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Animal and bird diseases – the food chain of the snow leopard in the highlands of the Tian Shan

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Abstract. The snow leopard (*Panthera uncia*) is a rare and vulnerable species that is threatened with extinction and listed in the Red Book of the Kyrgyz Republic. It inhabits the inaccessible high-mountain areas of the Tian Shan, where the ecological balance directly depends on the state of the fauna that makes up its food chain. In recent years, there has been an increase in the number of diseases among wild and domestic animals, which may affect the health of the snow leopard population and the stability of the ecosystem as a whole. The aim of this study was to investigate parasitic diseases in mammals that are part of the snow leopard's food chain, determining their biological characteristics, sources of infection and impact on the epizootic situation in mountainous areas. The study used field observations, helminthological autopsies, microscopic analysis of biomaterial, comparative morphological and descriptive analysis of veterinary research data. As a result, it was established that alveococcosis and muelleriosis are the most epidemiologically significant of the identified parasitic diseases, posing a serious threat to both wild and domestic animals. The causative agent of alveococcosis is the larval stage of the tapeworm *Alveococcus multilocularis*, which affects the liver and causes the formation

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of multiple cystic parasitic nodes capable of infiltrative growth and metastasis. The final hosts of this parasite are carnivorous animals (dogs, cats, wolves, foxes, manuls, etc.), and the intermediate hosts are small wild rodents. It has also been established that the pathogen *Mullerius capillaris* causes lung damage in goats, sheep and wild ruminants, manifested by multiple foci of productive alveolitis and a decrease in the overall resistance of animals. A comprehensive analysis of the biological and ecological characteristics of pathogens allows for assessing their circulation in natural conditions and potential risks to humans. The practical significance of the study lies in the possibility of using the data obtained to develop a system of preventive and diagnostic measures aimed at protecting rare predators and stabilising the epizootic well-being of the high-mountain ecosystems of Kyrgyzstan

Keywords: Siberian ibex; argali; roe deer; alveococcosis; mulleriosis; cysticercosis

Introduction

The conservation of wild fauna and rare animal species in the context of global environmental change is one of the priority tasks of modern biological and veterinary science. In recent decades, against the backdrop of increasing anthropogenic impact, climate change and the degradation of natural ecosystems, there has been a decline in the numbers of many mammals in Kyrgyzstan, including Red Book species. The most vulnerable species include the snow leopard (*Panthera uncia*), Siberian ibex (*Capra sibirica*), argali (*Ovis ammon*) and roe deer (*Capreolus capreolus*), which play an important role in maintaining the biological balance of the Tian Shan Mountain ecosystems. Disruption of food chains, deterioration of the food base and the spread of parasitic diseases among animals in these chains have a significant impact on the epizootic situation and the stability of ecosystems (Esson *et al.*, 2019). In recent years, there has been a trend towards an increase in the number of parasitic diseases in wild animals (Chrétien *et al.*, 2023). Parasitic infestations, including alveococcosis and muelleriosis, are becoming an important factor limiting the growth of ungulate and predator populations in Central Asia. These diseases affect not only internal hosts (rodents and ungulates) but also final hosts – carnivorous animals, including the snow leopard, for which parasite infection can have fatal consequences. According to S. Ostrowski & M. Gilbert (2024), parasitic infections cause complex morphofunctional changes in internal organs, disrupt metabolism, suppress the immune system and reduce the ability of animals to adapt to extreme environmental conditions.

The immune system of vertebrates is a collection of organs, tissues and cells that recognise and destroy foreign agents. The primary organs of immunogenesis – the thymus and bone marrow – are the source of the formation and maturation of lymphocytes, which are responsible for cellular and humoral immunity. Secondary organs – lymph nodes, spleen and lymphoid formations of the mucous membranes – ensure the implementation of immune responses and the formation of immunological memory (Weiskopf *et al.*, 2016). According to G. Schaller (2012), the morphological organisation of the immune system in animals living in high-altitude conditions differs from that of lowland species due to hypoxia, low temperatures and limited food diversity. The adaptive mechanisms of the immune system in wild animals are formed under the influence of natural selection, but constant stress, parasitic load, and environmental factors can cause depletion of immune resources. Research by M. Luo *et al.* (2023) has shown that chronic parasitic diseases lead to changes in the structure of lymphoid organs, in particular thymus atrophy and reduction of the follicular zones of the spleen. Similar changes have been observed in domestic ruminants infected with *Mullerius capillaris* (Shao *et al.*, 2019). In wild species living in the mountains, these processes are more pronounced due to limited access to food and increased physiological stress.

Parasitic diseases such as alveococcosis and mulleriosis have a direct impact on the immune system of animals. The larval stage *of Alveococcus multilocularis* affects the liver, causing the formation of cystic nodules, infiltrative tissue growth, and metastatic spread to the lungs and brain (Shao *et al.*, 2021). These processes are accompanied by a pronounced immune response, activation of macrophages and lymphocytes, which ultimately leads to depletion of the lymphoid organs. The pathogen *Mullerius capillaris* affects the lungs, causing chronic alveolitis and fibrosis, which also leads to changes in the structure of secondary organs of the immune system, especially the lymph nodes. Research by M. Osborne & J. Laird (2022) confirms that prolonged parasitic infections lead to the restructuring of lymphoid tissue, impaired lymphocyte differentiation, and a decrease in the effectiveness of the immune response.

Despite the growing number of publications on parasitology and immunology of domestic animals, the morphological features of the immune system in wild ungulates of Central Asia have been studied extremely poorly. To date, there is no comprehensive data on structural changes in the thymus, spleen, and lymph nodes of Siberian ibex, argali, and roe deer in parasitic diseases. Meanwhile, such information is necessary to assess the biological stability of populations, predict their condition, and develop preventive measures in the system of protection of rare species. The study of the morphology of immune organs in wild fauna has not only scientific but also practical significance. The morphological features identified in the course of research can be used to diagnose invasive diseases, develop criteria for epizootic monitoring, and assess the impact of parasitic load on animal health (Ale, 2007). In addition, the results of such analysis make it possible to clarify the mechanisms of immunogenesis in extreme conditions and determine the body's adaptive capacity to prolonged exposure to pathogens. An important direction in modern research is the interdisciplinary approach, combining data from morphology, histology, parasitology, and immunology. As noted by S. Ashokumar (2023) noted, only a comprehensive study of structural changes in the immune system allows for an adequate assessment of the impact of infectious agents on the body and the development of effective biosecurity measures. In Kyrgyzstan, where wildlife is under constant exposure to climatic and anthropogenic factors, such research is of particular importance.

An analysis of scientific publications shows that the morphology of immune organs is a key indicator of animal health and their ability to adapt to external influences. However, there have been no systematic studies devoted to wild species in Kyrgyzstan to date. The aim of this study was to identify morphological changes in the main, primary and secondary organs of the immune system (thymus, spleen and lymph nodes) in Siberian ibex, argali and roe deer affected by parasitic diseases, and to determine the characteristics of their immune reactivity and adaptive mechanisms in the high-altitude ecosystems of the Tian Shan.

Materials and Methods

The study was conducted in the Kyrgyz Republic from May 2023 to March 2025 and included two main areas: monitoring wild animal populations and pathomorphological study of the organs and tissues of hunted individuals. The objects of the pathomorphological study were wild ungulates: Siberian ibex (*Capra sibirica*), argali (*Ovis ammon*) and roe deer (*Capreolus capreolus*), which are the main components of the snow leopard (*Panthera uncia*) food chain in the high-altitude ecosystems of the Tian Shan. The animals were shot in strict accordance with licence No. 45/2025, issued by the Ministry of Hunting and Fisheries of the Kyrgyz Republic on 10 March 2025, as well as with the Guidelines for Wildlife Research (2022). A total of five individuals were studied, weighing between 35 and 48 kg. The culling was carried out in the Katta-Taldyk district of the Talas region between 12 and 15 March 2025.

Automatic camera traps were used to assess the abundance and spatial distribution of wild animals in the study area. The cameras were installed on 17 May 2023 in the areas of Zindi-Suu, the Chon-Emgek gorge, Zhaia, Koi-Suu in the Chon-Kemin valley, as well as on the Kakshaal-Too ridge at an altitude of 2,500 to 4,500 m above sea level. A total of 13 cameras were installed at various exposures on the slopes. The camera traps were checked between May and September 2023. Immediately after the shooting, a detailed inspection and photographing of the animals was carried out.

Samples of the following organs and tissues were taken from the shot animals for histological examination: liver, lungs, heart, kidneys, spleen, thymus, lymph nodes, thigh and back muscles, skin, and pancreas. The size of the samples taken was 1.0-2.5 cm^3, and the weight of each was 1.2-3.5 g. The material was fixed in 10% neutral formalin to preserve the morphological structure of the tissues. After fixation, the samples were sequentially dehydrated in alcohols of increasing concentration (70%, 80%, 90%, 96%, 100%). Further processing was carried out according to the following scheme: alcohol/chloroform (50:50), chloroform, paraffin/xylene (50:50) at a temperature of 37°C, followed by sequential impregnation with paraffin at 56-57°C (paraffin 1, paraffin 2) and final immersion in pure paraffin to compact the tissues. All stages of processing, storage and preparation of samples were carried out in the laboratory conditions of the Research Laboratory of Zoology of the Kyrgyz National Agrarian University named after K.I. Skryabin in compliance with standard safety and hygiene protocols. The prepared samples were used for subsequent microscopic examination according to standard methodology (Eckert *et al.*, 2001; Huynh *et al.*, 2022). Serial sections 5-7 μm thick were prepared from paraffin blocks using a sliding microtome. The histological preparations were stained with haematoxylin and eosin according to standard methodology. The histological preparations were examined using Biolam LOMO (Russia) and PZO Warszawa (Poland) light microscopes at magnifications of ×40, ×100, ×200 and ×400. Microphotography was performed using a Leica ICC50 HD microscope (Leica Microsystems, Germany) equipped with a built-in high-resolution digital camera. During the pathological autopsy, a visual examination of the internal organs was performed to detect macroscopically visible parasitic lesions. The pathological changes identified were photographed and described morphologically. Parasites were identified based on the morphological characteristics of the larval and sexually mature stages of helminths in histological sections.

The study area is located in the high-mountain zone of the Tian Shan at an altitude of 700 to 4,500 m above sea level. The territory is characterised by mountainous relief with pronounced vertical zonation, including alpine meadows, rocky areas and upland scree. Climatic conditions are characterised by low temperatures, hypoxia and limited food diversity, which determines the specific adaptation mechanisms of the fauna inhabiting this area.

Results and Discussion

Kyrgyzstan is a mountainous country located within three physical-geographical territories: the Central Asian Plain, the Central Asian Highlands, and the

Central Asian Plateau. The Central Asian Plain is located in the Turan Lowland and is characterised by desert landscapes. Within its boundaries, in the north of Kyrgyzstan, there is the Chui Valley at an altitude of 850-900 m, the Talas Valley at an altitude of 700-800 m, and in the south, the sloping plains of the Fergana Valley stretch at an altitude of 1,000-1,100 m above sea level. The Central Asian Highlands cover most of Kyrgyzstan, which is divided into two large regions: the mountainous area of the Northern and Inner Tian Shan and the Fergana mountainous area. These areas are characterised by mountain ranges with heights of 1,500-5,500 m above sea level. The Central Asian highlands include the southern and south-eastern regions of Kyrgyzstan, namely the Alay Valley in the south-west and the north-east up to the Sary-Jaz River basin. Among these highlands is the mountain-syrty part of Kyrgyzstan, where syrty is a type of highland with a flat relief, mainly used as high-altitude summer pasture. The fauna in these areas is very diverse, including birds such as the alpine chough, golden eagle, capercaillie, mountain turkey or ular, saker falcon, gyrfalcon, vultures, bearded vulture, Himalayan ular, eagles, etc. (Bar, 2021). Mammals include marmots, mountain goats, argali, snow leopards, wolves, foxes, wild boars, brown bears, Turkestan lynxes, and manuls (Table 1).

Table 1. Species diversity of wild animals on the Kakshaal-Too ridge

Name	Name (lat.)	Approximate number
Snow leopard	*Uncia uncia*	1
White-clawed bear (Tian Shan)	*Ursus arktos*	3
Arhar	*Ovis ammon*	145
Mountain goat	*Carpa sibirica*	150
Manul	*Felis manul*	3
Red fox	*Vulpes vulpes*	18
Wolf	*Canis lupus*	7
Badger	*Meles meles*	5
Golden eagle	*Aquila chrysaetus*	2
Bearded vulture	*Gypaetus barbatus*	1
Himalayan ibis	*Tetraogallus himalayensis*	34

Source: compiled by the authors based on reports from the NABU (n.d.) monitoring department for 2024

To count the number of snow leopards, mountain goats, argali, roe deer, wild boars and other mammals in the snow leopard's food chain, camera traps were installed on the mountain slopes of the Turkestan Range, Teskey Ala Too, Central Tian Shan and other locations. The camera traps were installed in the study areas at various exposures on slopes at an altitude of more than 2,500-3,000 metres above sea level. The installation of camera traps began on 17 May 2023, and 13 cameras were installed in the areas of Zindi-Suu, in the Chon-Emgek Gorge, Zhay, Koi-Suu, and the Chon-Kemin Valley, at altitudes of 500-4,500 m above sea level. When checking the camera traps on 26 May 2023 in the Zindi-Suu area at an altitude of 3,175 m above sea level, the presence of a snow leopard was recorded. This graceful, beautiful animal has a smoky grey coat with dark rings. Its fur is thick and fluffy, and it is more commonly found at the edge of the permanent snow line, descending to the coniferous forest belt in winter, as confirmed by camera traps (Tetzloff & Schwartz, 2024). In the second half of September 2023, an expedition was conducted to the Ak-Sai Valley in the At-Bashinsky District in collaboration with employees of NABU (The Nature and Biodiversity Conservation Union) Kyrgyzstan. During the expedition, camera traps previously installed on the Kakshaal-Too ridge were removed. The images captured snow leopards, ibexes, argali sheep, wolves, martens, foxes and other species of fauna. Figure 1 shows the species diversity of wild animals recorded on the Kakshaal-Too ridge in 2024. The data reflects the approximate number of individuals of each species identified during field observations by NABU's (n.d.) monitoring department. The graph clearly shows the abundance of the most common species, including argali, mountain ibex and rare predators such as snow leopards and golden eagles. The most numerous among the observed species are the mountain goat (150 individuals) and the argali (145 individuals). Moderate numbers were recorded for the Himalayan ibex (34 individuals) and the red fox (18 individuals). Other species, such as the wolf (7 individuals), badger (5 individuals), manul and white-toothed Tian Shan bear (3 individuals each), golden eagle (2 individuals), bearded vulture and snow leopard (1 individual each), are much less common. The data show a clear predominance of large ungulates in the ecosystem of the ridge. During the study, observations were made and the locations of wild animals on the Kakshaal-Too ridge were recorded. Figure 2 shows the locations of the animals, reflecting their spatial distribution in the study area.

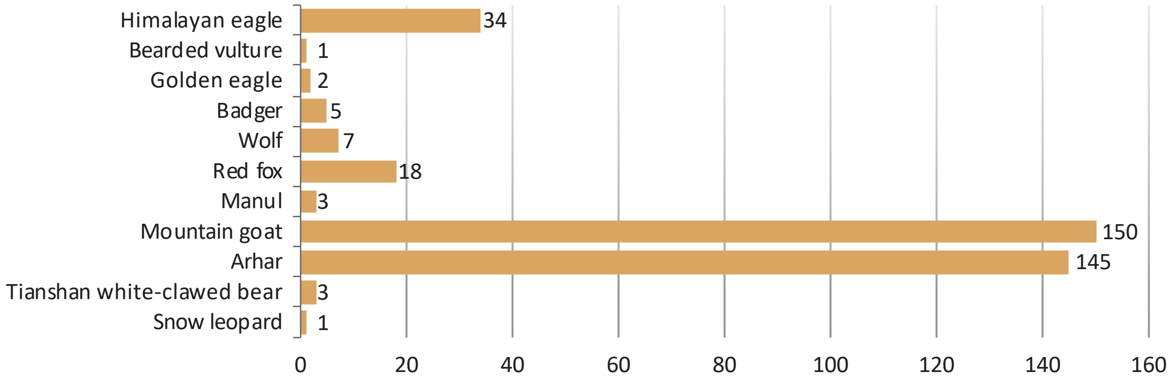

Figure 1. Species diversity of wild animals on the Kakshaal-Too ridge
Source: compiled by the authors based on reports from the NABU (n.d.) monitoring department for 2024

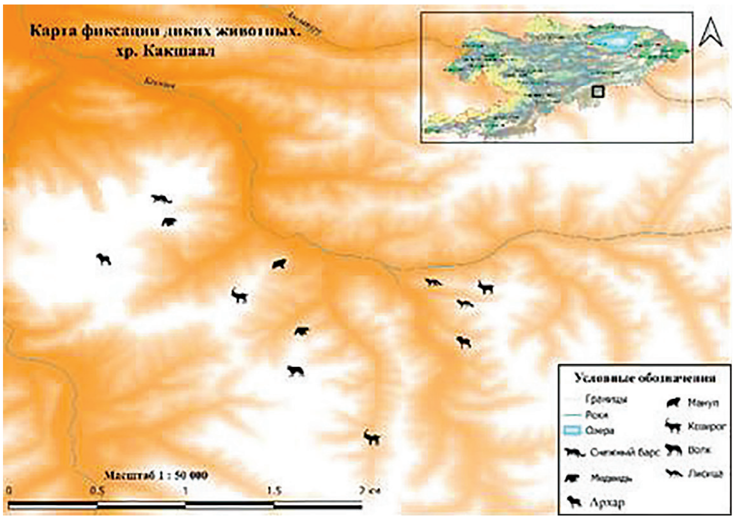

Figure 2. Points where wild animals were recorded on the Kakshaal-Too ridge
Source: compiled by the authors

The cartographic diagram in Figure 2 shows the location of the points where wild animals were recorded (detected) in the Kakshaal-Too ridge area. The map is drawn to a scale of 1:50,000. The scale bar in the figure allows the distances on the ground to be estimated. For clarity, the map includes symbols representing: the boundaries of the study area; rivers and lakes (hydrography); the animals observed – snow leopards and argali (mountain sheep); and the routes along which the observations were presumably made. The distribution of animal symbols on the map allows for a visual assessment of the areas of concentration and spatial distribution of key fauna species – snow leopards and argali – within the Kakshaal-Too ridge.

The snow leopard (Fig. 3) is one of the rare and endangered species of animals. Body length: 100-130 cm; tail length: 80-100 cm; height at the withers: 60 cm; weight: 37-55 kg (males), 35-42 kg (females); lifespan: ≈11 years, up to 21 years in captivity; number of offspring: 2-3 kittens; lifestyle: solitary predator; diet: medium-sized ungulates (ibex, argali, roe deer, wild boar, etc.), small mammals (marmots), and birds (ulars, etc.); habitat: high-altitude steppes and rocky terrain from 600 to 5,800 m above sea level; population: total number approximately 4,000-6,400 individuals. As noted by J. Khatiwada *et al.* (2007), the total area of the historically established range of the snow leopard is about 2.2 million square kilometres, which is less than 2% of the total land area. This territory is located in the highlands and inaccessible areas of the world – the Himalayas, Tibet, Karakoram, Hindu Kush, Pamir, Pamir-Alai, Tian Shan, Altai and Sayan.

One of the prey species of the snow leopard is the Siberian ibex or mountain goat (Fig. 4), which inhabits steep mountain slopes with abundant rocks and scree at an altitude of 2,500-4,000 metres above sea level. Ibex graze on alpine meadows, hiding from danger in the rocks, and descend to lower slopes with less snow in winter (Justa & Lyngdoh, 2023). They live in small herds of 10-30 individuals, with adult males forming separate groups of up to 10 individuals and spending most of the year in the most inaccessible places, separate from the females. On summer days, mountain goats graze in the morning and evening hours, and during the hot part of the day, they spend time under the shelter of rocks on windy mountain ridges. Depending on the locality and weather conditions, the mating season for Siberian goats is in November or December and lasts 10 days or more. The gestation period is 170-180 days, with females giving birth to one or two kids in late May or June. Their lifespan in the wild is 15-20 years.

Figure 3. Snow leopard (*Panthera uncia*)
Source: authors' photo

Figure 4. Siberian ibex (*Capra sibirica*)
Source: authors' photo

One of the diseases diagnosed among Siberian ibex is larval alveococcosis of the liver. Larval or cystic alveococcosis is a naturally occurring focal disease of animals and humans caused by the cestode *Alveococcus multibocularis*. The sexually mature (tapeworm) stage of the alveococcus parasitises in the intestines of carnivores (foxes, dogs, wolves, jackals, etc.). According to J. Janecka *et al*. (2020), the larval form is more commonly found in the liver and other internal organs of animals and humans. The macroscopic larval form is a multi-chambered cyst consisting of a large number of small bubbles (alveoli) tightly packed together, containing fluid and the parasite's scolex (Bobdey *et al.*, 2023). The alveococcus bubble consists of a cuticular and germinative layer and hydatid fluid. The cuticular or protective layer is represented by hyaline, and the germinative layer is the source of the formation of excretory capsules with scolexes and a cuticular membrane. Alveococcus cysts develop primarily in the liver and then in other organs of the abdominal cavity. Exogenous growth of the lavrocyst (cyst) occurs through budding. The budded cysts penetrate the intercellular spaces and infiltrate the surrounding tissue. According to R. Pramod *et al*. (2021), the cells of the organ parenchyma are compressed, undergo dystrophy, atrophy and are gradually replaced by alveocytes. Alveococcal cysts metastasise to the lymph nodes, retroperitoneal tissue, lungs and brain. As the parasitic node grows, necrosis occurs in its centre due to insufficient blood circulation, and a capsule forms, which fills with a clear or cloudy fluid. The peripheral part of the node consists of actively multiplying parasite vesicles. The cavity of the vesicles contains a small amount of viscous fluid. When cut open, the parasitic node has a cellular structure with a cavity of decay in the centre. The larval form is represented by a conglomerate of small vesicles (parasitic node) connected by connective tissue and is characterised by exogenous reproduction and infiltrative growth (Ullah *et al.*, 2020).

Alveococcus is a biohelminth that develops by changing hosts. Its definitive hosts are carnivores: wolves, foxes, cats; and its intermediate hosts are wild rodents of the *Cricetidae family* (Vishnu *et al.*, 2024). A study by A. Lypska *et al*. (2023) also showed that rodents in natural populations can be carriers of multiple parasitic infections, including blood-borne zoonotic pathogens, which increases their epizootological significance in the circulation of pathogens between wild and domestic animals. The final host becomes infected by eating infected liver containing formed alveococcus vesicles with scolexes (Figs. 5, 6). Wild animals and humans suffer from natural focal diseases, with humans becoming infected during skinning, when eggs stuck to the fur get onto their hands and are carried into the mouth. Another route of human infection with is through the consumption of wild berries and herbs contaminated with the excrement of infected carnivorous animals.

