with probiotics (Hill *et al.,* 2014; Markowiak & Slizewska, 2017), drinks with omega-3 fatty acids, bars with β-glucan (Santos *et al.,* 2018; Mudgil & Barak, 2019) |
| 2 | Technological platforms for processing and structuring | Application of new processing and texturing methods that preserve nutrients and improve product properties | High pressure processing (HPP), pulsed electric fields (PEF), fermentation, 3D printing, extrusion (Tewari *et al.,* 2017) |
| 3 | Biotechnological and cellular platforms | Use of microorganisms, cell cultures and fermentation to produce alternative ingredients and proteins | Precision fermentation (milk proteins, collagen), cultured meat and fish, microalgae (Alizadeh Khaledabad *et al.,* 2020; Prates, 2025) |
| 4 | Digital and personalised platforms | Use of big data, AI and digital technologies for personalising nutrition, designing recipes and tracking quality | Personalised products based on genetics/ metabolomics, AI recipe development, digital product twins (Santhuja *et al.,* 2023; Derossi *et al.,* 2024) |

**Source:** developed by the author based on a review of scientific literature

The technical and technological platforms for NPD require production facilities to be equipped with modern equipment and experts in the field. The use of heat treatment in production has a negative impact on the bioavailability of nutrients and bioactive compounds. Alternative technologies, such as high hydrostatic pressure, pulsed electric fields, ultrasound, and microwaves, provide better preservation of nutrients in fruits and vegetables, prevent the growth of microorganisms, and consume less energy (Ozaybi, 2024). Consequently, they have a positive impact from a functional point of view and also contribute to the development of new functional products. The non-thermal food processing methods listed above have undergone significant development in recent years and are now a reality in many food processing plants around the world (Koker *et al.,* 2019).

However, it should be noted that the food industry in Kyrgyzstan lags behind in the implementation of the above-mentioned new technologies that accelerate NPD processes. A more common platform for developing new innovative products for the country is the new raw materials platform. It allows the use of new types of raw materials to create products with improved properties and functionality. This approach involves searching for and using new ingredients that can offer increased nutritional benefits, unique flavours or improved functional properties. According to T. Kiymaz & H. Alpas (2017), C. Björkbom (2023), an important aspect of the new raw material platform is sustainability, i.e. the use of ingredients that are obtained in a sustainable manner or produced with minimal environmental impact, such as algae, insect protein and plant-based protein substitutes. New products can be developed through the use of incompatible ingredients, as indicated in the work of F. Cedeno *et al.* (2025), or through the use of exotic raw materials, according to I. Ferreira & L. Barros (2019), or, conversely, through the use of regional raw materials (Iskakova *et al.,* 2023). As noted by F. Zare *et al.* (2012), the criteria for selecting functional ingredients depend on their chemical composition, cost, availability, and desired functionality.

The search for raw materials with high nutritional value and the study of new ingredients that may have physiologically functional and technological properties, such as improved texture and increased shelf life, are relevant for NPD. Examples include hydrocolloids, prebiotics and bioactive compounds. Consumer perception of new products will also be crucial when selecting ingredients for healthier, safer and more environmentally friendly foods. Therefore, in-depth research into regional raw materials as a source of physiologically functional ingredients, as well as the use of traditional products as a matrix for NPD, has good prospects.

## Conclusions

Innovation in food production is the process of creating and implementing new solutions (from ingredients and technologies to packaging and distribution) that improve the quality, safety, functionality, sustainability and appeal of food products for consumers. The current trend towards innovation aimed at developing healthier, safer and more sustainable food products encompasses a wide range of approaches. Three main areas can be identified: replacing traditional animal-based ingredients (meat and milk), developing functional products, and developing new production technologies. All three areas are interrelated. For example, structuring alternative protein sources (microbial or plant-based meat) using extrusion or 3D printing can improve consumer acceptance of new products. 3D food printing can also be used for targeted enrichment, i.e. for the development of functional products. Information about the chemical composition of regional food raw materials and products is important for the development of functional food products. This will allow for the targeted selection of sources of functional ingredients adapted to local conditions and dietary traditions. Of particular importance is a comprehensive assessment of the bioavailability and interaction of nutrients, which is necessary to predict their physiological effect. In addition, the introduction of innovative technologies – biotechnological and digital – ensures the creation of products with specified properties, increased nutritional value and improved sensory characteristics. At the same time, safety and compliance with modern regulatory requirements remain key factors, while taking into account consumer perceptions of innovation (taste, colour, consistency, food structure; consumer traditions, preferences and habits). All of the above studies form a broad interdisciplinary approach to the current state of innovation in the food industry. Further development of innovative food products should be aimed at integrating interdisciplinary approaches to nutrition, biotechnology, consumer psychology, marketing, etc., as well as at in-depth study of regional raw materials that are underutilised in nutrition and the formation of sustainable production strategies (waste-free technologies) in the context of global challenges.