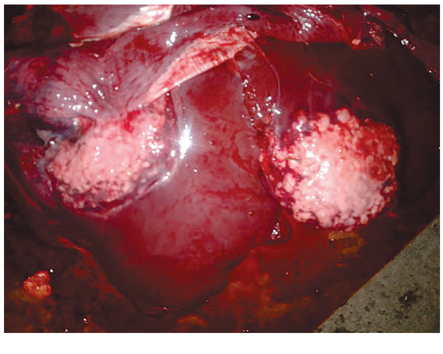

Figure 5. Alveococcosis, macro picture
Source: authors' photo

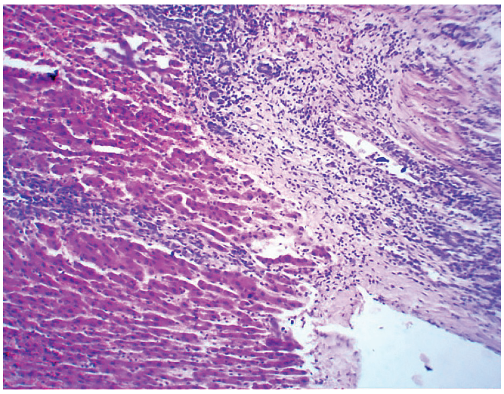

Figure 6. Alveococcosis, micrograph
Note: haematoxylin and eosin, 9×10
Source: authors' photo

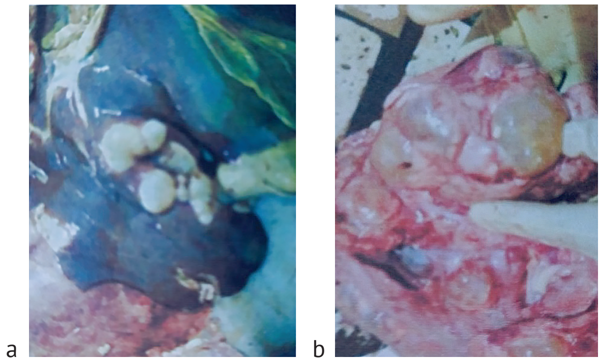

Figure 8. Larval echinococcosis in cattle
Note: the liver (a) and lungs (b) are affected by typical echinococcal cysts
Source: authors' photo

Another object in the snow leopard's food chain is the roe deer, a small, graceful deer with a relatively short body (Fig. 7). Its ears are long and pointed, and its tail is short and does not protrude from its fur. Its coat is single-coloured, bright red in summer and dull greyish in winter. Its body length is 150 cm, and it weighs up to 60 kg. Roe deer mate in August, and gestation lasts 4-4.5 months, resulting in 1-3 fawns.

Figure 7. Roe deer (*Capreolus capreolus*)
Source: authors' photo

Roe deer suffer from echinococcosis, which is carried by carnivores. Echinococcal cysts are round in shape and are most often found on the surface and in the thickness of the liver and lungs. Depending on the stage of the disease, the number of echinococcal cysts in the liver varied. The cysts are represented by a capsule containing a transparent fluid with a slightly yellowish tint (Fig. 8). The final stages of larval echinococcosis were accompanied by almost total organ damage, as indicated in the work of M. Bashari *et al.* (2018). The wall of the cyst consists of the following layers: the outer adventitial layer and the inner germinative layer.

Among roe deer, the lung disease mulleriosis was diagnosed (Fig. 9). Mulleriosis in animals, caused by *Mullerius capillaries*, belongs to the *Protostrongylidae* family and affects wild ruminants (Habib *et al.*, 2014). These are small, thin, separately hollow nematodes, almost indistinguishable to the naked eye against the background of the lungs. The lung tissues are involved in the pathological process, which is a pathological picture of chronic productive alveolitis. The affected areas of the lung have clear boundaries macroscopically and are coloured yellowish-grey. During invasion, numerous foci are scattered in various areas of the lungs, but mainly in the posterior lobes.

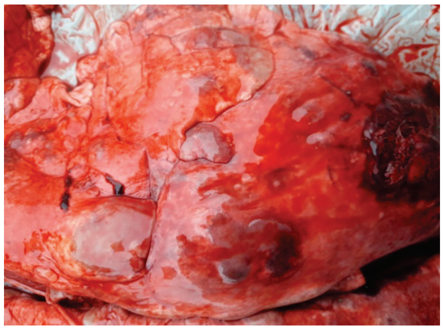

Figure 9. Macroscopic picture of muelleriosis
Source: authors' photo

At the same time, alveolar epithelial cells divide and multiply by amitotic and mitotic division. The process may begin with exudative phenomena, with the filling of the alveolar lumens with serous exudate. In such areas, the interalveolar septa are thin, and later they thicken noticeably due to lymphoid-histiocytic infiltration. Lymphoid cells, neutrophilic leukocytes, and histiocytes are mixed with desquamated epithelial cells in the alveolar lumens. Parasites that have reached sexual maturity, located in the bronchial branches or in the alveolar tissues, are localised in their lumens, where they lay eggs in the alveolar lumens and alveolar passages. Sexually mature parasites are found in areas bordering healthy tissue in the lumens of the alveoli or outside the foci of consolidation, among normal tissue (Fig. 10). Freshly laid eggs have unsegmented fine-grained cytoplasm and one large light nucleus. Subsequently, all stages of development can be seen in the sections, from the beginning of fragmentation into blastomeres to the formation of a finished larva inside the egg shell. In the areas where the eggs are located, the alveolar tissue, especially the alveolar septa, thins, becomes thread-like, disappears, and cavities of various sizes may form as a result of the fusion of adjacent alveoli filled with eggs or larvae.

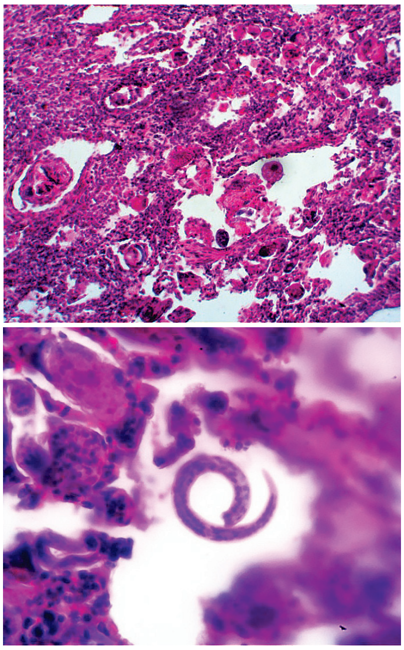

Figure 10. Paraffin section of the lungs – muellerian invasion in a roe deer
Note: staining – haematoxylin and eosin, ×90
Source: authors' photo

The pathological process involves the small bronchial branches, where catarrhal bronchitis initially develops. The bronchial lumens contain mucus, desquamated epithelial cells, and leukocytes. The number of goblet cells in the epithelial lining of the mucous membrane increases. Changes are observed in the walls of the small bronchi in the form of thickening. The epithelial layer of the mucous membrane hyperplasiates and papillary protrusions form in the lumen of the bronchi, where the base of the mucous membrane is infiltrated by lymphoid-histiocytic elements, later fibroblasts. The lumens of the bronchi become slit-like, and the layers of peribronchial tissue gradually expand and become infiltrated with cellular elements, mainly lymphoid cells. The lumens of the alveoli are filled with the bodies of sexually mature parasites, and the epithelial lining is compressed and atrophied. The pulmonary pleura and interlobular connective tissue septa are involved in the pathological process. They thicken and undergo severe sclerotic changes. In other areas of the lung parenchyma, proliferative changes develop, leading to thickening of the interalveolar septa due to cell proliferation consisting of lymphoid and histiocytic elements. Later, fibroblasts, collagen fibres and a small number of plasma cells appear. In the affected areas, the thickening of the alveolar septa is due to the growth of thick smooth muscle bundles, while the alveolar lumens narrow or disappear completely, and areas replaced by collagen and smooth muscle cells appear.

Another object of the snow leopard's food chain is the mountain sheep (*Ovis ammon*) – a very beautiful, slender animal, light in build, with long legs and a high head (Fig. 11). Its horns are beautifully curved, sometimes very large. The colouring of the sides and back is solid yellow or brown-grey in various shades. Mountain sheep are 120-130 cm tall at the withers and weigh 200-220 kg. These animals prefer vast open spaces with gently rolling terrain and gentle mountain slopes. In summer, adult males form separate herds and keep away from females. Gestation lasts 155-170 days, and from April to May, females give birth to 1 or 2 lambs.

Figure 11. Argali (*Ovis ammon*)
Source: authors' photo

During the pathological autopsy of a mountain sheep that had been culled for sanitary reasons, pathological changes were found on the serous membranes. A translucent oval-shaped bubble on a thin stalk was found under the peritoneum. The bubble was filled with a clear fluid in which a floating scolex was visible. This bubble is a thin-necked cysticercosis, which is the outer serous membrane of the host and the scolex's own membrane (Fig. 12). The snow leopard, eating such animals, becomes the definitive host, where a tapeworm begins to develop in its intestines, which has a head with suckers, a neck and a body. The body or tapeworm reaches 1.5-5 m and as the segments mature, they fall off, are excreted with faeces, contaminate the soil, grass and water, and the parasite's eggs are swallowed with the food of herbivorous animals. The causative agent is the cystic stage of the cestode *Taenia hydatigena*, which lives in the small intestine of carnivores (wolves, jackals). The sexually mature parasite reaches a length of 2 m, its scolex has 4 suckers and is armed with 32-44 hooks arranged in two rows. The thin-necked cysticercus is a bubble filled with a colourless liquid, oval in shape, up to the size of a goose egg, hanging down like a bubble. When the shell is cut open, the parasite, which has a long thin neck, a tail bubble and a scolex, is easily squeezed out of the bubble.

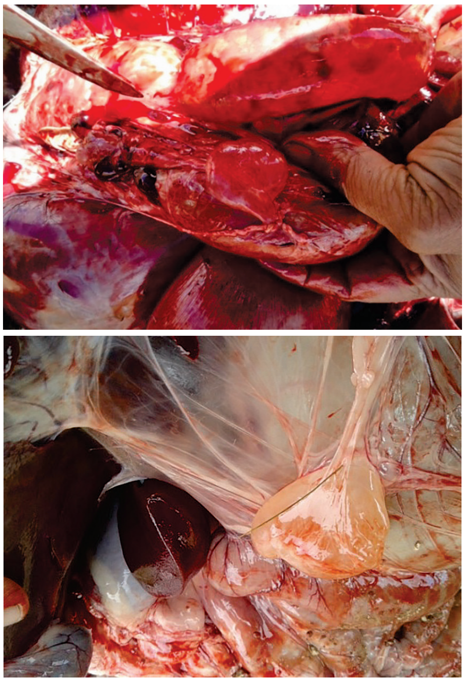

Figure 12. Thin-necked cysticercosis, macro picture
Source: authors' photo

The morphofunctional state of the thymus is expressed by its lobular structure and specific mass. Each lobe of the thymus is represented by cortical and medullary substance in different proportions in different lobules. The lobules are in different morphofunctional states. In the subcapsular zone, blast transformation and thymoblast proliferation are observed, and in most lobules of the thymus, the boundary between the cortical and medullary substances is blurred. In some lobules, small and large Gassall's cells with calcifications are found in the medullary layer (Fig. 13). Clusters of labrocytes, lymphocytes, and macrophages are observed, as well as products of cell breakdown. Blood vessels are hyperemic. Lymphoid cells in mitosis are found in the cortical substance and sporadically in the medullary substance.

The morphofunctional state of a lymph node is the cortical zone or cluster of lymphatic follicles, or the B-dependent zone and paracortical zone, or the T-dependent zone and medulla. The histological picture showed that the structure of the lymphatic follicle centres of the lymph nodes was destroyed, with a large accumulation of blood and haemorrhages. Hyperplasia of the B-dependent zone was noted (Fig. 14).

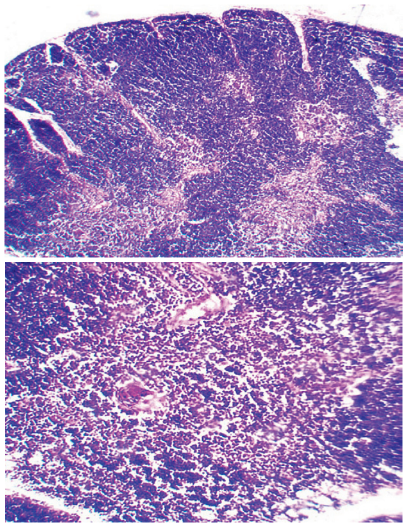

Figure 13. Thymus gland of a roe deer with Müllerian invasion
Note: staining – haematoxylin and eosin, ×90
Source: authors' photo

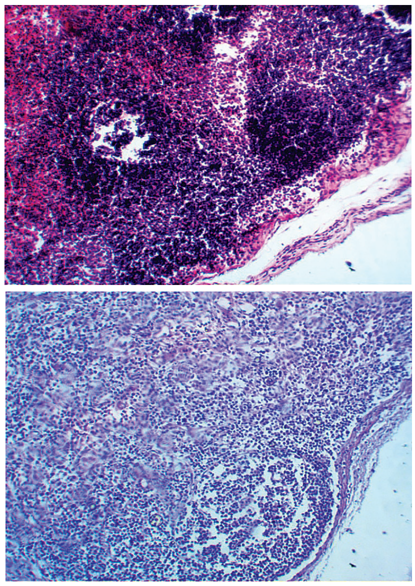

Figure 14. Paraffin section of a lymph node
Note: staining – haematoxylin and eosin, ×90
Source: authors' photo

The spleen is similar in structure to the histological structure of other animal species, where a distinction is made between white and red pulp. In roe deer, in this case, it stands out in the form of lymphonodules, the B-dependent zone, while the T-dependent zone is poorly developed and is detected near the central vessels. The red pulp is abundantly injected with blood, and hyperplasia of B-dependent zones is observed in the white pulp. The red pulp of the spleen is represented by a large number of erythrocytes, T- and B-lymphocytes, and macrophages. Cells in mitosis are found. Macrophages are located in large numbers around the white pulp and in smaller numbers in the red pulp and sinuses. Apoptosis occurs in both the white and red pulp of the spleen (Fig. 15a). In the white pulp of the spleen, T- and B-dependent zones are distinguished, where T-dependent zones of the white pulp are represented by T-lymphocytes. The central artery of the lymphoid follicles is located eccentrically. Lymphoid formations with light centres have clearly defined centres of lymphoid follicles. The mantle zone is clearly distinguished by the dense arrangement of B and T lymphocytes, plasma cells, and macrophages. Lymphoid follicles without light centres are distinguished by the loose arrangement of B lymphocytes, and the zones are not distinguished. Mitosis of blast cells is rare (Fig. 15b).

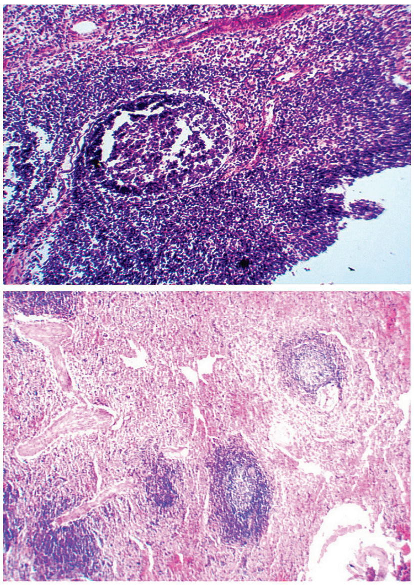
a
b

Figure 15. Paraffin section of the spleen
Note: staining – haematoxylin and eosin, ×90
Source: authors' photo

Analysis of data on the morphology and functional state of the organ allows for concluding that the condition of the white pulp of the spleen corresponds to a state of relative rest and moderate functioning. A large number of red blood cells in the organ is evidence of the highest degree of depositing function. Larvae, entering the roe deer's intestines with food and water, penetrate the submucosal layer of the intestines and, together with the chyme, enter the lymph, reach the large thoracic duct and, with the lymph, penetrate the blood of the small circle of blood circulation and, through the walls of the capillaries, enter the small bronchi, provoking bronchopneumonia. Histological sections stained with haematoxylin and eosin reveal eggs, larvae and sexually mature forms of the pathogens, which are localised in the small bronchi, alveolar passages and alveoli. Focal, diffuse lymphoid, histiocytic, and plasma cell infiltrates are observed in the bronchial walls and peribronchially.

The described morphological structural changes in the primary and secondary organs of immunogenesis in wild cloven-hoofed animals (Siberian ibex, argali, and roe deer) in invasive diseases (alveococcosis, muelleriosis, and cysticercosis) revealed functional tension in the above-mentioned organs of the immune system. This manifested itself in the form of cellular infiltrates, where the number of plasma cells, clusters of macrophages, small lymphocytes, neutrophilocytes, and fibroblasts increased, and where the effectiveness of immunity depended on the coordinated interaction of cellular and humoral immunity (Vishnu *et al.*, 2024). The morphological picture was revealed by the depletion of light centres in the secondary organs of immunogenesis, which indicated a sharp decline not only in the body's immune reactivity, but also in other vital processes. A deficient state arose in the thymus, characterised by morphological changes in secondary organs of immunogenesis in the form of increased proliferation in the B-dependent zone, which is associated with the endocrine system and central nervous system controlling the homeostasis of the animal organism.

In conclusion, it should be noted that anthropogenic factors such as an increase in livestock numbers and degradation of grazing lands, as well as climate change, have a negative impact on the snow leopard's food supply and habitat. M. Bashari *et al.* (2018) emphasised that direct and indirect human impact on the snow leopard's range and food supply is changing the snow leopard's lifestyle. This is also evidenced by a number of examples from the Kyrgyz Republic. In 2020 alone, there were three recorded incidents involving snow leopards descending from the highlands to populated areas. In January 2020, the Department for Biodiversity Conservation and Specially Protected Natural Areas reported the discovery of a snow leopard in the village of Kok-Oy (600-800 m above sea level) in the Talas region. Employees of the Bars Group travelled to the site together with a veterinarian. At the examination site, NABU veterinarian B. Azhybekov assessed the predator's health as critical. After discussing the issue with representatives of state authorities, it was decided to transport the snow leopard to the NABU office in Bishkek. An X-ray of the snow leopard showed that the animal had been shot in the head. A council of veterinarians decided to perform emergency surgery. At present, the leopard's life is not in danger, and it is recovering.

Second example: on 10 January 2020, information was received from a hunting expert in the Zhumgal district of the Naryn region about the discovery of a snow leopard in a shepherd's barn in one of the winter areas (1,800-2,000 metres above sea level). The "Bars Group" immediately left for the Zhugals district of the Naryn region. Upon arrival in the Zhugaly district, the hunting expert showed the snow leopard and drew up a transfer report. After these activities, the snow leopard was taken to the NABU office in Bishkek, where, in agreement with the state authorities, it was decided to deliver the snow leopard to the NABU rehabilitation centre.

Third example: in May 2020, a snow leopard was brought to the rehabilitation centre from the village of Emgek Talaa in the Naryn region (Teskey Torpu, 1,700-1,800 m above sea level). It was brought by the director of the "Ysyq-Köl" biosphere territory, T. Asykulov. The snow leopard was in serious condition and unable to move. Upon examination, it was found that its right eye was damaged and there was a wound on its front paw. The snow leopard brought from the Naryn region was examined by a veterinarian, who noted that the animal was in a state of stress and prescribed the necessary treatment. The snow leopard was given the nickname Tenteq and sent to the NABU rehabilitation centre. The rescued snow leopards caused a public outcry. In the same year, a gamekeeper from the Kara-Buurinsky district of the Talas region reported that he was keeping an argali lamb in his barn. After notifying government officials in advance, the commission decided on the future fate of the red-listed animal. These examples show that anthropogenic factors are severely disrupting the snow leopard's habitat, which is closely linked to climate change. The preservation of the snow leopard population is influenced not only by anthropogenic factors in the habitat, but also by diseases of wild animals, not only of an infectious and invasive nature, but also, in this case, alveococcosis, muelleriosis, cysticercosis and other parasitic diseases.

Conclusions

Studies of wild ungulates – Siberian ibex, roe deer and argali, which constitute the food base of the snow leopard in the highlands of Kyrgyzstan – have revealed a significant prevalence of invasive diseases. Pathological and parasitological studies diagnosed helminthiasis such as alveococcosis, echinococcosis, muelleriosis, and cysticercosis. The most significant result is a detailed description of the specific immunomorphological response of the organs of immunogenesis to these invasions. Characteristic changes were observed in the primary organs (thymus) and secondary organs (spleen, lymph nodes) of infected animals: hyperplasia of lymphoid tissue, an increase in the number and size of germinative centres in lymphoid follicles, and significant plasmacytic infiltration, indicating a strong humoral immune response. The intensity and nature of morphological changes directly correlated with the type of pathogen and the intensity of invasion. For example, in echinococcosis, the formation of a pronounced fibrous capsule around parasitic cysts was recorded, while in muelleriosis, a cellular reaction prevailed. The data obtained, including specific pathological indices and histological descriptions, are of fundamental importance for understanding the pathogenesis of helminthiasis in wild ungulates and serve as a scientific basis for the development of practical measures. Based on these data, effective preventive measures can be developed to preserve wild fauna populations and reduce the risk of pathogen circulation in high-altitude ecosystems. Prospects for further research include conducting monitoring studies to assess the dynamics of disease incidence, studying the role of the snow leopard as the definitive host in the development cycle of cestodiasis, as well as in-depth immunohistochemical analysis to identify subpopulations of immunocompetent cells involved in the formation of the immune response.

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Conflict of Interest

None.

References

[1] Ale, S.B. (2007). *Ecology of the snow leopard and the Himalayan tahr in Sagarmatha (Mt. Everest) National Park, Nepal*. Chicago: University of Illinois at Chicago.

[2] Ashokumar, S. (2023). The threat of poaching on biodiversity and the environment. *Indian Journal of Law and Legal Research*, 5(2).

[3] Bar, H. (2021). COVID-19 lockdown: Animal life, ecosystem and atmospheric environment. *Environment, Development and Sustainability*, 23, 8161-8178. doi: 10.1007/s10668-020-01002-7.

[4] Bashari, M., Sills, E., Peterson, M.N., & Cubbage, F. (2018). Hunting in Afghanistan: Variation in motivations across species. *Oryx*, 52(3), 526-536. doi: 10.1017/S0030605316001174.

[5] Bobdey, A., Tewari, U., Srivastava, A., & Ramteke, P. (2023). *Wildlife ecology: Management and conservation*. Bhopal: AGPH Books.

[6] Chrétien, E., *et al*. (2023). Few studies of wild animal performance account for parasite infections: A systematic review. *Journal of Animal Ecology*, 92, 794-806. doi: 10.1111/1365-2656.13864.
[7] Eckert, J., Gemmell, M.A., Meslin, F., & Pawłowski, Z.S. (Eds.). (2001). *WHO/OIE Manual on echinococcosis in humans and animals*. Geneva: World Health Organization.
[8] Esson, C., *et al*. (2019). Health and zoonotic infections of snow leopards *Panthera unica* in the South Gobi desert of Mongolia. *Infection Ecology & Epidemiology*, 9(1), article number 1604063. doi: 10.1080/20008686.2019.1604063.
[9] Guidelines for Wildlife Research issued by the Wildlife Research Center of Kyoto University. (2022). Retrieved from https://www.wrc.kyoto-u.ac.jp/en/guidelines/wild.html.
[10] Habib, B., Gopi, G.V., Noor, A., & Mir, Z.R. (2014). *Ecology of leopard Panthera pardus in relation to prey abundance and land use pattern in Kashmir Valley*. New Delhi: Department of Science and Technology, Government of India.
[11] Huynh, T., McKean, E.L., & Hawdon, J.M. (2022). Mini-Baermann funnel, a simple device for cleaning nematode infective larvae. *The Journal of Parasitology*, 108(4), 403-407. doi: 10.1645/22-47.
[12] Janecka, J.E., *et al*. (2020). Noninvasive genetics and genomics shed light on the status, phylogeography, and evolution of the elusive snow leopard. In J. Ortega & J.E. Maldonado (Eds.), *Conservation genetics in mammals: Integrative research using novel approaches* (pp. 83-120). Cham: Springer. doi: 10.1007/978-3-030-33334-8_5.
[13] Justa, P., & Lyngdoh, S. (2023). Understanding carnivore interactions in a cold arid trans-Himalayan landscape: What drives co-existence patterns within predator guild along varying resource gradients? *Ecology and Evolution*, 13(5), article number e10040. doi: 10.1002/ece3.10040.
[14] Khatiwada, J.R., Chalise, M.K., & Kyes, R.C. (2007). *Survey of snow leopard (Uncia uncia) and blue sheep (Pseudois nayaur) populations in the Kangchenjunga Conservation Area (KCA), Nepal*. Seattle: International Snow Leopard Trust.
[15] Luo, M., Xu, L., Qian, Z., & Sun, X. (2021). Infection-associated thymic atrophy. *Frontiers in Immunology*, 12, article number 652538. doi: 10.3389/fimmu.2021.652538.
[16] Lypska, A., Semenko, O., Boyko, O., Ishiniwa, H., & Galat, G. (2023). The role of mouse-like rodents in the Chornobyl Exclusion Zone in the spread of blood-borne diseases. *Ukrainian Journal of Veterinary Sciences*, 14(3), 100-113. doi: 10.31548/veterinary3.2023.100.
[17] Osborne, M.P., & Laird, J. (2022). *Snow leopards and other wild cats* (Vol. 44). New York: Random House Books for Young Readers.
[18] Ostrowski, S., & Gilbert, M. (2024). Diseases of wild snow leopards and their wild ungulate prey. In D. Mallon & T. Mccarthy (Eds.), *Snow leopards* (2nd ed., pp. 95-111). Oxford: Academic Press. doi: 10.1016/B978-0-323-85775-8.00050-9.
[19] Pramod, R.K., Nair, A.V., Tambare, P.K., Chauhan, K., Kumar, T.V., Rajan, R.A., Mani, B.M., Asaf, M., & Pandey, A.K. (2021). Reverse zoonosis of coronavirus disease-19: Present status and the control by one health approach. *Veterinary World*, 14(10), 2817-2826. doi: 10.14202/vetworld.2021.2817-2826.
[20] Schaller, G.B. (2012). The snow leopard. In *Tibet wild: A naturalist's journeys on the roof of the world* (pp. 325-356). Washington, DC: Island Press/Center for Resource Economics. doi: 10.5822/978-1-61091-232-7_15.
[21] Shao, X., Lu, Q., Xiong, M., Bu, H., Shi, X., Wang, D., Zhao, J., Li, S., & Yao, M. (2021). Prey partitioning and livestock consumption in the world's richest large carnivore assemblage. *Current Biology*, 31(22), 4887-4897.
[22] Shao, X., Song, D., Huang, Q., Li, S., & Yao, M. (2019). Fast surveys and molecular diet analysis of carnivores based on fecal DNA and metabarcoding. *Biodiversity Science*, 27(5), 543-556. doi: 10.17520/biods.2018214.
[23] Tetzloff, J., & Schwartz, K.R. (2024). Role of zoos in snow leopard conservation: The Species Survival Plan® in North America. In D. Mallon & T. Mccarthy (Eds.), *Snow leopards* (2nd ed., pp. 333-346). Oxford: Academic Press. doi: 10.1016/B978-0-323-85775-8.00020-0.
[24] The Nature and Biodiversity Conservation Union (NABU). (n.d.). Retrieved from https://en.nabu.de/index.html.
[25] Ullah, Z., Ullah, I., Ullah, I., Mahmood, S., & Iqbal, Z. (2020). Poaching of Asiatic black bear: Evidence from Siran and Kaghan valleys, Pakistan. *Global Ecology and Conservation*, 24, article number e01351. doi: 10.1016/j.gecco.2020.e01351.
[26] Vishnu, O., Pandiyan, J., Balan, A., Jose, C.P., & Roshnath, R. (2024). Domestic dogs and vultures feed on the same carcasses in Wayanad Wildlife Sanctuary, Kerala, India. *Biotropica*, 56(6), article number e13377. doi: 10.1111/btp.13377.
[27] Weiskopf, S.R., Kachel, S.M., & McCarthy, K.P. (2016). What are snow leopards really eating? Identifying bias in food-habit studies. *Wildlife Society Bulletin*, 40(2), 233-240. doi: 10.1002/wsb.640.

Бийик тоолуу Тянь-Шандагы илбирстердин азыктануу чынжыры, жаныбарлардын жана канаттуулардын ылаңдары

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Аннотация. Ак илбирс – жоголуу коркунучунда турган жана Кыргыз Республикасынын Кызыл китебине киргизилген сейрек кездешүүчү жана аялуу жаныбар болуп саналат. Ал Тянь-Шандын жетүүгө кыйын бийик тоолуу райондорунда жашайт, ал жерде экологиялык тең салмактуулук анын азык тизмегин түзгөн фаунанын абалына түздөн-түз көз каранды. Акыркы жылдары жапайы жана үй жаныбарлары арасында оорулардын көбөйүшү байкалууда, бул ак илбирстин популяциясынын абалына жана жалпысынан экосистеманын туруктуулугуна таасирин тийгизиши мүмкүн. Бул иштин максаты ак илбирстин азык тизмегине кирген сүт эмүүчүлөрдүн мите ооруларын изилдөө, алардын биологиялык өзгөчөлүктөрүн, булгануу булактарын жана тоолуу райондордогу эпизоотиялык кырдаалга таасирин аныктоо болуп саналат. Изилдөөнүн жүрүшүндө талаалык байкоолордун, гельминтологиялык аутопсиялардын, биоматериалдын микроскопиялык анализинин, ветеринардык изилдөөлөрдүн маалыматтарынын салыштырма морфологиялык жана сыпаттама анализинин методдору пайдаланылды. Натыйжада, аныкталган мите ооруларынын ичинен эң чоң эпидемиологиялык мааниси жапайы жана үй жаныбарлары үчүн олуттуу коркунуч туудурган альвеококкоз жана мюллериоз экендиги аныкталды. Альвеококкоздун козгогучу боорго таасир этүүчү жана инфильтративдик өсүүгө жана метастазга жөндөмдүү бир нече кистикалык мите түйүндөрүнүн пайда болушуна алып келүүчү лентанын личинка стадиясы болуп саналат. Бул митенин акыркы кожоюндары жырткычтар (иттер, мышыктар, карышкырлар, түлкүлөр, манулалар ж.б.), ал эми ортодогу майда жапайы кемирүүчүлөр. Ошондой эле патоген эчкилерде, койлордо жана жапайы кепшөөчүлөрдө өпкөнүн жабыркашын шарттайт, бул продуктивдүү альвеолиттин көп очоктору жана жаныбарлардын жалпы каршылыгынын төмөндөшү менен көрүнөт. Патогендердин биологиялык жана экологиялык өзгөчөлүктөрүн комплекстүү талдоо жаратылыш шарттарында алардын айлануу жолдорун жана адам үчүн мүмкүн болуучу тобокелдиктерди баалоого мүмкүндүк берет. Изилдөөнүн практикалык мааниси сейрек кездешүүчү жырткычтарды коргоого жана Кыргызстандын бийик тоолуу экосистемаларынын эпизоотиялык бейпилдигин турукташтырууга багытталган алдын алуу жана диагностикалык иш-чаралардын системасын иштеп чыгууда алынган маалыматтарды пайдалануу мүмкүндүгүндө турат

Негизги сөздөр: сибирь текеси; аркарлар; эликтер; альвеококкоз; мюллериоз; цистицеркоз

Болезни животных и птиц – пищевой цепи снежного барса в высокогорьях Тянь-Шаня

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Аннотация. Снежный барс (*Panthera uncia*) является редким и уязвимым видом, находящимся под угрозой исчезновения и занесенным в Красную книгу Кыргызской Республики. Он обитает в труднодоступных высокогорных районах Тянь-Шаня, где экологическое равновесие напрямую зависит от состояния фауны, составляющей его пищевую цепь. В последние годы наблюдается рост числа заболеваний среди диких и домашних животных, что может оказывать влияние на здоровье популяции снежного барса и устойчивость экосистемы в целом. Целью настоящей работы было исследование паразитарных заболеваний млекопитающих, входящих в пищевую цепь снежного барса, с определением их биологических особенностей, источников заражения и влияния на эпизоотическую ситуацию в горных районах. В ходе исследования использованы методы полевых наблюдений, гельминтологических вскрытий, микроскопического анализа биоматериала, сравнительного морфологического и описательного анализа данных ветеринарных исследований. В результате установлено, что наибольшее эпидемиологическое значение среди выявленных паразитарных заболеваний имеют альвеококкоз и мюллериоз, представляющие серьезную опасность как для диких, так и для домашних животных. Возбудителем альвеококкоза является личиночная стадия цепня *Alveococcus multilocularis*, поражающая печень и вызывающая образование множественных кистозных паразитарных узлов, способных к инфильтративному росту и метастазированию. Конечными хозяевами данного паразита выступают плотоядные животные (собаки, кошки, волки, лисицы, манулы и др.), а промежуточными – мелкие дикие грызуны. Установлено также, что возбудитель *Mullerius capillaris* вызывает поражения легких у коз, овец и диких жвачных, что проявляется множественными очагами продуктивного альвеолита и снижением общей резистентности животных. Комплексный анализ биологических и экологических особенностей возбудителей позволяет оценить пути их циркуляции в природных условиях и потенциальные риски для человека. Практическая значимость исследования заключается в возможности использования полученных данных при разработке системы профилактических и диагностических мероприятий, направленных на охрану редких хищников и стабилизацию эпизоотического благополучия высокогорных экосистем Кыргызстана

Ключевые слова: сибирский козерог; архар; косули; альвеококкоз; мюллериоз; цистицеркоз

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Promising varieties of fruit crops of local and introduced selection in Kazakhstan

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Abstract. The article presented the results of many years of research by the Kazakh Scientific Research Institute of Fruit and Vegetable Growing LLP on the study and improvement of apple and pear varieties. The relevance of the work is due to the need to increase the adaptability, yield and quality of fruit production in the south and south-east of Kazakhstan. The study was aimed at the agrobiological evaluation of local and introduced varieties in order to identify the most promising forms for intensive horticulture. Over the past 20 years, 97 apple varieties and 25 pear varieties have been submitted for state variety testing, and more than 70 new varieties have been added to the institute's gene pool, including 'Honeycrisp', 'Champion', 'Red Chief', 'Pink Lady', 'Samurlet', 'Lyra', 'Muratovskaya' and others. The research was conducted in 2022-2024 in the climatic conditions of the south and south-east of the republic. The evaluation was based on a number of economically valuable characteristics: early fruiting, yield, adaptability, fruit shelf life, resistance to diseases (scab, powdery mildew, bacterial burn) and pests. As a result, varieties with the highest degree of adaptability, stable productivity (up to 550 cwt/ha), high taste qualities and suitability for storage were selected. The article contains characteristics of 12 apple varieties and 10 pear varieties, including data on biological and economic indicators. The practical significance of the work lies in the possibility of using the results obtained when planting industrial orchards and optimising the variety composition in regions with similar growing conditions

Keywords: winter hardiness; yield; adaptability; apple tree; pear tree; disease resistance

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Introduction

The natural and climatic conditions of southern and south-eastern Kazakhstan create favourable conditions for the development of industrial horticulture, especially for the cultivation of pome fruits. Fertile soils, a developed irrigation network and active temperatures ranging from 2,600 to 4,000°C allow for the successful cultivation of varieties of different origins and ripening times. Apple and pear trees occupy a leading place in the structure of fruit plantations in the republic, providing the main share of commercial production and playing an important role in the country's food security. In recent decades, breeding institutions in Kazakhstan, including the Kazakh Scientific Research Institute of Fruit and Vegetable Growing (KazNIIPO), have been actively working to expand and improve the assortment by introducing varieties from the United States, Canada, Australia, the Czech Republic, Russia and other countries. The institute's gene pool includes more than 1,800 samples collected from regions with different climatic conditions, which serves as the basis for adapting new varieties to the specifics of the southern regions of Kazakhstan. The study of wild species growing in Central Asia plays an important role in expanding the genetic diversity of fruit crops. Research by U. Manapkanova *et al*. (2025) on the genetic diversity of wild cherry species in Kazakhstan and Uzbekistan revealed a high level of intraspecific variability and the presence of hybrid forms with valuable drought and frost resistance traits, which is of considerable interest for breeding programmes. As noted by R. Sestras & A. Sestras (2023), intensive horticulture places increased demands on the varieties used. These include high yield, resistance to major diseases (scab, powdery mildew, bacterial burn), long shelf life of fruits, high commercial and taste characteristics, as well as adaptability to local soil and climatic conditions.

The development of fruit growing as a priority sector of the agro-industrial complex of the Republic of Kazakhstan largely depends on the scientifically based formation of the varietal composition of fruit crops. Given the long-term nature of apple and pear trees, mistakes in the selection of varieties can reduce the productivity of plantations over 20-25 years of operation, resulting in significant economic losses (Sviridova & Vlasov, 2019). Therefore, as noted by A. Smykov (2020), one of the most important areas of breeding work is the effective use of the gene pool of fruit crops and its constant enrichment with promising forms adapted to the soil and climatic conditions of the region. Fruit quality is a key indicator determining the commercial attractiveness of a variety on the market. Studies show that, along with the biological characteristics of plant growth and development, resistance to stress factors and productivity, the commercial characteristics of fruit – weight, size, shape, colour and taste – are the most stable varietal traits (Havryliuk *et al*., 2022; Du *et al*., 2025; Ghonimy *et al*., 2025). Modern domestic and foreign market requirements dictate the need to grow varieties with high organoleptic characteristics and attractive appearance. Recent studies emphasise the importance of using molecular markers and genetic certification in the selection of breeding material. The work of Y. Yefremova *et al*. (2023) shows that marker-assisted selection (MAS) significantly accelerates the process of breeding varieties resistant to *Plasmopara viticola*, scab and other stressors. These approaches are particularly relevant in the context of climate change and for Kazakhstan, where it is necessary to create adaptive forms with complex resistance to abiotic and biotic environmental factors.

The aim of this study was to conduct a comprehensive agrobiological assessment of promising apple and pear varieties of local and introduced selection in the conditions of southern and south-eastern Kazakhstan in order to identify the most productive and adapted forms suitable for introduction into industrial production and further use in breeding programmes to create new competitive varieties.

Materials and Methods

Field studies were conducted in 2022-2024 at the experimental site of the Talgar Regional Branch of KazNIIPO LLP (Almaty Region, Talgar District, Almalyk Village, Kazakhstan), located in the foothills of the Zailiyskiy Alatau at an altitude of 1,070 m above sea level. The soils of the site are grey-brown, loamy, with a pH level of 7.1-7.3, humus content of 2.1-2.3%, and average mobile phosphorus and potassium content.

Research subjects:

- Apple tree (11 varieties): 'Voskhod', 'Makpal', 'Anel', 'Damira', 'Aizere', 'Dauren', 'Samurlet', 'Champion', 'Pink Lady', 'Honeycrisp', 'Red Chief'. Year of planting – 2011, planting pattern 5×3 m, rootstock – Arm-18. Control variety – 'Golden Delicious'.
- Pear (9 varieties): 'Aydana', 'Bostandyk', 'Nagima', 'Karyndas', 'Lyra', 'Harrow Sweet', 'Muratovskaya', 'Kyrgyzskaya Zimnyaya', 'Prosto Maria'. Year of planting – 2010, planting pattern 5×3 m, rootstock – EMA. Control variety – 'Talgar Beauty'.

The experiment was laid out using the Randomised Complete Block Design method in three replicates. Each replicate consisted of 5 trees of each variety (15 trees per variety in total). The variants were arranged in strips, taking into account the prevailing wind direction. Studies were conducted in accordance with the methodological guidelines of E. Sedov & T. Ogoltsova (1999). The following characteristics were taken into account: 1. Winter hardiness – based on the degree of freezing of wood, cambium and generative buds after natural overwintering, visually on a damage scale (1-5 points), as well as in the laboratory (after forced freezing and staining of the cambium with a tetrazolium solution). 2. Disease resistance (scab, powdery mildew) – visual assessment of the degree of damage to leaves and fruits on a 5-point scale during the growing season (Mavlyanova, 2015). 3. Yield – recorded in kilograms per tree and converted to hectares using formula (1):

$$Y = (M \times N \times 10{,}000) / (S \times n), \qquad (1)$$

where M is the average yield per tree, N is the number of trees per hectare, S is the area between rows and within rows, and n is the number of trees counted.

The quality of the fruit was determined organoleptically (appearance, taste, aroma, juiciness) on a 5-point scale; the weight of a single fruit, dry matter content (refractometrically), titratable acidity, vitamin C content (by iodometry) (Gritsenko *et al.*, 2022). In Table 1, the characteristics of the fruit included weight and taste qualities, determined on the basis of organoleptic tasting on a 5-point scale. The weight of the fruit was indicated in grams as the average value for a sample of 10-20 fruits, with an accuracy of 5 g. Taste was assessed based on a combination of characteristics such as sweetness, acidity, aroma and juiciness. Average yield was expressed in centners per hectare (c/ha) and was calculated based on data for 2022-2024 from experimental plots, converted to 1 hectare. The shelf life of the fruit reflected the duration of their storage at a temperature of 0...+2°C and a humidity of 85-90%, until they lost their marketable appearance and taste. The NSR05 indicator (the smallest significant difference at a significance level of 5%) was used to assess the reliability of differences between varieties in terms of yield. Drought resistance was determined by the water-holding capacity of the leaves, water deficit and turgor recovery according to the method of S. Temirbekova *et al.* (2023).

Intensive cultivation techniques included spindle-shaped pruning, drip irrigation, gentle pruning, mineral nutrition according to growth stages, and inter-row mulching. The results were processed using analysis of variance (ANOVA) with the NSR05 criterion (smallest significant difference) to determine the reliability of differences between variants. The processing was carried out using Statistica 13.0 and Excel 2016 software. The significance threshold was $p < 0.05$. The study was conducted in accordance with the ethical principles of the Convention on Biological Diversity (1992) and the Convention on International Trade... (2000). The involvement of experts for organoleptic evaluation complied with the ethical standards of the WMA Declaration of Helsinki (1964).

Results and Discussion

As a result of many years of breeding work by KazNIIPO LLP, 97 apple varieties and 25 pear varieties were submitted for state variety testing. Of these, 27 apple varieties and 3 pear varieties were included in the State Register of Breeding Achievements Approved for Use in the Republic of Kazakhstan. Over the past 20 years, as part of the introduction programme, about 50 foreign apple varieties have been tested and introduced, including 'Honeycrisp', 'Champion', 'Red Chief', 'Pink Lady', 'Samurlet', 'Quinte', 'Jenny Grant', and others. Twenty-one pear varieties have been introduced, including 'Lyra', 'Yesenevskaya', 'Muratovskaya', 'Cheremshina', 'Vrodliva', 'Claude Sablin', 'Williams', and others. Table 1 presents the production and biological characteristics of promising apple and pear varieties, both locally bred (KazNIIPO LLP) and adapted varieties from other countries, based on data for 2022-2024.

Table 1. Key indicators for promising fruit crop varieties of local and introduced selection (average values for 2022-2024)

Variety name	Ripening period	Fruit quality		Average yield (centners per hectare)	Fruit shelf life
		foetal weight (g)	fruit flavour, points		
Apple tree					
'Anel'	summer-autumn	210	4.8	240	until December
'Voskhod'	winter	260	5.0	220	until April
'Makpal'	winter	205	4.7	230	until April
'Damira'	winter	225	5.0	195	until April
'Aizere'	winter	220	5.0	210	until April
'Dauren'	winter	270	4.8	200	until May
'Pink Lady'	winter	200	4.7	500	until June
'Samurlet'	late summer	210	4.6	350	until January
'Champion'	winter	220	4.6	350	until February
'Honeycrisp'	winter	250	4.8	550	until April
'Red Chief'	winter	210	4.8	550	until March
'Golden Delicious'	winter	180	4.5	160	until May
HCP_{05}				17.0	
Pear					
'Nagima'	autumnal	190	4.8	180	until December
'Karyndas'	autumnal	170	4.5	160	until January
'Bostandyk'	winter	170	4.4	170	until December
'Aydana'	winter	150	4.3	160	until December
'Prosto Maria'	winter	230	4.5	200	until December

Table 1. Continued

Variety name	Ripening period	Fruit quality		Average yield (centners per hectare)	Fruit shelf life
		foetal weight (g)	fruit flavour, points		
Pear					
'Lyra'	winter	205	4.3	175	until December
'Harrow Sweet'	winter	210-450	4.7	205	until December
'Kyrgyzskaya Zimnyaya'	winter	210	4.0	170	until April
'Muratovskaya'	autumnal	180	4.3	–	until November
'Talgar Beauty'	winter	179	4.5	150	until February
HCP_{05}				12.0	

Note: NSR05 – the smallest significant difference at a significance level of 5%; the lack of yield in the 'Muratovskaya' variety is due to insufficient observations during the study period, as the variety is currently undergoing adaptation testing
Source: compiled by the authors based on data from NASEC (n.d.)

Apple tree variety 'Voskhod'. Variety bred by KazNIIPO LLP. Winter ripening period, high winter hardiness. Resistant to powdery mildew and scab. Medium-sized tree with a rounded, compact crown. It starts bearing fruit 2-3 years after planting in the garden. High yield. The fruits are large, up to 260 g, candlestick-shaped, light yellow in colour with a delicate blush (Fig. 1). The taste is sweet and sour, with a pleasant aroma. The flesh is white, dense, tender, juicy, and fine-grained. The fruits ripen in mid-September. They can be stored until April. The variety is regionalised in the Almaty and Zhambyl regions.

Figure 1. Apple tree variety 'Voskhod'
Source: photo by the authors

Apple tree variety 'Makpal'. A variety bred by KazNIIPO LLP. A winter-ripening variety. High winter hardiness. Resistant to powdery mildew and scab. Medium-sized trees with oval crowns of medium density. Begins bearing fruit in the third year after planting in the orchard. High yield. Fruits are large, up to 205 g, elongated-conical in shape, mainly yellow in colour with a bright red blurred blush over most of the fruit. The flesh is white, with a medium aroma. The fruits ripen in mid-September. They can be stored until April. Regionalised in the Almaty region.

Apple tree variety 'Anel'. Created at KazNIIPO. Obtained by crossing the varieties 'Starkrimson' and 'Aport'. Trees with moderate growth, winter-hardy, disease-resistant. Bears fruit in the third year after planting in the garden. The fruits are above average in weight, very attractive, have a solid bright crimson colour, excellent dessert taste, and are fragrant (Fig. 2). The fruits ripen in late summer and can be stored in the refrigerator for three months. It is regionalised in the Almaty, Zhambyl and Zhetysu regions.

Figure 2. Apple tree variety 'Anel'
Source: photo by the authors

Apple tree variety 'Damira'. A variety bred by KazNIIPO LLP, created by crossing the 'Fantasia' and 'Almaty Sinap' varieties. The variety is winter-hardy and resistant to major diseases. The tree has a spreading crown, suitable for intensive orchards. It starts bearing fruit 3-4 years after planting. The variety is high-yielding. The fruits are medium to above average in size, elongated and conical in shape. The skin colour is bright red all over the fruit. The flesh is white, fine-grained, and has a good taste. It can be stored until April. The variety is undergoing state variety testing.

Apple tree variety 'Aizere'. A variety bred by KazNIIPO LLP, ripening in autumn and winter. Winter-hardy. Disease-resistant. Medium-sized tree with a rounded, spreading, moderately dense crown. Begins bearing fruit 2-3 years after planting in the orchard. High-yielding variety. The fruits are medium-sized, 200-220 g, elongated-conical, yellow in colour, with a raspberry blush, blurred and striped over most of the fruit, sweet in taste, with a strong aroma, creamy, juicy, dense and tender flesh. The fruits ripen in mid-September. They can be stored in the refrigerator until April.