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## Conflict of Interest

The author declares that there is no conflict of interest.

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# Азык-түлүк өндүрүшүндөгү инновациялар

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**Аннотация.** Калктын рационунун сапатына болгон талаптардын өсүшү жана пайдалуу азыктарга кызыгуунун жогорулашы шартында инновациялык технологияларды жана функционалдык азыктарды иштеп чыгуу өзгөчө актуалдуулукка ээ болууда. Изилдөөнүн максаты – инновациялык азык-түлүк продукцияларын жаратуунун негизинде жаткан заманбап илимий негиздерди жана ыкмаларды талдоо болуп саналат. Инновациялык азык-түлүк продукцияларын иштеп чыгууга арналган илимий жана практикалык изилдөөлөрдүн системалуу анализи Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, eLIBRARY жана башка маалымат базаларында жүргүзүлдү. Изилдөөнүн негизги багыттары катары альтернативалуу белок булактарын издөө, функционалдык ингредиенттерди колдонуу, биотехнологиялык ыкмалар (так ферментация, микопротеиндер, биореакторлордо булчуң клеткаларын өстүрүү), жасалма интеллектти колдонуу, ошондой эле жаңы азык-түлүк продукцияларын иштеп чыгуу жана алардын сапатын көзөмөлдөө процессинин санариптештирилиши каралды. Азык-түлүк продукцияларын пастеризациялоо же стерилдештирүү үчүн жогорку басымды колдонуу да үмүт арткан технология катары белгиленди. Кароонун жүрүшүндө азык-түлүктөрдү таңгактоонун көптөгөн жаңы иштелмелери бар экени аныкталды. Чийки зат калдыктарын (жеми, суусат, кабык ж.б.) ун, белоктор, клетчатка, полифенолдук концентраттар өндүрүү үчүн кайра иштетүү – туруктуулук менен функционалдуулуктун кесилишинде өнүгүп жаткан багыт болуп саналат. Макалада өзгөчө көңүл жаңы функционалдык азыктарды иштеп чыгуу маселелерине бурулду. Инновациялардын илимий базасын түзүүдө дисциплиналар аралык изилдөөлөрдүн ролу көрсөтүлдү. Жүргүзүлгөн талдоо азык-түлүк технологияларын өнүктүрүүнүн келечектүү жолдорун аныктоого жана инновацияларды өндүрүшкө киргизүүдө стратегиялык багыттарды белгилөөгө мүмкүнчүлүк берди

**Негизги сөздөр:** инновациялык тамак-аш азыктары; альтернативдик белоктор; микробдук эт; функционалдык ингредиенттер; технологиялар; акылдуу таңгак; инновациялык платформалар

# Инновации в производстве пищевых продуктов

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**Аннотация.** В условиях растущих требований к качеству рациона и повышенного интереса к здоровой пище, разработка инновационных технологий и функциональных продуктов приобретает особую актуальность. Целью исследования был анализ современных научных основ и подходов, лежащих в основе создания инновационных пищевых продуктов. Систематический анализ современных научных и практических исследований, посвященных разработке инновационных продуктов питания, осуществлялся в базах данных Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, eLIBRARY и др. Были проанализированы ключевые направления исследований, включая поиск альтернативных источников белка, использование функциональных ингредиентов, биотехнологические методы (точное ферментирование, микопротеины, культивирование мышечных клеток в биореакторах), использование искусственного интеллекта, а также цифровизацию процессов разработки новых пищевых продуктов и контроля их качества. Использование высокого давления в целях пастеризации или стерилизации пищевых продуктов также было рассмотрено как многообещающая технология. Обзор показал, что существует большое количество новых разработок в области упаковки пищевых продуктов. Инновационные упаковки могут быть биоразлагаемыми, активными, умными или многоразовыми. Переработка отходов сырья (жмыхи, сыворотка, кожура и т.п.) для производства муки, сывороточных белков, клетчатки, полифенольных концентратов – направление, развивающееся на стыке устойчивости и функциональности. Особое внимание в статье было уделено вопросам разработки новых функциональных продуктов. Показана роль междисциплинарных исследований в формировании научной базы для инноваций в пищевой отрасли. Проведенный анализ позволил выявить перспективные пути развития и определить стратегические ориентиры для дальнейших исследований в области пищевых технологий и внедрения инноваций в производство

**Ключевые слова:** инновационные пищевые продукты; альтернативные белки; микробное мясо; функциональные ингредиенты; технологии; умные упаковки; платформы инноваций

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