Apple tree variety 'Dauren'. A variety bred by KazNIIPO LLP, parent forms 'Sinap Almatinsky' and 'Fantasia'. The trees are winter-hardy. The crown is pyramidal in shape and spreads under the weight of the harvest. It starts bearing fruit 3-4 years after planting in the orchard. The fruits ripen in autumn-winter and can be stored until April. The fruits are candlestick-shaped, mainly greenish-yellow in colour, with a blurred blush over most of the fruit (Fig. 3). The fruits are highly attractive and have a dessert flavour. The variety is undergoing state variety testing.

Figure 3. Apple tree variety 'Dauren'
Source: photo by the authors

'Pink Lady' apple variety. This variety was bred in Austria and ripens in winter. The tree is conical and dense. The fruits are large, up to 6-10 cm in diameter, and round-conical in shape. The apples weigh 180-200 g. The skin is thick, shiny, and greenish-yellow in colour. It is covered with a blush, which can range from light pink to red. The flesh is cream-coloured, dense, and very juicy. The taste is pleasant, sweet and sour, with a hint of vanilla and forest berries. Harvesting begins in late October or mid-November. The fruits store well and are suitable for transport. They can be stored in a refrigerator, cellar or cool basement for up to 10 months. They retain their taste until May.

'Honeycrisp' apple variety. American variety. Winter consumption period (removable maturity in mid-September, consumer maturity in early November). Highly winter-hardy. In the first 3-4 years, the tree has a narrow oval shape, later – a compact wide oval shape. The fruits are large, weighing 180-250 g, uniform in size, elongated-rounded-conical, sometimes asymmetrical, yellowish-light green with an orange-red blurred blush on most of the fruit and dull red strokes and spots on its background. The skin is of medium thickness, very dense, smooth, and moderately shiny. The flesh is yellowish-cream, dense, crumbly, crisp, very juicy, with a light aroma. The taste is excellent, harmoniously sweet and sour. The fruit can be stored in the refrigerator for 6-7 months. The variety is resistant to scab.

'Champion' apple variety. Variety of Czech origin. Variety – self-infertile. Trees are weak in growth, with a compact, oval, medium-dense crown. Apple fruits are large, oval-cylindrical, regular in shape. The skin is smooth, thin, but quite strong and elastic, greenish-yellow in colour, covered with an orange-red blush. The flesh is light cream in colour, sweet in taste, with a slight sourness, and amazingly juicy. The fruit's shelf life is not the longest, but under the right storage conditions, the fruit remains in excellent condition for 5-6 months. Transportation requires good packaging. Ripening period is the end of September. Trees begin to bear fruit on medium-sized rootstocks in 4-5 years.

Apple tree variety 'Red Chief'. Selected in the USA as a clone of the 'Red Delicious' variety. Trees are of medium vigour, with a broad pyramidal crown of medium density. Bears fruit mainly on spurs. The fruit is above average size and large (180-210 g), truncated-conical, sometimes slanted, of average uniformity. The surface is broadly ribbed. The skin is of medium thickness, with a waxy coating. The main colour is greenish-yellow, the overcolour is a dark red striped blush, later bright red, merging and covering the entire fruit. The subcutaneous dots are large, numerous and clearly visible. The flesh is light cream, medium density, fine-grained, medium juiciness, dessert flavour (4.8 points), with a strong aroma. The fruit reaches harvest maturity in the second half of September. Shelf life is 6-7 months. Mainly used fresh. It starts bearing fruit on low-growing rootstocks in the third year, with a yield of up to 55 t/ha and regular fruiting. The variety is characterised by insufficient winter hardiness and average drought resistance. It is moderately susceptible to scab and resistant to powdery mildew.

Apple tree variety 'Samurlet'. Late summer, universal. Large, fast-growing tree. Medium density, rounded crown. Large fruits, average weight 210 g, uniform, ovoid, regular shape. The surface of the fruit is slightly ribbed. The flesh is white, medium density, prickly, medium coarseness, fine-grained, very juicy. The taste is sour-sweet, with a strong aroma. Resistant to diseases and pests. Winter-hardy, drought-resistant and heat-resistant.

Pear variety 'Nagima'. Selected by KazNIIPO LLP. Autumn ripening period. Good winter hardiness. Medium-sized tree. Broad pyramidal, dense crown. Begins bearing fruit in the fourth year after planting in the orchard. Average yield. Susceptible to bacterial blight. Large, broadly pear-shaped fruit (Fig. 4). Yellow-green colour with a scarlet blush on the sun-exposed side. Juicy, sweet flesh with excellent taste. Undergoing state variety testing.

Pear variety 'Bostandyk'. Selected by KazNIIPO LLP. Winter ripening period. High winter hardiness. Tall tree. Broad rounded crown, medium density. Begins bearing fruit in the 5^{th} year after planting. High yield. Medium-sized, round fruit with a juicy sweet-sour taste. Main colour is green-yellow. Harvest maturity occurs in mid-September, fruit can be stored until December. Passes state variety testing.

Figure 4. Pear variety 'Nagima'
Source: photo by the authors

Pear variety 'Aydana'. Selected by KazNIIPO LLP. Winter ripening period. High winter hardiness. Medium-sized tree. Pyramidal crown. Begins bearing fruit in the third year after planting on quince rootstock. High yield. Medium to large, round fruit with a juicy sweet-sour taste. Main colour is green-yellow. Harvest maturity occurs in mid-September, fruit can be stored until December. The variety is resistant to bacterial burn and is included in the State Register of Selection Achievements Recommended for Use in the Republic of Kazakhstan.

Pear variety 'Karyndas'. Selected by KazNIIPO LLP. Autumn ripening period. High winter hardiness. Medium-sized tree. Broad pyramidal crown, medium density. Begins bearing fruit in the fourth year after planting. High yield. Moderately resistant to bacterial burn. Medium-sized pear-shaped fruit. Main colour is yellow with a red blush (Fig. 5). Juicy, grainy flesh with a sweet-sour taste. Can be stored until mid-January. Passes state variety testing.

Figure 5. Pear variety 'Karyndas'
Source: photo by the authors

'Harrow Sweet' pear variety. A winter ripening variety, bred in Canada. The fruit is pear-shaped, weighing 260-450 g, sometimes up to 500 g, with greenish-yellow skin and a blurred tan on the sunny side, turning yellow when fully ripe. The flesh is juicy, sweet with a pleasant sourness, and fragrant. The fruit reaches harvest maturity at the end of September. Under normal conditions, it can be stored for about 2-3 months, and in the refrigerator until early March. It has high winter hardiness. Resistance to diseases and pests is quite high. Fruiting begins in the 3rd-4th year after planting. Fruiting is regular, stable, and high-yielding. The 'Harrow Sweet' pear is relatively new but promising for Kazakhstan. The trees are low-growing, up to 3 m.

'Prosto Maria' pear variety. The tree is medium-sized, can grow up to 3 m tall, and has a broad pyramidal crown with a diameter of up to 2.5 m (at 10 years of age). This tree is considered a late variety – it bears fruit in autumn (October). The fruits are round and pear-shaped, smooth, shiny, with thin skin. The main colour is greenish-yellow with a faint reddish blush. The fruits are large, weighing 200-230 g. It is worth noting that it is advisable to pick the fruits when they are unripe, as they store well and ripen in a dark, cool place for 90 days.

Figure 6. Pear variety 'Prosto Maria'
Source: photo by the authors

Pear variety 'Kyrgyzskaya Zimnyaya'. Kyrgyz variety, winter ripening period. Resistant to bacterial burn disease. Medium-sized tree. Broad pyramidal crown, medium density. High yield, large, oblong fruit, golden yellow in colour with a bright carmine blush. The flesh is creamy, coarse-grained with a tart taste. High shelf life and transportability.

Pear variety 'Muratovskaya'. Autumn variety bred by the All-Russian Scientific Research Institute of Fruit Crop Breeding. Medium-sized trees. The tree crown is broad-pyramidal, of medium density. The predominant type of fruit formation is simple and complex ringlets. The fruits are medium-sized, uniform, pear-shaped, with ribbing at the top of the fruit, slightly slanted. The flesh is light yellow, dense, tender, buttery, juicy, with a sweet and sour taste and a slight aroma. The appearance of the fruit is rated at 4.5 points, and the taste at 4.3 points. Harvest maturity occurs in the last ten days of August – early September, and the fruit can be stored until November. The variety is early-fruiting, high-yielding, and winter-hardy. It is resistant to major diseases.

Pear variety 'Lyra'. An early winter pear variety bred by the All-Russian Scientific Research Institute for Fruit Crop Breeding. The trees are large with a broad pyramidal crown of medium density. The predominant types of fruit formations are ring-shaped and spear-shaped. The fruits are large, weighing 205 g, attractive in appearance, uniform in size, broadly pear-shaped or elongated pear-shaped, and slanted. The surface of the fruit is smooth and broadly ribbed.

The skin of the fruit is smooth, dry, and dull. Colour at harvest maturity: the main colour is greenish, with a light tan covering a smaller part of the fruit in a brownish-red colour. The flesh is white, creamy, dense, fine-grained, very juicy, with a good sweet taste and a slight sourness, with a faint aroma. The fruit reaches harvest maturity in September. The consumer period lasts from early October to late December. Yields are high and regular. Winter hardiness is average. The variety is resistant to major diseases.

The differences in productivity and adaptability of modern apple and pear varieties obtained during the study are consistent with current trends in the introduction and selection of pome crops. The high yield of intensive plantings of a number of 'Golden Delicious' clones, as well as the stable yield of 'Honeycrisp' and 'Pink Lady', correspond to the literature data that the key quantitative characteristics – early fruiting, regularity of fruiting, resistance to scab/powdery mildew – are important for the introduction and selection of new varieties. 'Pink Lady' correspond to the literature data that key quantitative traits – early fruiting, regularity of fruiting, resistance to scab/powdery mildew and fruit quality – are formed by a combination of additive and non-additive effects and benefit significantly from the selection of low-growing rootstocks and high-density planting schemes. This is confirmed by the comprehensive review by R. Sestras & A. Sestras (2023). The issue of genetic diversity of the assortment used is important for Kazakhstan. The data obtained in this study on the differentiation of varieties in terms of resistance and fruit quality fit into a broader picture: molecular genetic studies by M. Omasheva *et al.* (2018) show that both local and introduced genotypes with a wide range of variability coexist in the country's collections and production orchards, which creates a basis for targeted selection for specific environmental stressors.

The practical differences between the apple varieties tested in terms of shelf life and storage quality are consistent with numerous reports on the role of ethylene inhibitors (1-MCP) and controlled atmosphere regimes. Studies by E. Cocci *et al.* (2014), R. Fernandes *et al.* (2021), S. Steffens *et al.* (2022) showed that 1-MCP treatment slows down respiration and softening, maintains acidity and turgor during long-term storage and subsequent "shelf life", which directly correlates with the ability of individual clones to remain marketable until late spring, as noted in this study. This provides technological leeway for extended sales and smoothing out price volatility.

'Harrow Sweet' deserves special attention among pears: in this study, it combined high productivity with satisfactory fruit quality. These observations have a genetic basis, which explains the better field tolerance noted in the literature and in practice compared to a number of older varieties and makes it a promising component of the intensive orchard assortment (Maag *et al.*, 2024). The advantages of intensive technologies (drip irrigation, trellis, compacted schemes) shown in this study (accelerated entry into fruiting, more uniform crop load) correspond to data from Europe and Central Asia: the optimal combination of low-growing rootstocks and training systems provides early economic benefits without compromising basic quality indicators. At the same time, the literature highlights the potential risks of ultra-intensive orchards – a more vulnerable root system and related phenomena in the case of unfavourable rootstock-scion combinations and moisture/temperature stresses (Lezzer *et al.*, 2022). These factors should be taken into account when scaling up technologies in arid regions. Thus, the summarised data indicate the importance of a comprehensive approach to assortment formation based on scientific achievements, genetic diversity and breeding work. This makes it possible to significantly increase the sustainability and productivity of fruit crops that meet the requirements of modern intensive horticulture.

Conclusions

Many years of research conducted at the experimental site of KazNIIPO LLP have made it possible to significantly expand and update the range of apple and pear varieties by including promising forms of both local Kazakhstani and foreign selection in the variety study. Among the locally selected apple varieties, such varieties as 'Damira', 'Anel', 'Dauren' and 'Aizere' were highly valued for their combination of economically valuable characteristics. These varieties were distinguished by their high adaptability to the conditions of the Zailiyskiy Alatau, good shelf life, high organoleptic indicators (taste 4.7-5.0 points) and average yield of 195 to 240 centners per hectare. Winter varieties ('Dauren', 'Damira', 'Aizere') were also characterised by a long shelf life (until May-June). In pear breeding, the varieties 'Nagima', 'Karyndas', 'Aydana', 'Bostandyk' were selected, which showed resistance to stress factors, stable yield (up to 200 cwt/ha), good taste (4.3-4.8 points) and shelf life until January-February. Some varieties (e.g., 'Kyrgyzskaya Zimnyaya', 'Harrow Sweet') were characterised by high marketability and versatility in use.

In addition, apple varieties from other countries ('Champion', 'Samurlet', 'Pink Lady', 'Red Chief', etc.) and pear varieties were successfully introduced, which made it possible to expand genetic diversity and conduct a comparative assessment with Kazakhstani analogues. These varieties demonstrated high yields (up to 550 cwt/ha for apple trees and up to 205 cwt/ha for pear trees), high organoleptic characteristics, and good adaptability to the agro-ecological conditions of south-eastern Kazakhstan. The study confirmed the feasibility of introducing new-generation varieties into commercial plantations focused on intensive horticulture. The results are important for the development of variety policy and breeding programmes in the context of climate change. Prospects for further research include an in-depth assessment of the resistance of the studied varieties to abiotic stresses and biotic pathogens, as well as the use of molecular markers for accelerated selection of adaptive forms.

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Conflict of Interest

None.

References

[1] Cocci, E., Sacchetti, G., Rocculi, P., & Dalla Rosa, M. (2014). Response of Pink Lady® apples to post-harvest application of 1-methylcyclopropene as a function of applied dose, maturity at harvest, storage time and controlled atmosphere storage. *Journal of the Science of Food and Agriculture*, 94(13), 2691-2698. doi: 10.1002/jsfa.6610.

[2] Convention on Biological Diversity. (1992, June). Retrieved from https://surl.li/sriqmg.

[3] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1973, March). Retrieved from https://cites.org/eng.

[4] Du, K., Yuan, F., Huo, M., Mao, N., Zhao, S., Yang, X., Sang, Y., & Tian, G. (2025). Nutrients, bioactives, health-promoting effects, and related products of pears: Different varieties, growth stages and parts. *Journal of Functional Foods*, 129, article number 106844. doi: 10.1016/j.jff.2025.106844.

[5] Fernandes, R.C., Steffens, C.A., Anami, J.M., Mosquera, D.J.C., do Amarante, C.V.T., & Brackmann, A. (2021). Quality of 'Cripps Pink' apples stored under controlled atmosphere with ultra-low and extremely low oxygen partial pressures or treated with 1-methylcyclopropene. *Bragantia*, 80, article number e5921. doi: 10.1590/1678-4499.2021115.

[6] Ghonimy, M., Alayouni, R., Alshehry, G., Barakat, H., & Ibrahim, M.M. (2025). Integrated physical-mechanical characterization of fruits for enhancing post-harvest quality and handling efficiency. *Foods*, 14(14), article number 2521. doi: 10.3390/foods14142521.

[7] Gritsenko, D., Pozharskiy, A., Dolgikh, S., Aubakirova, K., Kenzhebekova, R., Galiakparov, N., Karimov, N., & Sadykov, S. (2022). Apple varieties from Kazakhstan and their relation to foreign cultivars assessed with RosBREED 10K SNP array. *European Journal of Horticultural Science*, 87(1), 1-8. doi: 10.17660/eJHS.2022/006.

[8] Havryliuk, O., Kondratenko, T., & Mazur, B. (2022). Commodity quality of apple fruits of columnar type. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 18(2). doi: 10.31548/dopovidi2022.02.002.

[9] JSC "National Agrarian Science and Educational Centre" (NASEC). (n.d.). Retrieved from https://nasec.kz/ru.

[10] Lezzer, P., Tustin, S., Corelli-Grappadelli, L., Serra, S., Anthony, B., Dorigoni, A., & Musacchi, S. (2022). Influences of propagation method, rootstock, number of axes, and cultivation site on 'Fuji' scions grown as single or multi-leader trees in the nursery. *Agronomy*, 12(1), article number 224. doi: 10.3390/agronomy12010224.

[11] Maag, M., Wensing, A., Zetsche, H., & Peil, A. (2024). Establishment of a dense genetic map for the pear cultivar 'Harrow Sweet' and detection of fire blight QTL. *Acta Horticulturae*, 1412, 125-128. doi: 10.17660/ActaHortic.2024.1412.20.

[12] Manapkanova, U., Rymkhanova, N., Reim, S., Fritzsche, E., Höfer, M., Beshko, N., Satekov, Y., & Kushnarenko, S.V. (2025). Genetic diversity and phenotypic variation of indigenous wild cherry species in Kazakhstan and Uzbekistan. *Plants*, 14(11), article number 1676. doi: 10.3390/plants14111676.

[13] Mavlyanova, R.F. (2015). Improved vegetable varieties for central Asia and the Caucasus developed from AVRDC – The World Vegetable Center Germplasm. *Ekin Journal of Crop Breeding and Genetics*, 1(2), 100-104.

[14] Omasheva, M.E., Pozharsky, A.S., Smailov, B.B., Ryabushkina, N.A., & Galiakparov, N.N. (2018). Genetic diversity of apple cultivars growing in Kazakhstan. *Russian Journal of Genetics*, 54, 176-187. doi: 10.1134/S1022795418020138.

[15] Sedov, E.N., & Ogoltsova, T.P. (Eds.). (1999). *Program and methodology for variety study of fruit, berry and nut crops*. Orel: VNIISPK.

[16] Sestras, R.E., & Sestras, A.F. (2023). Quantitative traits of interest in apple breeding and their implications for selection. *Plants*, 12(4), article number 903. doi: 10.3390/plants12040903.

[17] Smykov, A.V. (2020). Prospects for breeding and genetic research of fruit crops. *Plant Biology and Horticulture: Theory, Innovations*, 2(155), 112-129. doi: 10.36305/2712-7788-2020-2-155-112-129.
[18] Steffens, C.A., Soardi, K., Heinzen, A.S., Amaral Vignali Alves, J., da Silva, J.C., Talamini do Amarante, C.V., & Brackmann, A. (2022). Quality of "Cripps Pink" apples following the application of 1-MCP, ethanol vapor and nitric oxide as pretreatments for controlled atmosphere storage. *Journal of Food Processing and Preservation*, 46, article number e16121. doi: 10.1111/jfpp.16121.
[19] Sviridova, A.D., & Vlasov, A.I. (2019). An integrated approach to the organization and operation of an intensive orchard is the key to success in restoring the fruit-growing industry. *Economy and Ecology of Territorial Entities*, 2, 95-108. doi: 10.23947/2413-1474-2019-3-2-95-108.
[20] Temirbekova, S., *et al*. (2023). Sustainable agriculture: Growing safflower oilseed in arid climates. *Journal of Biochemical Technology*, 14(4), 90-99. doi: 10.51847/YZLS81LfHh.
[21] WMA Declaration of Helsinki. (1964, June). Retrieved from https://www.wma.net/policies-post/wma-declaration-of-helsinki/.
[22] Yefremova, Y.M., Urazayeva, M.V., & Kazybaeva, S.S. (2023). Rootstocks and varieties of fruits, berry crops, and grapes, used for intensive gardening in Kazakhstan. In A.B. Küden (Ed.), *Apple cultivation-recent advances* (Chapter 8). London: IntechOpen. doi: 10.5772/intechopen.108360.

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Аннотация. Бул макалада алма жана алмурут сортун изилдөө жана жакшыртуу боюнча Казакстандын мөмө-жемиш жана жашылча өстүрүү боюнча илимий-изилдөө институту (Казахстандын мөмө-жемиш жана жашылча өстүрүү боюнча илимий-изилдөө институту) тарабынан жүргүзүлгөн узак мөөнөттүү изилдөөлөрдүн жыйынтыктары келтирилген. Бул иштин актуалдуулугу Казакстандын түштүк жана түштүк-чыгыш аймактарынын шарттарында мөмө-жемиш продукцияларынын ыңгайлашуусун, түшүмдүүлүгүн жана сапатын жакшыртуу зарылдыгынан келип чыгат. Изилдөөнүн максаты интенсивдүү багбанчылык үчүн эң келечектүү формаларды аныктоо максатында жергиликтүү жана интродукцияланган сортторду агробиологиялык баалоону жүргүзүү болгон. Акыркы 20 жылда мамлекеттик сорттун сыноосуна 97 алма жана 25 алмурут сорту тапшырылган, ал эми институттун генофондуна 70тен ашык жаңы сорттор кошулган, анын ичинде ‘Honeycrisp’, ‘Champion’, ‘Red Chief’, ‘Pink Lady’, ‘Samurlet’, ‘Lyra’, ‘Muratovskaya’ жана башкалар. Изилдөө 2022-жылдан 2024-жылга чейин республиканын түштүгүнүн жана түштүк-чыгышынын климаттык шарттарында жүргүзүлгөн. Баалоо бир катар экономикалык жактан баалуу белгилердин негизинде жүргүзүлдү: эрте бышышы, түшүмдүүлүгү, ыңгайлашуусу, сактоо мөөнөтү жана ооруларга (козу карын, порошоктуу көктүн, оттун күйүшү) жана зыянкечтерге туруктуулугу. Натыйжада, эң жогорку ыңгайлашуу даражасына, туруктуу түшүмдүүлүгүнө (550 ц/га чейин), эң сонун даамына жана сактоо мөөнөтүнө ээ болгон сорттор аныкталды. Макалада биологиялык жана экономикалык көрсөткүчтөр боюнча маалыматтарды камтыган 12 алма жана 10 алмурут сорту баяндалат. Изилдөөнүн практикалык мааниси алынган жыйынтыктарды коммерциялык бакчаларды түзүүдө жана окшош өстүрүү шарттары бар аймактарда сорттук курамды оптималдаштырууда колдонуу мүмкүнчүлүгүндө жатат

Негизги сөздөр: кышкы чыдамкайлык; түшүмдүүлүк; ыңгайлашуу; алма дарагы; алмурут; ооруларга туруктуулук

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Аннотация. В статье представлены результаты многолетних исследований ТОО «Казахский научно-исследовательский институт плодоовощеводства» по изучению и совершенствованию сортимента яблони и груши. Актуальность работы обусловлена необходимостью повышения адаптивности, урожайности и качества плодовой продукции в условиях юга и юго-востока Казахстана. Исследование было направлено на агробиологическую оценку сортов местной и интродуцированной селекции с целью выявления наиболее перспективных форм для интенсивного садоводства. За последние 20 лет на государственное сортоиспытание было передано 97 сортов яблони и 25 сортов груши, а в генофонд института привлечено свыше 70 новых сортов, в том числе такие, как ‘Honeycrisp’, ‘Champion’, ‘Red Chief’, ‘Pink Lady’, ‘Samurlet’, ‘Lyra’, ‘Muratovskaya’ и др. Исследования проводились в 2022-2024 гг. в климатических условиях юга и юго-востока республики. Оценка осуществлялась по ряду хозяйственно-ценных признаков: скороплодность, урожайность, адаптивность, лежкость плодов, устойчивость к болезням (парша, мучнистая роса, бактериальный ожог) и вредителям. В результате выделены сорта с наивысшей степенью адаптации, стабильной продуктивностью (до 550 ц/га), высокими вкусовыми качествами и пригодностью к хранению. Статья содержит характеристику 12 сортов яблони и 10 сортов груши, включая данные о биологических и хозяйственных показателях. Практическая значимость работы заключается в возможности использования полученных результатов при закладке промышленных садов и оптимизации сортового состава в регионах с аналогичными условиями выращивания

Ключевые слова: зимостойкость; урожайность; адаптивность; яблоня; груша; устойчивость к болезням

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Institutional mechanisms for transboundary water resource management and their impact on agricultural sustainability in Kyrgyzstan in the context of climate change

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Abstract. The Kyrgyz Republic occupies a strategic position in the hydrological system of Central Asia as an upstream state controlling the formation of the flow of the region's largest transboundary rivers, the Amu Darya and Syr Darya. Climate change, which increases interannual variability in river flow, poses critical challenges to the sustainability of the region's agricultural sector and the implementation of regional water management policies in Central Asia. The structural conflict between the energy interests of the upper reaches (water storage in winter for hydroelectric power stations) and the agricultural needs of the lower reaches (maximum water supply in summer for irrigation) threatens the region's food security. The aim of the study was to analyse institutional mechanisms for transboundary water management and their adaptive potential to ensure agricultural sustainability. Critical deficiencies in the current institutional system have been identified; the analysis showed that the Interstate Water Management Coordination Commission (IWCCC) has limited regulatory powers, and the commission's decisions are advisory in nature. Basin organisations do not have mechanisms to enforce water consumption limits. In conditions of low water availability, the effectiveness of the system is sharply reduced, and there is no formal system of sanctions for violations of water distribution agreements. The study examined ways to harmonise Kyrgyzstan's national water policy with regional initiatives on transboundary water management, as well as the possibilities for adapting existing contractual mechanisms to climate risks and creating a system for monitoring the implementation of intergovernmental obligations. A model of adaptive water resource management was proposed, and a three-level system was developed: (1) seasonal redistribution of flows through reservoir storage; (2) a flexible quota mechanism that takes climate forecasts into account; (3) a system of economic incentives for water conservation in the agricultural sector. The results of the study fill a gap in understanding the link between the institutional architecture of water management and agricultural vulnerability and allow for the formulation of scientifically sound recommendations for the creation of a more sustainable and institutionally effective system of transboundary water management, contributing to the minimisation of conflict potential and stimulating integrated regional development in Central Asia

Keywords: water security; water-energy nexus; hydropower potential; climate change adaptation

Introduction

In the context of global climate change, water management issues are becoming particularly relevant due to increasing water shortages and growing competition between different economic sectors and states in Central Asia. The region's geoclimatic characteristics make its hydrological systems highly vulnerable to

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anthropogenic climate change. The observed transformations are manifested in the accelerated degradation of the mountain-glacier complexes of the Pamir-Alai and Tian Shan Mountain systems in Kyrgyzstan and Tajikistan, modifications in the intra-annual distribution of river flow, an increase in the frequency of extreme hydrometeorological phenomena, and progressive climate aridisation. Together, these factors pose systemic risks to the economic stability and food security of the states of the Central Asian region, requiring the development of comprehensive adaptation strategies for water management.

Global climate change is having and will continue to have a significant impact on water resources in Central Asia (Issakov *et al.*, 2025). The consequences are already being felt, such as more frequent and severe floods and droughts, reduced water reserves, accelerated erosion and sedimentation, and a reduction in glaciers and snow cover. The impact of these factors leads to seasonal instability in water supply, which is particularly critical for the country's agriculture and energy sectors. In addition, pressure from neighbouring states on transboundary water use makes water resource management not only a national but also an international issue. All these phenomena have a direct impact on water quality and the state of ecosystems (Carec, n.d.). In the near future, almost all Central Asian countries will face negative consequences that will affect not only natural but also social and economic systems. Urgent measures are needed to integrate water resource management into climate change adaptation strategies. This should become a key element of any country's policy in order to minimise the consequences and protect the future of the region.

Water resources in Central Asia are not only economically important, but also geopolitically significant. Since all five countries in the region depend on shared water sources, effective water resource management is key to the stability and prosperity of the entire region. Kyrgyzstan, with its significant hydropower potential, plays a strategic role in the transboundary management of water resources in Central Asia. However, climate change, increasing water consumption and the need for transboundary water management require a comprehensive approach to their rational use and protection. The region's main waterways, the Amu Darya and Syr Darya, which originate in the mountain ranges of Kyrgyzstan and Tajikistan, play a crucial role in sustaining life, agriculture and the economies of these countries, and also serve as the main sources of fresh water for the downstream countries, in particular Uzbekistan, Kazakhstan and Turkmenistan. The strategic importance of water resources in Central Asia, as noted in the work of A. Prniyazova *et al.* (2025), extends beyond national borders, necessitating transboundary cooperation to prevent conflicts and ensure sustainable development. The experience of other regions, including North America, confirms the critical importance of institutionalising mechanisms for joint water resource management (Potekhin & Fesenko, 2022). According to G. Borankulova *et al.* (2025), agriculture, energy (especially hydropower), healthcare, and tourism all depend on a stable water supply, and climate change will lead to a deterioration in the conditions for their development. As a result, such changes will have a cascading effect on the health of the population and the economy of the region as a whole.

The aim of this study was to identify the institutional prerequisites and constraints affecting the effectiveness of regional water management mechanisms and to propose ways of adapting them to changing climatic conditions. The scientific hypothesis of the study was that reforming the water sector in Central Asia, taking into account both national and regional interests, could strengthen the sustainability and security of the entire region.

Literature Review

All major rivers in Central Asian countries are transboundary in nature. The main sources of water are the Amu Darya and Syr Darya rivers, which flow through the territory of several states – Tajikistan, Afghanistan, Uzbekistan and Turkmenistan. Their annual flow is about 77 km^3, of which about 96% is used for irrigation. In addition, such significant transboundary rivers as the Chu, Talas, Tarim and Irtysh flow through the region (Kukushkina & Sodikov, 2018). Among the five countries in the region, only Kyrgyzstan has water resources that are formed mainly on its own territory, which gives it strategic importance in ensuring water and energy security in Central Asia. The other states depend to varying degrees on water inflows from neighbouring territories. The most vulnerable are Uzbekistan and Turkmenistan, more than 90% of whose renewable water resources are formed outside their borders. Similar to other Central Asian states, the Kyrgyz Republic bases its water policy on the Constitution. Article 16 of the Constitution of the Kyrgyz Republic (2021) states: "The land, its subsoil, airspace, waters, forests, pastures, flora and fauna, and other natural resources are the exclusive property of the Kyrgyz Republic".

However, Kyrgyzstan does not fully implement this constitutional right due to persistent stereotypes. According to estimates by A. Sokeyev (2023), Kyrgyzstan directly uses only about 15-20% of the total water flow formed on its territory, while the majority is consumed by neighbouring states in the region. Historically, Kyrgyzstan has adhered to the principles of good neighbourliness, sharing its freshwater resources with neighbouring countries. This approach formed the basis of the strategic concepts formulated in the works of T. Usubaliev (1998), who was one of the first to identify the need to develop a national water strategy in balance with regional interests. His works emphasise that water for Kyrgyzstan is not only a natural resource but also a geopolitical resource that requires rational use, modernisation of irrigation systems and the search for fair mechanisms for inter-state distribution of water flow. Thus, T. Usubaliev's ideas remain relevant: he pointed out that only through fair regional cooperation and respect for the interests of Kyrgyzstan as a source country is it possible to achieve sustainable management of transboundary water resources in Central Asia.

In 2001, the Jogorku Kenesh of the Kyrgyz Republic adopted Law of the Kyrgyz Republic No. 76 (2001), which established the legal basis for the fair and mutually beneficial provision of the country's water resources to interested neighbouring states. The law regulates the use of water resources, taking into account market economic relations, and complies with international legal norms and the practices of other states. Despite this, neighbouring countries periodically misinterpret the provisions of the law, suggesting that all watercourses originating in Kyrgyzstan should be completely blocked. In fact, the law provides for the establishment of fees only for water accumulated in interstate reservoirs and supplied to countries downstream, and not for the entire natural flow.

For the Kyrgyz Republic, as an upstream country, it is strategically important to strike a balance between using water for hydropower generation and providing downstream countries (Kazakhstan, Uzbekistan, Turkmenistan) with water resources for irrigation. Geographical location and geopolitical factors objectively determine the need for regional integration and joint management of river basins based on the principles of international law. The difference in interests between upstream and downstream countries (Kyrgyzstan and Tajikistan – electricity generation; Kazakhstan, Uzbekistan and Turkmenistan – irrigation and agriculture) exacerbates regional tensions. This requires the formation of sustainable mechanisms for water diplomacy and the development of a comprehensive regional water strategy. Research by Ya. Pulatov & H. Mukhabbatov (2021) and I. Abdullaev *et al.* (2025) shows that a comprehensive basin-wide approach based on international legal norms and joint management mechanisms can mitigate conflicts and ensure water security in Central Asia. Comprehensive study of the institutional foundations of water diplomacy in the context of the Kyrgyz Republic allows to view it not only as a source of energy and water security, but also as a key element of regional stability and cooperation in Central Asia.

In the hot and arid climate of Central Asia, this is already reflected in the intensive melting of glaciers in mountain systems, leading to a decrease in river water flow. According to Kyrgyzhydromet (n.d.), over the past 70 years, the area of glaciers in Kyrgyzstan has decreased by 60%, indicating a significant reduction in freshwater reserves in the country's high-altitude regions and reflecting the effects of regional warming and changing climatic conditions. According to the Tajik Agency for Hydrometeorology (2025), 15 glaciers, each 4 to 5 km long, have disappeared in the Pamirs over the past 20 years. There are a total of 1,085 glaciers in the Pamir Mountains, including the largest, the 77 km long Fedchenko Glacier, while the area of glaciers in some parts of the Tian Shan Mountains is rapidly shrinking. The total volume of water contained in the Tian Shan glaciers is about 650 km^3. These trends underscore the need to protect Kyrgyzstan's glaciers, which are key sources of fresh water for Central Asia, and also highlight the task of widespread and rational use of the country's hydropower potential. The development of hydropower not only contributes to energy security, but can also be an important tool for mitigating the effects of regional warming and stabilising water resources.

The lack of a comprehensive mechanism for regulating the distribution of water resources among Central Asian countries significantly limits the potential for regional economic integration, including trade, transport and the labour market. This leads to increased transaction costs and hinders the achievement of sustainable development goals (SDGs) (ESCAP, 2017). Kyrgyzstan has experienced significant fluctuations in water resources due to changes in temperature, glacier melt and changes in precipitation. The impact of these factors leads to seasonal instability in water supply, which is particularly critical for the country's agriculture and energy sectors. Water resources in Central Asia have been significantly depleted in recent decades and are now almost exhausted. Per capita water availability in the region is declining rapidly: over the past 40 years, this indicator has fallen from 8.4 to 2.3 thousand cubic metres per year. According to A. Murzakulova *et al.* (2019), the reasons for this decline are population growth, climate change and irrational water use, especially in agriculture. According to forecasts by the Ministry of Finance of the Kyrgyz Republic (2025), if current trends continue, this figure could fall below the critical level of 1.7 thousand cubic metres per capita per year by 2030. At the same time, an additional 500-700 million cubic metres of water are required annually to support the region's population.

For the Kyrgyz Republic, located in the upper reaches of Central Asia's largest transboundary rivers, the Amu Darya and Syr Darya, the issue of water resource management takes on strategic importance. On the one hand, the country has significant hydropower potential, but on the other hand, it faces limited freshwater resources and conflicting interests between upstream and downstream countries. Kyrgyzstan and Tajikistan use water resources primarily for electricity generation, while Kazakhstan, Uzbekistan and Turkmenistan focus on irrigation and agricultural production. The mismatch between the seasonal needs of the energy and agricultural sectors creates the conditions for inter-state conflicts. Additional challenges include inefficient water use, deterioration of irrigation infrastructure, and insufficient integration of water-saving technologies. The issue of water resources and water and energy security has been the focus of researchers' attention over the past decade. Canadian scientist T. Homer-Dixon (1999) studied the relationship between environmental factors and conflicts over resources. The works of M. Zeitoun & J. Warner (2006) and M. Zeitoun & J. Allan (2008) emphasise the role of control over water resources as a key factor in regional stability. Russian researchers focus on a wide range of issues, from the legal basis for transboundary water use to the rational use of water by end users. Particular attention should be paid to the studies by O. Boyarkina (2015) and N. Rogozhina (2015), which consider water security as a crucial element of modern international relations, analysing problems at the inter-state, national and regional levels. Uzbek researchers V. Dukhovny & J. de Schutter (2011) and M. Rakhimov *et al.* (2024) justify the need for an integrated approach to water resource management and the development of comprehensive methods for solving local problems, while forecasting the prospects for regional cooperation. Thus, an analysis of the scientific literature shows that for the Kyrgyz Republic, as a key sector in the upper reaches of Central Asia, the urgent task remains to find a balance between its own national interests and the requirements of regional stability, which requires strengthening the institution of water diplomacy and integrating water management into the context of sustainable development of the agricultural sector.

Kyrgyzstan's research discourse also demonstrates a significant contribution to the development of the concept of transboundary water cooperation, viewed through the prism of national and regional interests. At the same time, it is important to emphasise that international political processes have had a significant influence on the formation of scientists' approaches to the problem in different historical periods. In the context of rapidly changing global and regional relations, Kyrgyzstan in particular needs to modernise its water management and diplomacy at both the national and intergovernmental levels. Transboundary river basins have a number of common characteristics that are of interest to all riparian states. Basin water management requires the coordination of political and technical, national and regional interests. Most researchers conclude that in order to achieve environmental, economic and political security goals, riparian states must jointly address water-related issues (Akunova, 2024). Kyrgyzstan performs a strategic function in ensuring regional water security in Central Asia by maintaining stable transboundary flows and the functioning of irrigation systems in downstream countries, while incurring significant economic costs. This highlights the need to further improve water diplomacy mechanisms and the equitable distribution of water resources at the regional level.

Materials and Methods

This study of institutional mechanisms for managing transboundary water resources in Kyrgyzstan was based on a comprehensive methodological framework combining qualitative and quantitative approaches to analysing water and agricultural issues in the context of climate change. The main methodological tool used was the structural-functional method, which allows identifying the interaction of various socio-legal institutions in the transboundary water use system. This method made it possible to analyse the architecture of institutional links between national water management bodies, international organisations and regional cooperation structures, as well as to determine the functional roles of each element in the water resources management system.

The study was based on institutional analysis, which examines the formal and informal rules governing access to water resources and their distribution. Particular attention was paid to studying the evolution of institutional mechanisms from the Soviet system of centralised management to modern forms of multilateral regional cooperation. The application of this method made it possible to identify institutional gaps and dysfunctions in the existing transboundary water management system. The historical-legal method was used to study the genesis of the regulatory and legal framework for water use in the Central Asian region and to analyse the continuity and transformation of legal norms in the post-Soviet period. The synthesis of historical perspectives made it possible to trace the evolution from a unified Soviet hydrotechnical infrastructure to a fragmented system of national water strategies and to identify the roots of contemporary transboundary water conflicts. A comparative (comparative legal) method was used to compare different models of institutional regulation of transboundary water resources in Kyrgyzstan and neighbouring Central Asian states (Kazakhstan, Uzbekistan, Tajikistan, Turkmenistan). This approach made it possible to identify best practices in regional water cooperation and determine the possibilities for their adaptation to the conditions in Kyrgyzstan.

The empirical basis of the study was a comprehensive analysis of international official documents, including The Helsinki Convention (1992), the Alma-Ata Agreement (1992), the Convention on the Protection... (1992), as well as an analysis of the national regulatory framework of the Kyrgyz Republic. To assess the impact of institutional mechanisms on agricultural sustainability, an analysis of national statistical data and international databases was conducted. Indicators of water supply for agriculture, dynamics of irrigated areas, and water use productivity were studied. Climate models and forecasts for the Central Asian region were used to assess the potential impact of climate change on water resources and the agricultural sector. Content analysis was used to systematise the provisions of international and national legal acts, identify trends in the evolution of legal regulation of transboundary water use, and study scientific publications on water resources issues in Central Asia in the Scopus and Web of Science databases and regional scientific journals. The study was based on an interdisciplinary approach integrating methods from jurisprudence, environmental economics, hydrology and agricultural sciences. This synthesis allowed for a comprehensive assessment of the interrelationships between institutional mechanisms, hydrological processes, climate change and agricultural sustainability. Geopolitical analysis was used to assess the positions of upstream countries (Kyrgyzstan, Tajikistan) and downstream countries (Kazakhstan, Uzbekistan, Turkmenistan) on the distribution of transboundary water resources, to study the strategies of these states and their influence on the institutional framework of regional water cooperation.

Particular attention was paid to key stages in the transformation of the regional water cooperation system and the impact of climate change, which has become particularly noticeable in the last two decades. The geographical scope of the study covered the territory of the Kyrgyz Republic, with a particular focus on transboundary river basins (Syr Darya, Amu Darya, Chu, Talas, Ili) and their catchment areas, as well as the territories of neighbouring Central Asian states with which water resources are shared. This methodological framework provided a scientifically sound basis for developing recommendations to improve institutional mechanisms for transboundary water resource management and enhance Kyrgyzstan's agricultural sustainability in the context of global climate change, which is of practical importance for the development of state policy in the field of water resources and regional cooperation.

Results and Discussion

Hydrology and geographical location of the region

All Central Asian states are characterised by their inland location, which limits their direct access to the world's oceans. At the same time, Uzbekistan is one of only two countries in the world with "double landlocked" status, i.e. it has no access to the sea even through neighbouring states, as it is surrounded by at least two countries. From a hydrological point of view, Central Asia is divided into three main zones: mountainous, foothill and flat. Mountainous areas form the bulk of underground and surface waters, which are mainly of a transit nature and determine the water supply of the lower-lying territories. This factor determines the special importance of mountain ecosystems for the sustainable functioning of the region's water management complex and for transboundary water cooperation.

The geographical location of the region is determined by the predominance of vast arid territories, where desert landscapes occupy a significant part of the area. Another important factor is that Central Asia does not receive any external inflow of water resources, which increases the dependence of the water balance exclusively on internal sources. The territory of Central Asia is located within the closed Aral-Caspian basin and covers significant inland areas. All states in the region are landlocked countries. Geographically, Central Asia is characterised by a predominance of inland deserts, significant plains and steppe areas, as well as high mountain ranges and ridges. The region is home to large mountain systems: the Altai and Sayan, Tian Shan and Pamir-Alai in the south-west. The area of mountainous territories is about 800,000 km^2, or approximately 20% of the total territory of the region (Vinokurov *et al.*, 2022). More than 90% of the territory of Tajikistan and over 90% of the territory of Kyrgyzstan are occupied by mountain ranges (Fig. 1). Eastern Kazakhstan (Kazakh Lowlands, Dzungarian Alatau, Tarbagatai and Altai) also has a pronounced mountainous relief. The south-eastern part of Uzbekistan (Western Tian Shan and Gissar Mountains) stretches to Afghanistan and China. The mountains act as a climatic regulator and are the main source of river flow. In Turkmenistan, mountains cover only about 1% of the territory. Glaciers cover approximately 4% of the area of Kyrgyzstan and 6% of Tajikistan; individual glaciers are also found in Kazakhstan and Uzbekistan. The total area of glaciation in Central Asia is 12-14 thousand km^2. Freshwater reserves in glaciers are estimated at 1,000 km^3, which is comparable to the ten-year flow of the region's largest rivers, the Amu Darya and Syr Darya (Borisova, 2012). The melting of snow, glaciers and perennial ice provides a significant part of the water balance of the region's river flow. As can be seen in Figure 1, the Amu Darya and Syr Darya rivers flow through several countries in the region, playing a key role in water supply. Both rivers feed the Aral Sea, which has shrunk to 10% of its original size due to excessive water withdrawal. This is the result of the irrational use of the Amu Darya and Syr Darya rivers for irrigation. From a geographical point of view, the territory of Central Asia can be divided into several large water basins, including the Aral Sea basin, the Balkhash Lake basin, the Caspian Sea basin (with the Ural and Emba rivers), and the Kara Sea basin. This division reflects the specific nature of the region's hydrographic network and its strategic importance for transboundary water use.

Historical experience shows that water resource management is a critical factor in the sustainability of socio-economic systems. As the source of the Syr Darya and Amu Darya rivers, the Kyrgyz Republic functions as the "water tower of Central Asia", providing water to downstream countries. Kyrgyzstan has unique hydrological potential, being the headwaters of major rivers in Central Asia, such as the Naryn, Talas and Chu. Their strategic importance extends beyond national borders, providing water supply and irrigation in Kazakhstan, Uzbekistan and Tajikistan. This geographical location necessitates the formation of effective institutional mechanisms for water resource management, as the sustainability of water supply throughout the region directly depends on Kyrgyzstan's water use policy. At the same time, existing systemic challenges – degradation of irrigation infrastructure, low energy efficiency of hydropower complexes and limited financial resources – highlight the need to develop innovative approaches to transboundary water management. In this context, water diplomacy is becoming a key institutional tool for ensuring national and regional water security.

Figure 1. Physical map of Central Asia

Source: Free World Maps (n.d.)

Transboundary rivers and population growth in Central Asia

The need for rational use of water resources based on mutually beneficial inter-state cooperation appears to be a key factor in the sustainable development of the region, political stability and security in Central Asia. In this context, international water law plays a special role, providing an institutional framework for building sustainable cooperation between basin countries and developing fair mechanisms for transboundary water management. Recognition of the social importance of water in the context of realising the human right to access safe and clean water forms the basis for water security policy. For the Kyrgyz Republic, finding ways to improve the efficiency of transboundary water resources and water bodies management is becoming a key priority on the regional agenda, aimed at preserving limited and valuable water resources for current and future generations. Some rivers in Central Asia are transboundary, including the Amu Darya and Syr Darya, which flow through Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan; the Talas and Chu, which flow through Kazakhstan and Kyrgyzstan; the Ili, which flows through Kazakhstan and China; the Tarim through Tajikistan, Kyrgyzstan and China; the Irtysh through China, Russia and Kazakhstan; and the Tobol, Ural and Ishim through Russia and Kazakhstan. These waterways play a key role in the regional water balance and require coordination of transboundary water management.

On 22 December 1993, the UN General Assembly adopted Resolution 47/193, which declares 22 March of each year as World Water Day (General Assembly, 1993). This resolution was adopted in response to the fact that many countries are facing water shortages as their populations grow, which in turn leads to economic underdevelopment. Water resources in Central Asia are under enormous pressure due to rapid population growth, climate change, inadequate management and transboundary disputes. About 90% of all water is used in agriculture, primarily for irrigation, making water management critical to food security and stability in the region. According to Worldometer (n.d.), the population of Central Asian countries will reach approximately 82.2 million by December 2024, having increased by almost one and a half times over the past 24 years (Table 1). It is expected to reach 95 million by 2050. As a result, if current water use trends continue, the region may face water shortages: water availability could fall to less than 1,000 m^3 per person per year by 2040, which corresponds to the water stress threshold. Rapid population growth, combined with a high proportion of the population employed in the agricultural sector, puts additional pressure on the region's water and land resources, challenging Central Asian states to ensure sustainable economic development, create jobs and increase agricultural productivity. The data in Table 1 show significant asymmetry in the distribution of the population of Central Asia: the upstream countries (Kyrgyzstan and Tajikistan) account for only 22% of the region's population, while the downstream countries (Kazakhstan, Uzbekistan and Turkmenistan) account for 78%. The largest population is in Uzbekistan (36.5 million people), and the smallest is in Kyrgyzstan (7.2 million people). According to data from the World Population Review (n.d.), the region's population continues to grow at an average rate of about 1.75% per year. The total area of irrigated land in Central Asia, according to the FAO, is approximately 9.85 million hectares, which highlights the critical importance of water resources for regional agriculture (Frenken, 2013). However, these figures also point to an urgent need to modernise water management infrastructure and improve water use efficiency in the context of population growth. During the growing season, this figure reaches about 74%, while in the autumn-winter period it is approximately 26% (Carec, n.d.).

Table 1. Population of Central Asian countries as of the end of 2024

Country	Area of irrigated land in 2024	Population	Share of the region's population, %
Kyrgyzstan	1.05 million hectares	7,224,195	9
Kazakhstan	2 million hectares	20,676,707	25
Tajikistan	0.85 million hectares	10,637,645	13
Turkmenistan	1.75 million hectares	7,031,200	8
Uzbekistan	4.2 million hectares	36,469,203	45
Total	9.85 million hectares	82,038,950	100

Source: compiled by the author based on Worldometer (n.d.)

In total, there are more than 89,000 rivers in Central Asia, but the largest rivers, the Amu Darya and Syr Darya, are of key importance for the region's water supply. In addition to these, the Ili River, which flows into Lake Balkhash, also plays an important role. The Amu Darya and Syr Darya, in turn, flow into the Aral Sea, providing its main source of water. In recent years, all Central Asian countries have adopted new water management programmes with the aim of improving water supply and reducing water consumption. However, there are external factors that can affect regional water resources. These include Russia and China, as transboundary rivers (e.g. the Caspian Basin, Ili, Irtysh) are shared by these states. In addition, Afghanistan should also be considered part of the upper reaches of the basins, as there may be disputes over the rights to use the Amu Darya River in the future. More than 18% of the Amu Darya's water resources come from Afghanistan, which is not a party to the diplomatic agreements between the Central Asian countries. In the northern part of the country, a large canal, Kush-Tepa, 285 km long and about 100 m wide, is under active construction, which creates a risk of drought for the lower reaches of the Amu Darya in Uzbekistan (including Karakalpakstan) and Turkmenistan. Experts note the absence of international legal mechanisms for settlement and the high probability of escalating conflicts. It is expected that about one-third of the Amu Darya's water resources will be used for the construction of the Kush-Tepa canal, which will become a problem for the lower reaches countries, especially Uzbekistan and Turkmenistan (Saida, 2023). The conceptual basis of environmental and water security assumes regional interdependence and cooperation between states to ensure their viability. The concept of water diplomacy is based on international relations arising from water security issues. International water law is directly related to the protection and use of transboundary rivers, lakes and groundwater aquifers. More than 150 countries in the world have transboundary water resources, which makes it critically important to define water use rights and volumes in a transparent and predictable manner. The problem of water resource distribution between upstream countries (Kyrgyzstan, Tajikistan) and downstream countries (Kazakhstan, Uzbekistan, Turkmenistan) of the Amu Darya and Syr Darya rivers remains one of the most sensitive aspects of inter-state relations, requiring the development of long-term compromise solutions based on the principles of sustainable development and equal use of transboundary water resources.

Institutional architecture of transboundary water management and international legal position

The Kyrgyz Republic is implementing a strategy of integrated water resources management based on the basin principle, with the gradual involvement of non-state actors in decision-making processes. The institutional architecture includes water user associations, and the country is divided into five large river basins, for each of which basin councils are established to identify basin problems, plan measures to address them, and coordinate water sector activities. The National Water Strategy of the Kyrgyz Republic until 2040 (2023) focuses on the rational use of water resources and reducing water losses. The programme provides for the modernisation of water and irrigation systems, as well as the construction of hydraulic structures for water accumulation and storage. One of the key tasks is the use of renewable energy sources in water management, such as small hydropower, in accordance with the Water Code of the Kyrgyz Republic (2005). In accordance with Law of the Kyrgyz Republic No. 257 (2009), Kyrgyzstan plans to increase the area of irrigated land from 1.0 million hectares to 1.7 million hectares. These programmes, designed for the period up to 2030-2040, include plans to expand irrigated land and introduce water-saving technologies.

The ratification of the Helsinki Convention (1992) by a number of states in the region (Kazakhstan, Turkmenistan, Uzbekistan) creates the conditions for harmonising national water legislation with international principles of fair and reasonable use of transboundary waters, which demonstrates a desire to harmonise national legislation with international water law and strengthen transboundary cooperation in the Central Asian region. However, Kyrgyzstan actively cooperates with UNECE (n.d.) within the framework of various water management programmes and participates in National Policy Dialogues on Integrated Water Resources Management, but the republic has not formally ratified the Convention. UNECE plays an important role in the region in the field of water cooperation, as it is the secretariat of the Convention on the Protection… (1992). The Commission conducts technical assistance programmes, national policy dialogues and promotes the exchange of experience in the field of transboundary water resources management. In 2021, the Kara Darya-Syr Darya-Amu Darya Basin Water Resources Management Authority was established, and in March 2024, the Issyk-Kul-Tarim, Naryn-Syr Darya, Talas and Chui Basin Management Authorities were established. However, the system faces serious challenges. After the transfer of internal irrigation canals to the balance sheet of water user associations in 2004, many of these organisations faced a lack of funding to maintain large-scale infrastructure, which led to a deterioration in the technical condition of the canals.

In accordance with the Alma-Ata Agreement (1992), the Interstate Water Commission of Central Asia (IWC-CA) was established. The institutional structure of the commission initially included three key executive bodies: the ICWC Secretariat, the Syr Darya Basin Water Management Association (BWMA) and the Amu Darya BWMA. Subsequent institutional development led to the creation of the ICWC Scientific and Information Centre (ICWC SIC) and the Energy-Water Coordination and Dispatch Centre, which contributed to strengthening regional cooperation in the field of hydrological monitoring, data exchange and water policy coordination. Nevertheless, the political and economic heterogeneity of the states in the region continues to hinder the formation of an integrated strategy for transboundary water resources management. According to the typology of transboundary basin organisations, the ICWC belongs to the category of coordination bodies with limited regulatory powers. Under the Alma-Ata Agreement (1992), the commission is vested with the functions of establishing and approving water use limits for member states and the region as a whole.

Despite their institutional mandate, the Amu Darya and Syr Darya River Basin Organisations have not acquired the status of supranational regulatory bodies with enforcement mechanisms. In conditions of hydrological deficit, the problem of ensuring compliance with agreed water consumption limits is exacerbated, as the ICWC and subordinate basin organisations do not have effective control instruments at their disposal. Critically important is the fact that the ICWC's jurisdiction does not cover the entire territory of the river basins, and its decisions are advisory rather than mandatory in nature. The most significant institutional gap is the lack of a mechanism for legal liability for violations of water distribution obligations and exceeding established limits. Despite the declared need to create a system of sanctions, formalised enforcement measures have not yet been developed. The diagram in Figure 2 illustrates the three levels of functioning of a transboundary basin organisation, reflecting the gradation of powers and the degree of integration in the management of shared water resources. The structure is organised according to the principle of increasing institutional complexity and depth of intergovernmental cooperation.

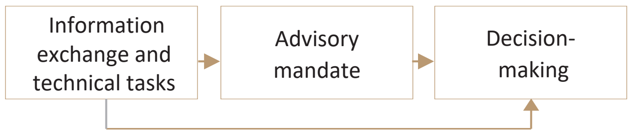

Figure 2. Structure of a transboundary basin organisation
Source: developed by the author

This three-level scheme reflects the evolutionary path of transboundary water cooperation institutions from the simplest forms of information exchange to complex joint management mechanisms. In the context of Central Asia, existing institutions, such as the Interstate Water Commission, are mainly at the first level with elements of the second, while the transition to the third level remains a strategic prospect requiring a significant strengthening of political will and institutional trust between the states of the region. The first level does not involve the transfer of sovereign powers and is limited to providing information for national decisions on water use. Interaction is mainly horizontal in nature between technical specialists from water management agencies in different countries. The second level, "Advisory mandate", is characterised by the formation of expert platforms for discussing strategic issues of transboundary basin management. At this stage, the basin organisation is granted the right to develop recommendations on the optimal distribution of water resources, propose scenarios for the development of water infrastructure, and formulate proposals for the harmonisation of national water policies. However, the final decisions remain the prerogative of national governments, which may accept or reject the recommendations of the basin organisation. The third level, "Decision-making", represents the most advanced form of institutionalisation of transboundary water cooperation, in which the basin organisation is vested with real management powers. Decisions are made on the basis of agreed criteria for the fair and reasonable use of water resources, taking into account the interests of all riparian states and environmental requirements.

The financial support for the activities of basin organisations is characterised by an asymmetrical distribution of obligations: the Amu Darya Basin Organisation is mainly financed by Uzbekistan and Turkmenistan, while the Syr Darya Basin Organisation is financed by Kazakhstan and Uzbekistan. However, the existing financing model does not comply with the principle of proportional parity and equity participation, which creates additional institutional imbalances in the regional water management system.

Conceptualisation of adaptive water resources management in the context of transboundary cooperation

Effective management of transboundary water resources in the context of increasing climate variability and demographic pressure requires the introduction of innovative institutional mechanisms based on the principles of adaptability and flexibility. Within the framework of the modern water management paradigm, a three-level system of adaptive management is being developed, integrating technological, institutional and economic instruments for regulating water use (Fig. 3).

Figure 3. Adaptive management system for transboundary water resources

Source: developed by the author

The first level of the system involves optimising the seasonal redistribution of water flows by creating a cascade of reservoirs with different functional purposes. This approach is based on hydrological modelling of intra-annual flow variability and involves the accumulation of excess water resources during periods of high water availability (spring and summer floods) with subsequent controlled release during low-water seasons. Technical implementation includes the modernisation of existing reservoirs and the construction of new multi-purpose hydraulic structures that simultaneously provide irrigation water supply, hydropower generation and flood protection functions. A critically important aspect is the integration of automated systems for monitoring and forecasting the hydrological regime, allowing real-time adjustment of reservoir regulation parameters in accordance with current hydrometeorological conditions.

The second level is represented by a mechanism of dynamic (flexible) water management quotas, adapted to the predicted climate scenarios and the actual state of the basin's water resources. Unlike the traditional system of fixed water abstraction limits, this model provides for annual adjustment of water use quotas based on long-term meteorological forecasts, data on snow accumulation in high-altitude areas where runoff is formed, and actual water availability indicators for the previous period. The institutional mechanism for implementation is basin commissions, which are empowered to approve adjusted plans for the distribution of water resources among different categories of water users and administrative-territorial units. The methodological basis is probabilistic hydrological forecasting using ensemble models of climate scenarios, which allows assessing the range of possible water availability conditions and forming alternative options for water management balances. It is fundamentally important to establish differentiated water use priorities that guarantee the satisfaction of priority needs for drinking water supply and the maintenance of ecological flow under any hydrological scenarios.

The third level of the system includes a set of economic incentives aimed at improving water use efficiency in the agricultural sector as the main consumer of water resources in the region. The key instruments are: (1) a progressive tariff policy providing preferential water rates for economic entities that meet the established standards for specific water consumption per unit of production; (2) a system of subsidies for the introduction of water-saving irrigation technologies (drip irrigation, sprinkler irrigation, precision farming systems), compensating for up to 50-70% of the initial capital costs; (3) a mechanism for trading water use rights within established basin limits, allowing water resources to be reallocated to the most efficient agricultural producers; (4) insurance instruments that minimise the risks for farmers when switching to less water-intensive crops in conditions of water scarcity.

The integrated application of a three-level adaptive management system provides a synergistic effect, creating the institutional prerequisites for improving the region's water security in conditions of climate uncertainty. At the same time, successful implementation of the model requires a significant transformation of the existing regulatory framework for water use, the development of hydrometeorological monitoring and forecasting infrastructure, and the formation of institutional capacity for basin organisations. Ensuring transparency in decision-making processes and involving a wide range of stakeholders, including non-state actors, in the development and implementation of adaptive water management strategies remains a critical factor.

Water, energy and socio-economic potential of Central Asian countries

The main problem in the distribution of water resources in Central Asia is related to hydropower. Both mountainous republics, Kyrgyzstan and Tajikistan, are heavily dependent on electricity supplies. The development of the hydropower sector requires consideration of the interests of all countries through which the Amu Darya and Syr Darya rivers flow, as water is vital not only for energy but also for agriculture in the region. The desire to develop hydropower, especially in Tajikistan and Kyrgyzstan, is driven by low energy independence, despite the significant potential of water energy sources. According to the United Nations (2025), Central Asia uses only 6% of its renewable hydropower potential. For example, electricity generation per capita varies greatly: in Kazakhstan – 4,730 kWh, in Kyrgyzstan – 1,375 kWh, in Tajikistan – 2,004 kWh, in Turkmenistan – 2,403 kWh, and in Uzbekistan – 1,650 kWh. For comparison, this figure is 8,400 kWh in Japan and 15,140 kWh in Canada. Tajikistan, which ranks eighth in the world in terms of hydropower potential, faces a problem of electricity shortages, especially in winter, when up to 70% of the population experiences shortages. The commissioning of the Rogun HPP, planned for the coming years, could increase the country's annual electricity production to 31-33 billion kWh (Ministry of Energy..., n.d.). Kyrgyzstan also plans to significantly increase its hydropower capacity by building a cascade of hydropower plants on the Naryn River, which could generate more than 25 billion kWh per year with an installed capacity of 6,450 MW.

The initial stage of cooperation between the Kyrgyz Republic and the Republic of Uzbekistan in the context of hydropower infrastructure development was characterised by a conflict of interests. Uzbekistan expressed concern about the potential negative impact of the Kambar-Ata-1 (1,900 MW) and Kambar-Ata-2 (360 MW) on the hydrological regime of the Naryn River and water supply to agricultural areas in the Fergana Valley. A shift in positions occurred in 2016-2017 as part of the intensification of bilateral dialogue at the highest level. In 2017, a Memorandum of Understanding was signed between the joint-stock company (JSC) Electric Power Plants (Kyrgyzstan) and JSC Uzbekhydroenergo, establishing the institutional framework for the joint development of the Kambar-Ata-1 project. This agreement marked the transition from a confrontational model to a cooperative approach in the field of transboundary water and energy cooperation. The conceptual basis for this transformation was Uzbekistan's new foreign policy strategy, initiated after 2016, which prioritises regional integration and the building of constructive relations with neighbouring states. Tashkent's recognition of the legitimacy of Kyrgyzstan's hydropower interests, while taking into account the water management needs of downstream countries, was of fundamental importance. This approach represents a departure from the traditional "zero-sum" paradigm in favour of a model of mutually beneficial cooperation based on the principles of sharing the benefits of transboundary water resources. This joint assessment mechanism is an innovative tool for preventive diplomacy in the region, aimed at minimising potential disagreements at the early stages of project design. The evolution of the legal framework for transboundary water use is characterised by a gradual transition from Soviet regulations to modern international legal standards. At the same time, the absence of a universal regional agreement regulating the use of transboundary water resources in the Amu Darya and Syr Darya basins remains a significant institutional gap. Table 2 shows the water and energy potential of Central Asian countries, with Tajikistan leading in terms of energy potential.

Table 2. Water and energy potential of Central Asian countries

Central Asian countries	Hydropower potential (MW)	Installed capacity (MW)
Kazakhstan	27,000	8,861
Kyrgyzstan	163,000	10,778
Tajikistan	317,000	15,086
Turkmenistan	2,000	–
Uzbekistan	15,000	7,278
Afghanistan	400	595
Total	524,400	42,598

Source: compiled by the author based on J. Granit *et al.* (2010)

In Central Asia, Tajikistan and Kyrgyzstan have a geographical advantage in terms of water resources, but economically they are weaker than the countries located downstream. For Tajikistan, water resources are practically the only external political asset in its relations with Uzbekistan and Turkmenistan. According to Worldometer (n.d.) data on the gross domestic product (GDP) of Central Asian countries, the Republic of Kazakhstan will have the largest GDP in 2024, estimated at approximately USD 261.42 billion. At the same time, the lowest GDP figures among the countries in the region are observed in Tajikistan, where it is forecast at USD 12.96 billion, and in Kyrgyzstan, at USD 13.6 billion (Table 3). The highest GDP growth among the countries in the region at the end of 2024 was demonstrated by Tajikistan (7.2%), Uzbekistan (6%) and the Kyrgyz Republic (5.8%). At the same time, Kazakhstan and Uzbekistan, given their population size, economic potential and geopolitical position with major international transport corridors passing through them, can be considered key regional players, and all neighbouring states are in constant interaction. However, the existence of multiple institutional mechanisms does not always translate into effective solutions to regional problems.

Table 3. Gross domestic product (GDP) of Central Asian countries

Country	GDP 2024, USD
Kyrgyzstan	13,600,000,000
Kazakhstan	261,420,000,000
Tajikistan	12,960,000,000
Turkmenistan	64,080,000,000
Uzbekistan	97,960,000,000
Total	450,020,000,000

Source: compiled by the author based on Worldometer (n.d.)

Recommendations for improving water diplomacy in Central Asia

Effective intergovernmental cooperation in the field of water use is becoming a decisive factor in ensuring sustainable development, political stability and security in Central Asia. A new intergovernmental compromise is needed to ease existing tensions. This would equally recognise the needs and interests of all Central Asian countries and lead to unified regional water resource management. Such an approach requires consideration of the economic and social interests of countries and takes into account the ecological balance in Central Asian water basins (Janusz-Pawletta & Gubaidullina, 2015). However, water shortages caused by climate change, population growth, increased demand for water and inefficient water management are exacerbating the region's problems. According to J. Sehring (2006), the water resources of Central Asia are of strategic importance that goes beyond the borders of individual states, making regional cooperation a necessary condition for preventing conflicts and achieving sustainable development goals.

An analysis of the current state of water diplomacy in Central Asia allows for formulating a set of strategic recommendations aimed at strengthening the institutional foundations of transboundary cooperation and establishing sustainable water resource management mechanisms. The proposed measures cover the legal, institutional, technological and diplomatic aspects of water cooperation, taking into account the special role of the Kyrgyz Republic as an upstream country and the need to balance the interests of all states in the region. The implementation of these recommendations will facilitate the transition from a confrontational model to an integrated approach to transboundary water resources management.

1. The role of water diplomacy as a tool for regional cooperation in Central Asia. The author believes that it is time for the states of Central Asia to move towards joint and coordinated management of water and energy resources, using the prism of water diplomacy. This could be facilitated by the creation of a commercial organisation, such as an international water and energy consortium, and the revival of a regional resource management organisation based on modern market mechanisms.

2. Sustainable water resource management in transboundary river basins. Countries located in transboundary river basins share a common culture, language, history and experience of joint water resource management. This aspect is a powerful factor for further unification and strengthening of cooperation between neighbouring countries.

3. Institutional and legal mechanisms for management. The author points to the weakness of the institutional framework for water resources management. It is necessary to strengthen and modernise institutional cooperation that will reflect the interests of all countries in the basin. Central Asian states should strengthen and improve the implementation of the existing legal framework by adding principles and improved cooperation mechanisms to it. In this context, there is a need to move away from declarative positions and develop legally binding documents on basin management based on international law. These documents should be aimed at adapting to climate change.

4. The importance of the "Central Asia as One Regional Voice" platform. It is expected that the creation of such a platform, which will include representatives of the Central Asian states and Afghanistan, will also contribute to the formation of experience in creating an institutional foundation.

5. A comprehensive approach to solving water problems. Not only professional water resource specialists, but also scientists and experts from various fields should be involved in solving water issues. Analytical platforms should be created and comprehensive studies conducted, including political, technical and environmental forecasts.

6. Kyrgyzstan's role in transboundary river management. Given that Kyrgyzstan is the source country for major transboundary rivers such as the Syr Darya and Chu, its role in water resource management in Central Asia is particularly important. Kyrgyzstan's position and its policies on water resource management and hydropower development have a direct impact on the entire hydrological situation in the region. Therefore, any strengthening of institutional cooperation and

development of water-energy consortia must take into account the interests and contribution of Kyrgyzstan as a key player in this system. Kyrgyzstan, along with other countries in the region, needs to participate in the creation of sustainable mechanisms that will ensure the equitable distribution of water resources and minimise the risks associated with climate change. This includes not only technical solutions, but also active participation in water diplomacy aimed at building trust and long-term partnerships with neighbouring countries.

7. The development of agreed criteria and methodologies for resolving inter-state water issues, the conclusion of bilateral and multilateral agreements related to new inter-state water sharing, compensation for damage caused by violations of inter-state water distribution agreements, and the creation of a modern information system.

8. It is necessary to develop cooperation between research institutes and universities in Central Asia to solve water problems in the region.

The implementation of these recommendations requires the political will of all Central Asian states and a willingness to compromise based on the principles of mutual benefit and sustainable development. Of particular importance is the creation of effective institutional mechanisms, backed by legally binding agreements and modern technological solutions. The Kyrgyz Republic, occupying a key position in the region's hydrological system, has the opportunity to initiate the formation of a new paradigm of water diplomacy based on the principles of equitable water use, environmental responsibility and long-term regional partnership. The successful implementation of these recommendations will not only ensure water and energy security in the region, but will also lay the foundation for broader economic and political integration among the countries of Central Asia.

Conclusions

The study of institutional mechanisms for transboundary water resources management in Kyrgyzstan has identified key factors determining the effectiveness of regional water cooperation and its impact on the agricultural sustainability of the republic in the context of climate change. The analysis showed that the existing institutional architecture for transboundary water management is fragmented and insufficiently adapted to the modern challenges associated with climate change and increasing competition for water resources in the region. It has been established that the transformation of the water use system from a centralised Soviet model to independent national strategies has led to institutional gaps that hinder the effective distribution of water resources between upstream and downstream states. The conflict between the energy interests of Kyrgyzstan as a mountainous country and the irrigation needs of neighbouring states remains a central problem for regional cooperation, requiring the development of compromise institutional solutions.

The study demonstrated that climate change exacerbates existing institutional problems, increasing the instability of water resources and creating additional risks for Kyrgyzstan's agricultural sector. The observed reduction in glacial runoff, changes in river regimes and the increasing frequency of extreme hydrological events require a review of traditional approaches to water resource management and the introduction of adaptive institutional mechanisms. It has been found that Kyrgyzstan's bilateral agreements with neighbouring states, although providing a legal basis for cooperation, do not contain sufficient mechanisms for flexible response to climate-induced changes in the water balance. An analysis of the impact of institutional mechanisms on agricultural sustainability has shown that uncertainty in the distribution of water resources negatively affects the country's food security, reducing the predictability of agricultural production and hindering long-term investment planning in irrigation infrastructure. There is a need to develop integrated institutional approaches that synchronise water, energy and agricultural policies at the national and regional levels.

Prospects for further research are linked to a detailed study of the economic mechanisms for compensating for water ecosystem regulation services provided by the mountainous areas of Kyrgyzstan, the development of institutional design models for adapting water management systems to different climate scenarios, and analysis of the role of international organisations and donor institutions in shaping regional water policy. In-depth research is needed on the potential of digital technologies and remote monitoring to increase transparency and objectivity in the distribution of transboundary water resources. A relevant area of research is the study of the social aspects of water use and the participation of local communities in water management decision-making, which can contribute to the legitimacy and effectiveness of institutional mechanisms.

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Conflict of Interest

The author declares that there is no conflict of interest.

References

[1] Abdullaev, I., *et al*. (2025). Current challenges in Central Asian water governance and their implications for research, higher education, and science-policy interaction. *Central Asian Journal of Water Research*, 7(1), 47-58. doi: 10.29258/CAJWR/2025-R1.v11-1/47-58.eng.

[2] Agency for Hydrometeorology of the Republic of Tajikistan. (n.d.). Retrieved from https://meteo.tj/en.

[3] Agreement between the Republic of Kazakhstan, the Kyrgyz Republic, the Republic of Uzbekistan, the Republic of Tajikistan and Turkmenistan on Cooperation in the Field of Joint Management of the Use and Protection of Water Resources of Interstate Sources (Alma-Ata Agreement). (1992, February). Retrieved from https://online.zakon.kz/Document/?doc_id=1045698&pos=2;-121#pos=2;-121.

[4] Akunova, G.Ch. (2021). Features of water diplomacy in Central Asia. *Post-Soviet Issues*, 8(2), 229-241. doi: 10.24975/2313-8920-2021-8-2-229-241.

[5] Borankulova, G., Altybayev, G., Tungatarova, A., Yeraliyeva, B., Dulatbayeva, S., Murzakhmetov, A., & Bekbolatov, S. (2025). Development of real-time water-level monitoring system for agriculture. *Sensors*, 25(17), article number 5564. doi: 10.3390/s25175564.

[6] Borisova, E.A. (2012). Features of the water crisis in Central Asia. *History and Modernity*, 1(15), 138-146.

[7] Boyarkina, O.A. (2015). Theoretical aspects of international water conflict research. *Conflictology*, 1, 65-77.

[8] Carec. (n.d.). Retrieved from https://centralasiaclimateportal.org/ru/topics/.

[9] Constitution of the Kyrgyz Republic. (2021, April). Retrieved from https://mkk.gov.kg/%D0%BA%D0%BE%D0%BD%D1%81%D1%82%D0%B8%D1%82%D1%83%D1%86%D0%B8%D1%8F-%D0%BA%D1%8B%D1%80%D0%B3%D1%8B%D0%B7%D1%81%D0%BA%D0%BE%D0%B9-%D1%80%D0%B5%D1%81%D0%BF%D1%83%D0%B1%D0%BB%D0%B8%D0%BA%D0%B8/.

[10] Convention on the Protection and Use of Transboundary Watercourses and International Lakes. (1992, March). Retrieved from https://treaties.un.org/pages/viewdetails.aspx?src=treaty&mtdsg_no=xxvii-5&chapter=27&clang=_en.

[11] Data from the Ministry of Finance of the Kyrgyz Republic. (2025). Retrieved from https://economist.kg/ekonomika/2025/09/01/rost-vvp-na-8-2-v-ghod-22-mlrd-tovarooborota-sriedniaia-zp-v-61-8-tysiachi-somov-chto-zhdiet-kyrghyzstan-k-2030-ghodu/.

[12] Dukhovny, V.A., & de Schutter, J. (2011). *Water in Central Asia: Past, present, future*. Boca Raton: CRC Press.

[13] Economic and Social Commission for Asia and the Pacific (ESCAP). (2017). *Achieving the sustainable development goals in North and Central Asia*. Bangkok: United Nations Publication.

[14] Free World Maps. (n.d.). Retrieved from https://www.freeworldmaps.net/asia/central/physical.html.

[15] Frenken, K. (Ed.). (2013). *Irrigation in Central Asia in figures*. Rome: FAO.

[16] General Assembly of the United Nations. (1993). *Resolution 47/193. Observance of World Day for Water*. Retrieved from https://docs.un.org/en/A/RES/47/193.

[17] Granit, J., Jägerskog, A., Löfgren, R., Bullock, A., de Gooijer, G., Pettigrew, S., & Lindström, A. (2010). Regional water intelligence report Central Asia. Stockholm: SIWI.

[18] Homer-Dixon, T.F. (1999). *Environment, scarcity, and violence*. Princeton: Princeton University Press.

[19] Issakov, Y., Sarkytkan, K., Gajić, T., Akhmetova, A., Berdygulova, G., Zhoya, K., Razia, T., & Matigulla, B. (2025). Climate-induced transboundary water insecurity in Central Asia: Institutional challenges, adaptation responses, and future research directions. *Water*, 17(12), article number 1795. doi: 10.3390/w17121795.

[20] Janusz-Pawletta, B., & Gubaidullina, M. (2015). Transboundary water management in Central Asia. *Cahiers d'Asie Centrale*, 25, 195-215.

[21] Kukushkina, A.V., & Sodikov, Sh.D. (2018). The problem of the international legal status of water resources in Central Asia. *Law and Right*, 12, 31-39. doi: 10.24411/2073-3313-2018-10258.

[22] Kyrgyzhydromet. (n.d.). Retrieved from https://meteo.kg/ru/pages/agrometerological-forecasts-and-references.

[23] Law of the Kyrgyz Republic No. 76 "On the Interstate Use of Water Bodies, Water Resources and Water Management Structures of the Kyrgyz Republic". (2001, July). Retrieved from https://cbd.minjust.gov.kg/483/edition/282586/ru.

[24] Law of the Kyrgyz Republic No. 257 "On the Introduction of a Moratorium on the Transfer (Transformation) of Irrigated Arable Lands into Other Land Categories and Types of Lands". (2009, July). Retrieved from https://cbd.minjust.gov.kg/4-4021/edition/1285841/ru.

[25] Ministry of Energy and Water Resources of the Republic of Tajikistan. (n.d.). Retrieved from https://www.mewr.tj/.

[26] Murzakulova, A., Schmidt-Vogt, D., Balla, D., Darr, D., Hamidov, A., Kasymov, U., Mendelevitch, R., & Orazgaliyev, S. (2019). Water for agriculture and other economic sectors. In S. Xenarios, D. Schmidt-Vogt, M. Qadir, B. Janusz-Pawletta & I. Abdullaev (Eds.), *The Aral Sea basin* (Chapter 7). London: Routledge.

[27] National Water Strategy of the Kyrgyz Republic until 2040. (2023). Retrieved from https://faolex.fao.org/docs/pdf/kyr229064.pdf.

[28] Potekhin, O., & Fesenko, M. (2022). Solving the Border Issues of the USA and Canada in the Field of Joint Use of Water Resources. *Foreign Affairs*, 32(2), 9-15. doi: 10.46493/2663-2675.32(2).2022.9-15.

[29] Prniyazova, A., Turaeva, S., Turgunov, D., & Jarihani, B. (2025). Sustainable transboundary water governance in Central Asia: Challenges, conflicts, and regional cooperation. *Sustainability*, 17(11), article number 4968. doi: 10.3390/su17114968.

[30] Pulatov, Ya.E., & Mukhabbatov, H.M. (2021). Water resources of the Aral Sea basin, water separation and ways to solve water scarcity. *Central Asian Journal of Geographical Research*, 1-2, 70-83.

[31] Rakhimov, M.A., Umarov, A., & Ismailova, G. (Eds.). (2024). *Central Asia and European Union: In search of sustainability*. Tashkent: University of World Economy and Diplomacy.

[32] Rogozhina, N.G. (2015). *Environmental policy of developing states*. Moscow: Aspekt-Press.

[33] Saida, N. (2023). *The Taliban's new canal threatens water security in Uzbekistan and Turkmenistan*. Retrieved from https://thediplomat.com/2023/07/the-talibans-new-canal-threatens-water-security-in-uzbekistan-and-turkmenistan/.

[34] Sehring, J. (2006). *The politics of water institutional reform in neo-patrimonial states. A comparative analysis of Kyrgyzstan and Tajikistan*. Wiesbaden: VS Verlag. doi: 10.1007/978-3-531-91377-3.

[35] Sokeyev, A. (2023). *Kyrgyzstan considers water a foundation for mutually beneficial cooperation*. Retrieved from https://news.un.org/ru/interview/2023/03/1439172.

[36] The Helsinki Convention. (1992, April). Retrieved from https://helcom.fi/about-us/convention/.

[37] United Nations Economic Commission for Europe (UNECE). (n.d.). Retrieved from https://unece.org/.

[38] United Nations. (2025). *Why are over 670 million people going hungry?* Retrieved from https://news.un.org/en/story/2025/10/1166108.

[39] Usubaliev, T.U. (1998). *Water is more valuable than gold. Kyrgyzstan's water resources are its national wealth*. Bishkek: Sham.

[40] Vinokurov, E., Ahunbaev, A., Usmanov, N., & Sarsembekov, T. (2022). *Regulation of the water energy complex of Central Asia*. Almaty: Eurasian Development Bank.

[41] Water Code of the Kyrgyz Republic. (2005, January). Retrieved from https://cbd.minjust.gov.kg/1605/edition/1201418/ru.

[42] World Population Review. (n.d.). *Population pyramids of the world from 1950 to 2100*. Retrieved from https://www.populationpyramid.net/world/.

[43] Worldometer. (n.d.). Retrieved from https://www.worldometers.info/.

[44] Zeitoun, M., & Allan, J.A. (2008). Applying hegemony and power theory to transboundary water analysis. *Water Policy*, 10(2), 3-12. doi: 10.2166/wp.2008.203.

[45] Zeitoun, M., & Warner, J. (2006). Hydro-hegemony – a framework for analysis of transboundary water conflicts. *Water Policy*, 8(5), 435-460. doi: 10.2166/wp.2006.054.

Чек аралык суу ресурстарын башкаруунун институционалдык механизмдери жана алардын климаттын өзгөрүшү шарттарында Кыргызстандын айыл чарба туруктуулугуна тийгизген таасири

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Аннотация. Кыргыз Республикасы Борбордук Азиянын гидрологиялык системасында стратегиялык орунду ээлейт, анткени ал аймактын эң ири чек аралык дарыяларынын – Амудария жана Сырдариянын агымын калыптандырууну көзөмөлдөгөн жогорку агымдагы мамлекет болуп саналат. Климаттын өзгөрүшү дарыялардын жылдар аралык агымынын өзгөрмөлүүлүгүн жогорулатып, аймактын айыл чарба секторунун туруктуулугу жана Борбордук Азиядагы суу башкаруунун аймактык саясатын ишке ашыруу үчүн критикалык кыйынчылыктарды жаратууда. Жогорку агымдын энергетикалык кызыкчылыктары (кышында ГЭС үчүн суу топтоо) менен төмөнкү агымдын айыл чарба муктаждыктарынын (жайда сугат үчүн максималдуу суу берүү) ортосундагы структуралык конфликт Борбордук Азиянын азык-түлүк коопсуздугуна коркунуч туудурат. Изилдөөнүн максаты чек аралык сууларды башкаруунун институционалдык механизмдерин жана алардын айыл чарбанын туруктуулугун камсыз кылуу үчүн адаптациялык потенциалын талдоо болуп саналат. Учурдагы институционалдык системанын критикалык кемчиликтери аныкталды; талдоо Мамлекеттер аралык координациялык суу чарба комиссиясынын (МКСКК) чектелүү жөнгө салуу ыйгарым укуктарына ээ экенин көрсөттү, комиссиянын чечимдери сунуштоо мүнөзүнө ээ. Бассейндик уюмдарда суу керектөө лимиттерине баш ийдирүү механизмдери жок. Суунун азаюу шарттарында системанын эффективдүүлүгү кескин төмөндөп, суу бөлүштүрүү макулдашууларын бузгандык үчүн формалдуу санкциялар системасы жок. Изилдөөнүн алкагында Кыргызстандын улуттук суу стратегияларын трансчектүү суу ресурстарын биргелешип башкаруу боюнча аймактык демилгелер менен шайкештирүү мүмкүнчүлүктөрү, келишим-укуктук механизмдерди климаттык тобокелдикке адаптациялоонун келечектери жана мамлекеттер аралык милдеттенмелерди аткарууну текшерүү механизмдерин өнүктүрүү талданды. Суу ресурстарын адаптивдүү башкаруунун модели сунушталды, үч деңгээлдүү система иштелип чыккан: (1) резервуар сактагыч аркылуу маусымдуу агымдарды кайра бөлүштүрүү; (2) климаттык болжолдорду эске алуу менен ийкемдүү квоталардын механизми; (3) айыл чарба секторунда сууну үнөмдөө үчүн экономикалык стимулдардын системасы. Изилдөөнүн жыйынтыктары суу башкаруунун институционалдык архитектурасы менен айыл чарбанын алсыздыгынын ортосундагы байланышты түшүнүүдөгү боштукту толтурат жана Борбордук Азияда конфликттик потенциалды минималдаштырууга жана интеграцияланган аймактык өнүгүүнү стимулдаштырууга салым кошкон, туруктуу жана институционалдык жактан натыйжалуу чек аралык суу ресурстарын башкаруу системасын түзүү боюнча илимий негизделген сунуштарды түзүүгө мүмкүндүк берет

Негизги сөздөр: суу коопсуздугу; суу-энергия байланышы; гидроэнергетикалык потенциал; климаттын өзгөрүшүнө адаптация

Институциональные механизмы управления трансграничными водными ресурсами и их влияние на аграрную устойчивость Кыргызстана в условиях климатических изменений

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Аннотация. Кыргызская Республика занимает стратегическое положение в гидрологической системе Центральной Азии как государство верховьев, контролирующее формирование стока крупнейших трансграничных рек региона – Амударьи и Сырдарьи. Климатические изменения, увеличивающие межгодовую изменчивость речного стока, создают критические вызовы для устойчивости аграрного сектора региона и реализации региональной политики водного управления в Центральной Азии. Структурный конфликт между энергетическими интересами верховьев (накопление воды зимой для гидроэлектростанций) и аграрными потребностями низовьев (максимальная водоподача летом для ирригации) угрожает продовольственной безопасности региона. Целью исследования был анализ институциональных механизмов управления трансграничными водами и их адаптационного потенциала для обеспечения аграрной устойчивости. Выявлены критические дефициты действующей институциональной системы; анализ показал, что Межгосударственная координационная водохозяйственная комиссия (МКВК) обладает ограниченными регуляторными полномочиями, решения комиссии носят рекомендательный характер. Бассейновые организации не имеют механизмов принуждения к соблюдению лимитов водопотребления. В условиях маловодья эффективность системы резко снижается, и отсутствует формальная система санкций за нарушения водораспределительных соглашений. В исследовании рассмотрены пути согласования национальной водной политики Кыргызстана с региональными инициативами по управлению трансграничными водами, а также возможности адаптации существующих договорных механизмов к климатическим рискам и создания системы контроля за выполнением межгосударственных обязательств. Предложена модель адаптивного управления водными ресурсами, разработана трехуровневая система: (1) сезонное перераспределение потоков через резервуарное хранилище; (2) механизм гибких квот с учетом климатических прогнозов; (3) система экономических стимулов для водосбережения в аграрном секторе. Результаты исследования заполняют пробел в понимании связи между институциональной архитектурой водного управления и аграрной уязвимостью и позволяют сформулировать научно обоснованные рекомендации по созданию более устойчивой и институционально эффективной системы трансграничного управления водными ресурсами, способствующей минимизации конфликтного потенциала и стимулированию интегрированного регионального развития в Центральной Азии

Ключевые слова: водная безопасность; водно-энергетическая связь; гидроэнергетический потенциал; адаптация к изменению климата

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Foreign investments as a factor in the modernisation of agriculture and the strengthening of foreign economic relations

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Abstract. In the context of globalisation and the growing interdependence of world markets, foreign investment serves as a key driver for the modernisation of agriculture, technological advancement, and the strengthening of external economic relations. For the Kyrgyz Republic, where the agricultural sector traditionally plays a crucial role in ensuring employment, food security, and export capacity, the attraction of long-term foreign capital is of strategic importance. The study aimed to analyse the mechanisms for attracting foreign investment into the agricultural sector of Kyrgyzstan and to assess its impact on enhancing the competitiveness of domestic agri-food products in international markets. Special attention was given to identifying the factors that facilitate or hinder investment activity, as well as to defining priority areas for cooperation with foreign partners. The research employed comparative and structural analysis, methods of economic and statistical modelling, and a review of international best practices in agricultural investment development. This methodological approach allowed the identification of both general trends and specific features of investment dynamics in the Kyrgyz agricultural

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sector. The analysis revealed that foreign investment contributes to the introduction of modern technologies, the development of processing industries, the improvement of rural infrastructure, and the growth of export potential. However, institutional, legal, and organisational barriers – such as imperfect legislation, bureaucratic procedures, and insufficient investor protection – continue to limit investment inflows. The study proposed a set of measures to improve the investment climate, strengthen the regulatory framework, promote public-private partnerships, and encourage innovative financing mechanisms. The practical significance of the research lies in the potential use of its findings by government bodies, investors, and business entities in developing effective strategies for agricultural modernisation and for integrating the Kyrgyz Republic into the global economic system

Keywords: agricultural sector; state; globalisation; development; regulation; export

Introduction

In the context of globalisation of the world economy, improving the efficiency of the national economy is only possible on the basis of accelerated innovation and investment development. A country's potential upon entering the global economic space largely determines its prospects. In this context, foreign investment is a key factor in increasing competitiveness, stimulating economic growth and deepening the integration of the national economy into the global economic system. According to FAO (n.d.) estimates, annual investment in agriculture in developing countries should amount to approximately USD 205 billion per year in the period 2025-2030. This is necessary to provide food for 9 billion people, as well as to improve the efficiency of soil fertility management, rational use of water resources and conservation of biological diversity.

According to NSCKR (n.d.), as of 2024, agriculture accounted for approximately 8.6% of Kyrgyzstan's gross domestic product (GDP). At the same time, approximately 23.9% of the working-age population was employed in the agricultural sector. Agricultural exports in 2024 were estimated at approximately 34 billion soms. For millions of residents, rural areas remain the main source of income and employment, making the agricultural sector not only economically but also socially significant for development. However, according to the United Nations (2024), the current state of agriculture in Kyrgyzstan is characterised by a number of systemic problems, including low levels of technological equipment in production processes, limited access to modern agricultural technologies, weak development of processing enterprises, and inadequate infrastructure for storage, transport and marketing of products. All this reduces the competitiveness of local agricultural products and limits their opportunities to enter foreign markets (Dzhailov & Mardalieva, 2025). In such conditions, as noted by I. Ryskulbekov (2023), foreign investment is seen as one of the key instruments for modernising the agricultural sector. Its inflow contributes not only to the renewal of the material and technical base, but also to the introduction of modern management approaches, increased labour productivity and expanded export opportunities.

Expanding foreign economic ties through the export of agricultural and processed products, introducing xinternational quality standards, product certification, and participation in integration associations (in particular, within the Eurasian Economic Union) opens up new horizons for the development of Kyrgyzstan's agricultural sector. Foreign investment plays an important role in this process, promoting the introduction of innovative technologies, the development of transport and logistics infrastructure, increasing processing efficiency and ensuring the sustainable development of rural areas (Yang *et al.*, 2025). As noted by D. Omuralieva & S. Zholdoshbekova (2024), the modernisation of agriculture is of particular importance for Kyrgyzstan, as it is directly linked to the diversification of the economy, the growth of employment and living standards in the regions, the strengthening of food independence, and the sustainable development of the agro-industrial sector, which plays a key role in ensuring the country's food security and economic growth in general. The development of the agricultural sector based on attracting foreign capital not only increases production and export volumes, but also enhances the overall investment attractiveness of the republic's economy. The aim of this study was to conduct a comprehensive analysis of the role of foreign investment in the modernisation of agriculture in the Kyrgyz Republic and to assess its significance for strengthening the country's foreign economic relations.

Literature Review

The issue of attracting foreign investment in agriculture has been the focus of economists, researchers and practitioners over the past decades. In the context of globalisation and the formation of a global food market, investment is seen as a key tool for the sustainable development of the agricultural sector and increasing its competitiveness. K. Mateeva & L. Mazur (2024) studied trends in Kyrgyzstan's foreign economic cooperation and the problems of integration into the Eurasian Economic Union (EAEU). E. Zakirova (2017) examined mechanisms for financing the agricultural sector, including public-private partnerships. R. Makhmudov (2025) analysed the impact and determinants of foreign investment on economic growth, structural transformation and the competitiveness of the host country. Regional studies on Central Asia by the EDB (2023) showed that investments aimed at developing infrastructure, irrigation, processing and certification of products according to international standards were the most effective. This directly affected the competitiveness of agricultural products in foreign markets and strengthened foreign economic ties.

From the perspective of sustainable development, investments in the agricultural sector should be directed not only towards improving economic efficiency, but also towards ensuring environmental balance, rational use of natural resources and social sustainability in rural areas (Chupryna *et al.*, 2025). These principles were first systematically set out by WCED (1987), but were further developed in the UN Sustainable Development Goals adopted in 2015 and updated in subsequent strategies of other international organisations (United Nations, 2015). This is particularly important for the Kyrgyz Republic, where agriculture provides employment for a significant part of the working-age population, forming the basis of food security and making a significant contribution to the development of the country's regions (National Development Strategy of the Kyrgyz Republic, 2018; FAO, n.d.). Sustainable investment in agriculture makes it possible to simultaneously address the challenges of increasing productivity, protecting the environment and developing rural areas.

Research by the World Bank (2024), FAO (n.d.) and ADB (n.d.) shows that foreign direct investment in the agricultural sector of developing countries contributes to: growth in the production and export of agricultural products; the introduction of innovative technologies in crop and livestock production; the formation of agro-industrial clusters; the improvement of rural personnel qualifications; and the development of infrastructure for storage, processing and marketing of products. However, the positive impact of foreign investment is not automatic – it largely depends on the investment climate, the level of institutional development, the transparency of the legal system, and government policy in the field of investment regulation (Saha *et al.*, 2022). In the absence of effective control and support mechanisms, foreign capital may concentrate only in the most profitable areas, without contributing to the development of socially significant sectors of agriculture.

In the context of Kyrgyzstan, the problem of attracting foreign investment in the agricultural sector takes on a particular specificity. On the one hand, the country has favourable natural and climatic conditions, labour resources and a geographical location that provides access to the large markets of the EAEU and China. On the other hand, institutional constraints remain, including unstable legislation, bureaucratic barriers, weak infrastructure, and limited financial instruments to support investors. Thus, a review of theoretical and empirical sources leads to the conclusion that foreign investment is an integral element of the sustainable development of Kyrgyzstan's agricultural sector, providing an inflow of capital, technology and management expertise. Their effective use requires the creation of a favourable institutional environment and long-term government policies aimed at increasing the investment attractiveness of agriculture.

Materials and Methods

The theoretical basis of the study was based on the concept of investment attractiveness, the OLI paradigm model of foreign direct investment by J. Dunning (2001), and the investment multiplier theory, which reflects the relationship between the volume of investment and the growth of national income. The application of these approaches made it possible to comprehensively examine the impact of foreign investment on the structural modernisation of agriculture and its integration into the global economic system. The study used comparative and structural analysis methods, as well as a systematic approach and a review of international experience in the field of investment development in the agricultural sector. This comprehensive approach made it possible to identify general patterns and specific features of investment dynamics in the agricultural sector of the Kyrgyz Republic.

The study analysed the mechanisms for attracting foreign investment in the agricultural sector and their impact on the modernisation of agriculture, as well as the strengthening of foreign economic ties. Three countries were selected for comparative analysis: Uzbekistan, Russia and China, each of which represents different models of agricultural policy and strategies for attracting foreign investment. Uzbekistan was selected for its active reform of the agricultural sector, aimed at creating institutional conditions for attracting investment and developing agricultural clusters, which can serve as an example for Kyrgyzstan in forming a favourable investment environment. Russia was highlighted as a country with a developed system of state subsidies and support for agricultural exports, which is important for the Kyrgyz Republic in terms of expanding its export potential and strengthening its infrastructure. China is interesting for its large-scale technological modernisation and integration into global production chains, including the use of digital technologies and mechanisms to stimulate foreign direct investment, which could be a useful reference point for Kyrgyzstan in developing its agro-industrial complex.

The experimental basis for the study was provided by statistical data from national statistical agencies and international organisations – FAO (2023; n.d.), World Bank (2024), IMF (2024), etc. The research methods included: comparative analysis to identify similarities and differences in approaches to attracting foreign investment and the results of their impact on the agricultural sectors; structural analysis to assess the distribution of investments by type of activity, form of investment and their impact on production processes and exports; statistical analysis to determine the significance of the differences identified between countries.

Results and Discussion

Figure 1 shows the structure of foreign investment by sector of the Kyrgyz Republic's economy in 2020-2024, reflecting the dynamics of sectoral priorities and the degree of diversification of flows.

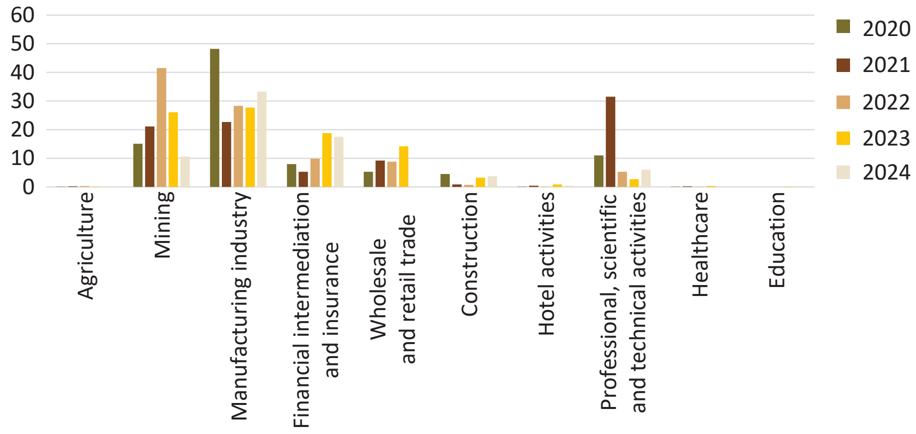

Figure 1. Structure of foreign investment in the economy of the Kyrgyz Republic

Source: compiled by the authors based on NSCKR (n.d.)

The analysis showed that the largest share of foreign investment in the Kyrgyz Republic continues to be in mining and manufacturing, which together accounted for up to 70% of total inflows. In 2024, the share of mineral extraction decreased to 10.6% (compared to 26.1% in 2023), while the share of manufacturing increased to 33.3% (compared to 27.7% in 2023). This indicates a redistribution of investment within the industrial sector and a further strengthening of the manufacturing industry's position. Agriculture, tourism, healthcare and education remain the least attractive to foreign investors, indicating an imbalance in the distribution of capital. In 2024, the share of agriculture remained at 0.1%, healthcare at 0%, and education at 0.3%. Tourism also continues to remain on the periphery with a share of 0.4% in 2024, despite the industry's high potential.

The raw materials sector continues to dominate, but in 2024 there was a redistribution of flows within the industrial bloc. Mineral extraction is declining, while manufacturing is regaining its share, indicating potential diversification of the economy. The financial sector continues to grow steadily, confirming the development of financial technologies and the expansion of the banking sector. This reflects improved confidence in financial services in the country. Wholesale and retail trade and construction have shown significant fluctuations: trade significantly reduced its share in 2024, while construction regained its position, which is associated with the return of investor interest in infrastructure projects. Social sectors continue to remain on the periphery of foreign investment, requiring reforms to stimulate investment in strategically important industries. In particular, agriculture, healthcare and education remain the least attractive to foreign investors. Tourism continues to be unattractive to foreign investment, indicating the need for additional measures to stimulate growth in this sector. An analysis of the dynamics of foreign investment inflows is presented in Table 1.

Table 1. Foreign investment inflows into the Kyrgyz Republic in 2020-2024 (million USD)

Years	Total	Foreign direct investment	Portfolio investments	Other investments	Grants and assistance
2020	6,926.8	537.6	0.0	6,363.7	25.5
2021	6,331.4	1,006.1	1.0	5,289.0	35.3
2022	9,025.6	1,202.6	0.4	7,768.2	54.4
2023	7,110.6	844.9	0.3	6,168.8	96.6
2024	6,921.0	1,029.7	3.1	5,865.4	22.8

Source: compiled by the authors based on NSCKR (n.d.)

Table 1 shows that total foreign investment in 2024 returned to 2020 levels (USD 6,921.0 million), which may be due to changes in the global economic and investment climate, as well as the influence of external factors such as economic instability, global inflation, or the geopolitical situation. Foreign direct investment (FDI) showed growth until 2022, but declined in 2023, which may be due to economic uncertainty or changes in the priorities of foreign investors. In 2024, FDI increased slightly again, but did not reach the level of 2022. Portfolio investment remains extremely low, reflecting limited investor interest in short-term investments in securities and other financial assets in Kyrgyzstan. Other investments remain the main category of foreign investment, accounting for the bulk of foreign inflows into the economy. A peak was recorded in 2022, but their volume has declined slightly in the last two years. Grants and aid show a slight increase in 2022-2023, but in 2024 there is a significant reduction, which may indicate a reduction in international aid or grants to Kyrgyzstan. Figure 2 shows data on the distribution of foreign direct investment by investor country.

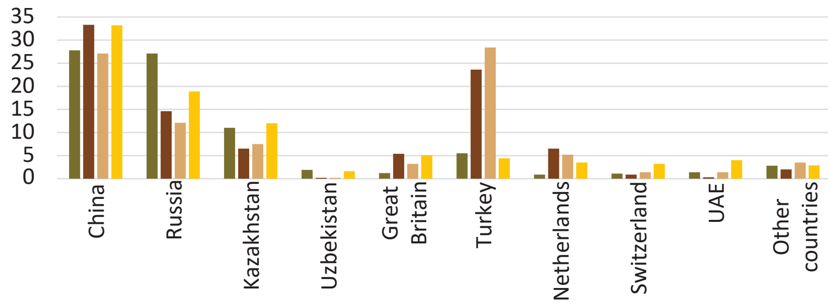

Figure 2. Main countries investing in the economy of the Kyrgyz Republic in 2020-2023
Source: compiled by the authors based on research by NSCKR (n.d.)

The results of the analysis showed that the structure of foreign investment in Kyrgyzstan is characterised by high geographical concentration. In 2023, the main investments came from China and Russia, whose shares were 27.8% and 27.1%, respectively. These countries continue to occupy dominant positions in the Kyrgyz economy, reflecting their strategic partnership with the republic. Turkey and Kazakhstan remain important investors, but their shares vary, which may indicate instability in the political and economic situation in these countries. At the same time, the United Kingdom and the Netherlands have significantly reduced their investments in Kyrgyzstan, which may be due to a decline in their interest in the republic for economic and political reasons. Switzerland and the UAE have shown mixed dynamics: the UAE is gradually increasing its investments, while Switzerland is maintaining a stable but low level of investment. The share of investments from other countries has also decreased. In 2023, the volume of foreign direct investment from non-CIS countries increased by 4.1% compared to 2022. This was made possible by growth in investments from Turkey and China. Investments from CIS countries increased 1.6 times, which is associated with growth in investments from Russia, Kazakhstan and Uzbekistan. The main investor countries in 2023 were China (27.8% of total investment), Russia (27.1%), Kazakhstan (11%) and Turkey (5.5%).

The analysis showed that attracting foreign investment to the economy of the Kyrgyz Republic is limited by a number of systemic factors that hinder the long-term development of foreign economic relations. Among these barriers, the most significant are institutional risks, infrastructure constraints and legal instability. Infrastructure constraints also had a significant impact: despite its favourable geographical location, the underdevelopment of transport, energy and digital infrastructure hampered Kyrgyzstan's integration into international value chains and restrained investment activity. Similar conclusions are presented in reports by the World Bank and ADB (2023), which view the modernisation of logistics, energy and digital services as a necessary condition for reducing trade costs and attracting investment. Legal instability manifested itself in frequent changes to tax and customs legislation and insufficient protection of property rights, which created significant risks for long-term investments. The World Bank (2025) emphasised that it was precisely the unpredictability of the legal environment that remained one of the key factors in investors' cautious attitude towards Kyrgyzstan.

The results of the study confirm that foreign direct investment has a positive impact on productivity and technological modernisation in the agricultural sector of the Kyrgyz Republic, especially in the livestock and processing segments. Empirical studies conducted in Kyrgyzstan show a positive correlation between the volume of investment and the efficiency of the agro-industrial complex, and also note the significant role of the transfer of management practices and technologies. FAO (2025) notes that in Kyrgyzstan and other Central Asian countries, the cluster approach in the agricultural sector has increased cooperation between farmers, agro-processing enterprises and financial institutions, contributing to productivity growth and market access.

FDI plays a key role in modernising Kyrgyzstan's agricultural sector, contributing to increased productivity, the introduction of new technologies and improved management. However, in order to maximise its impact, existing barriers such as limited access to modern technologies and insufficient coordination between the public and private sectors must be overcome. To gain a deeper understanding of the characteristics of attracting and utilising foreign direct investment in the agricultural sectors of the countries under review, it is advisable to conduct a comparative analysis of key indicators and mechanisms for their implementation. This approach will identify effective practices and strategies that can be adapted to the conditions in Kyrgyzstan, taking into account its economic and climatic context. Table 2 presents a comparative analysis of foreign investment in the agricultural sector of the three countries.

Table 2. Comparison of foreign investment in the agricultural sector of Uzbekistan, Russia and China

Country	Foreign investment in the agricultural sector, billion USD	Share of agriculture in GDP	Exports of agricultural products, billion USD	Main areas of investment
Uzbekistan	2.1 (2023)	17%	5.3 (2023)	Water conservation technologies, infrastructure modernisation, agricultural technologies
Russia	3.0 (2023)	4.5%	35.6 (2023)	Innovative agricultural technologies, processing, export of agricultural products
China	4.5 (2023)	7.2%	120.4 (2024)	Export of dairy products, agricultural technology, sustainable agriculture

Source: compiled by the authors based on IMF (2024), World Bank (2024), Rosstat (n.d.), National Bureau of Statistics of China (n.d.), National Statistics Committee of the Republic of Uzbekistan (n.d.)

An analysis of foreign investment trends in the agricultural sectors of Uzbekistan, Russia and China reveals significant differences due to the economic potential, scale of production and government policy priorities of each country. With investments of USD 2.1 billion in 2023 and agriculture accounting for about 17% of GDP, Uzbekistan is characterised by the high importance of the agricultural sector for the national economy. The main areas of investment here are focused on water-saving technologies, infrastructure modernisation and the introduction of agricultural technologies. This strategy is aimed at improving the efficiency of natural resource use and sustainable agricultural development, which is particularly relevant for a country with limited water resources. Russia, despite the smaller share of agriculture in GDP (4.5%), attracts a relatively high volume of foreign investment – about USD 3 billion. Investments are directed towards innovative agricultural technologies, processing and the development of agricultural exports. The significant volume of exports (USD 35.6 billion) testifies to a developed processing industry and a focus on foreign markets. Investments contribute to the modernisation of the industry and increase the competitiveness of the Russian agro-industrial complex. China stands out with the largest volume of foreign investment – USD 4.5 billion in 2023, with agriculture accounting for about 7.2% of GDP. Agricultural exports reached USD 120.4 billion in 2024, reflecting the scale and efficiency of the country's agricultural sector. Investments are focused on the development of dairy exports, the introduction of agricultural technologies and sustainable agriculture, which is in line with the state strategy to improve food security and environmental sustainability. Table 3 provides a comparative analysis of methods for attracting foreign investment in the agricultural sector of the countries analysed.

Table 3. Comparative analysis of methods for attracting foreign investment in the agricultural sector of Uzbekistan, Russia and China

Mechanisms for attracting investment	Key strategies and programmes	Effectiveness assessment	Notes
Uzbekistan			
Preferential taxation, simplified business registration procedures, subsidies for agricultural technology	Sustainable Agriculture Programme, infrastructure improvement	Growth in agricultural production, increase in agricultural exports	Active reforms, support for small and medium-sized enterprises in the agricultural sector, especially in the field of agricultural technology. Subsidies contribute to the modernisation and development of farms.
Russia			
State investment projects, support for digitalisation, incentives for investors	National Strategy for the Development of Agriculture, Mechanisation and Digitalisation	Growth in livestock farming and increased productivity	The programme to support the digitalisation and mechanisation of the agricultural sector has contributed to significant growth in productivity and an increase in agricultural production volumes.
China			
Innovation incentive programmes, subsidies, export support	Green agriculture policy, modernisation of processing	Increasing exports and introducing innovative technologies	The export promotion programme has significantly increased foreign trade in agricultural products.

Source: compiled by the authors based on IMF (2024), World Bank (2024), Rosstat (n.d.), National Bureau of Statistics of China (n.d.), National Statistics Committee of the Republic of Uzbekistan (n.d.)

A comparative analysis of practices for attracting foreign investment in the agricultural sector in Uzbekistan, Russia and China shows that each country adapts investment flows to its own economic conditions and priorities for the development of the agricultural sector. Uzbekistan focuses on the rational use of resources and basic infrastructure, Russia on technological modernisation and export potential, and China on large-scale production with a focus on sustainability and innovation. Kyrgyzstan can learn from these models, taking into account its own resources and challenges, to develop a balanced strategy for attracting and effectively utilising foreign investment in agriculture. Uzbekistan, Russia and China are achieving sustainable growth in foreign investment in the agricultural sector through institutional reforms, government support and innovative solutions.

Each country adapts its investment attraction strategy to its national economic, climatic and social characteristics. In Uzbekistan, according to the Ministry of Economy and Finance of the Republic of Uzbekistan (n.d.), institutional reforms aimed at simplifying business and supporting agricultural technologies have made it possible to modernise agricultural infrastructure and increase exports. In Russia, government projects and the promotion of digitalisation in the agricultural sector are ensuring productivity growth and strengthening export potential (Rosstat, n.d.). China is successfully implementing its Green Agriculture programme, actively introducing innovations and modernising processing facilities, which is contributing to significant export growth (IARRP, 2025). A comparison of the approaches of the three countries reveals some common patterns. First, the effectiveness of foreign investment in agriculture directly depends on institutional transparency and the stability of the legal regime. Second, prioritising processing, digitalisation and environmental standards enhances the synergistic effect between economic growth and sustainable development. Finally, systematic interaction between the state, the private sector and international institutions ensures the sustainable expansion of agricultural markets and shapes long-term investment attractiveness.

The experience of Uzbekistan, Russia and China in attracting and effectively utilising foreign investment in the agricultural sector is a valuable source of knowledge for Kyrgyzstan, which is striving to modernise and sustainably develop its agricultural industry. Uzbekistan demonstrates how institutional reforms can be successfully combined with the introduction of water-saving technologies and infrastructure modernisation, which is particularly relevant for Kyrgyzstan, given its limited natural resources and the need for rational water use. Tax incentives and subsidies aimed at supporting small and medium-sized agricultural enterprises can serve as an example for creating a favourable environment for investors and stimulating innovation in Kyrgyzstan's agriculture. Russia demonstrates the importance of focusing on technological modernisation and the development of processing industries to increase the added value of agricultural products and enter foreign markets. Kyrgyzstan should pay attention to the development of the processing industry in the agricultural sector, which will not only increase exports but also create new jobs, thereby enhancing the economic sustainability of rural areas. China is an example of integrating large-scale investments in innovative agricultural technologies and sustainable agriculture with a focus on environmental safety and food security in the country. It is important for Kyrgyzstan to adopt China's approach to the digitalisation of agricultural enterprise management and the development of sustainable production methods, which will help to increase efficiency and minimise negative environmental impacts. Overall, combining the experience of these three countries will enable Kyrgyzstan to develop a comprehensive strategy aimed at increasing the investment attractiveness of the agricultural sector, technological modernisation, strengthening export potential and the sustainable use of natural resources. This approach will contribute to the long-term development of agriculture and improve the quality of life of the rural population.

Foreign investment in Kyrgyzstan's agricultural sector has contributed to the introduction of modern technologies (smart greenhouses, precision farming, drip irrigation), the development of the processing industry, infrastructure improvements and the alignment of products with international standards, which together have strengthened the country's export potential. The data obtained in the course of this study were generally consistent with the results of other scientific publications, but certain differences were also identified. M. Abdiev & T. Kerimbaeva (2024) state that the successful operation of agricultural complexes largely depends on the volume of investment and its direction, with the most characteristic areas of agricultural investment being the introduction of the latest technologies and their adaptation to modern trends, investment in digital development, land and property leasing, and improving working conditions and animal care. A. Khitakhunov (2021) noted that in Central Asian countries, despite the vital role of agriculture in the regional economy, its development is hampered by low productivity and dependence on imports, which requires countries in the region to stimulate capital investment, improve institutional quality and implement climate adaptation strategies to enhance the sector's competitiveness. This conclusion was confirmed by the emphasis placed on the importance of investment in this study.

The work of K. Nurasheva *et al.* (2024) showed that foreign capital flowed mainly into labour-intensive industries, including agriculture, but the scale of investment remained low due to institutional and legal barriers. These findings coincided with the limitations identified in this study: institutional risks and legal instability seriously hampered the inflow of long-term capital. F. Cao *et al*. (2025), analysing the effectiveness of trade in agricultural products between China and Central Asian countries, concluded that countries with a more transparent institutional environment demonstrated significantly higher export performance. This result confirmed the conclusion made in the current work about the need for institutional support and the introduction of international quality standards to strengthen foreign economic relations. The experience of Kazakhstan is of particular interest. Kazakhstan's agricultural exports increased by 51% in 2020-2024 as a result of equipment modernisation and a focus on high value-added products (Investing in Kazakhstan's agriculture…, 2025). These data coincided with the findings of the current study on the importance of processing and modernisation, but the growth rate in Kyrgyzstan is lower due to smaller investments and weak infrastructure. A. Bekmuratov *et al*. (2025) examined the potential for cluster development in Kyrgyzstan's agricultural sector. The results showed that farmers belonging to cluster associations increased their yields by 15-25% and their profits by 20-30% by reducing production costs and expanding access to markets. These proposals were consistent with the findings of this study on the need to expand cooperation and value chains. However, the authors pointed to the lack of access for farmers to modern technologies and financial instruments, which was also confirmed by the results of this study.

The World Bank (2025) emphasised that the effectiveness of foreign investment increased when accompanied by technology transfer, the introduction of modern management practices, and increased competition. These findings coincided with the conclusions of this study on the importance of technology and processing, but the World Bank placed greater emphasis on market competition and the institutional environment, while this study focused on infrastructure and export standards. The literature paid particular attention to legal restrictions in the agricultural sector. According to the U.S. Department of State (2024), foreign investors were not allowed to directly own agricultural land in Kyrgyzstan, but joint ventures with local owners made it possible to reduce costs and improve product quality. This conclusion complemented the findings of the present study, which also noted the importance of partnerships for expanding export potential, although the legal aspects of land use were considered to a lesser extent. Finally, the study by I. Taranov & Y. Kawabata (2024) examined the role of participatory guarantee systems (PGS) in the development of organic agriculture in Kyrgyzstan. The authors showed that farmer cooperation and simplified certification mechanisms reduced transaction costs and facilitated the entry of products into organic markets. These results confirmed the thesis of this study on the need to diversify the export basket through niche products with high added value. Thus, the analysis showed that most contemporary studies confirm the key conclusions of this work: foreign investment is an important factor in the modernisation of agriculture and the strengthening of foreign economic ties. The differences primarily concerned the scale and speed of change, as well as the emphasis on the institutional environment or infrastructure aspects. Taken together, this reinforces the reliability of the recommendations made in this study on the need to prioritise funding for processing, logistics and certification systems, as well as on creating a sustainable investment climate in the agricultural sector of Kyrgyzstan.

The removal of institutional, infrastructural and legal barriers is a prerequisite for creating a favourable investment climate that promotes sustainable economic growth. For the Kyrgyz Republic, the priority in this area is the creation of specialised investment zones, industrial parks and industry clusters focused on priority sectors. This will ensure the inflow of both domestic and foreign investment, stimulate the modernisation of production capacity and increase employment in rural areas. Of particular importance is the development of public-private partnership mechanisms that provide financing for large-scale infrastructure and innovation projects and allow for the effective distribution of risks between the state and business. In this context, it is important to establish transparent rules for interaction, introduce project financing instruments and support investment-significant initiatives at the local level.

Further digitalisation of the economy, development of electronic government services and application of the "single window" principle for investors create additional incentives to improve the business environment, reduce administrative barriers and increase confidence on the part of private capital. Diversification of the structure of foreign investment is a key condition for sustainable and balanced growth. Attracting capital to agriculture, manufacturing, tourism, education and healthcare not only expands the economic base but also creates new sources of added value. Particular attention should be paid to the development of "green investments" – in renewable energy, resource-efficient technologies and environmentally safe production, which is in line with global trends in sustainable development. Thus, the use of adapted international experience, the improvement of legal and institutional mechanisms, and the creation of a predictable and stable investment environment can ensure a long-term inflow of capital into strategically important sectors. This will create the basis for a profound modernisation of agriculture, structural restructuring of the economy and strengthening of the Kyrgyz Republic's competitiveness in the global market.

Conclusions

The study provided a comprehensive assessment of the impact of foreign direct investment on the development of the agricultural sector in the Kyrgyz Republic, taking into account international experience. Based on a comparative analysis of investment dynamics in Uzbekistan, Russia and China, effective practices and strategic approaches were identified that contribute to the modernisation of agriculture, the strengthening of export potential and the sustainable use of resources. Analysis of statistical data showed that the largest volume of foreign investment in Kyrgyzstan is still concentrated in the extractive and processing industries, while the agricultural sector remains undercapitalised. This creates an imbalance in the structure of the economy and reduces opportunities for sustainable development in rural areas. At the same time, global experience shows that targeted government policies to attract investment, support for agricultural technologies, infrastructure development and institutional reforms can significantly increase the attractiveness of the agricultural sector to investors.

The results confirm that foreign direct investment is associated with productivity growth, innovation and technological upgrading, especially in segments such as livestock farming, product processing and sustainable agriculture. The examples of Uzbekistan, Russia and China show that successful agricultural transformation requires a combination of financial investment, competent regulation and strategic vision at the state level. For Kyrgyzstan, key areas of focus could include creating a favourable investment environment by simplifying procedures, developing agro-industrial clusters, supporting exports of high value-added products, and introducing digital solutions in the agricultural sector. It is also important to take environmental and social aspects into account, based on the principles of sustainable development. Prospects for further research include an in-depth econometric analysis of the impact of foreign investment on the production indicators of Kyrgyzstan's agro-industrial complex, a study of regional differences in investment activity, and the development of scenarios for the long-term development of the agricultural sector with the participation of foreign investors. In addition, the issue of assessing institutional barriers and risk factors that hinder the inflow of investment into the country's agriculture remains relevant.

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References
[1] Abdiev, M.Zh., & Kerimbaeva, T.E. (2024). Foreign experience of investments in agriculture. *Economics and Business: Theory and Practice*, 7(113), 6-9. doi: 10.24412/2411-0450-2024-7-6-9.
[2] Asian Development Bank (ADB). (2023). *Resilient and inclusive agricultural development and food security in the Central Asia Regional Economic Cooperation program member countries: Technical assistance report*. Retrieved from https://www.adb.org/projects/documents/reg-57033-001-tar.
[3] Asian Development Bank (ADB). (n.d.). *ADB annual reports*. Retrieved from https://www.adb.org/documents/series/adb-annual-reports.
[4] Bekmuratov, A., Mamashov, K., Tookeeva, D., Tashiev, N., & Mametova, G. (2025). Economic assessment of the impact of clusters on farm development in Kyrgyzstan. *Scientific Horizons*, 28(2), 157-169. doi: 10.48077/scihor2.2025.157.
[5] Cao, F., Li, X., & Zhang, Z. (2025). Does institutional openness improve the trade efficiency of China's agricultural products imported from Central Asian countries? A time-varying stochastic frontier gravity model. *Frontiers in Sustainable Food Systems*, 9, article number 1598004. doi: 10.3389/fsufs.2025.1598004.
[6] Chupryna, N., Loza, S., Nekrasova, O., Kobenko, Yu., & Volianskyi, V. (2025). Models of innovative and investment development of farms in the context of ecological economics. *Ekonomika APK*, 32(4), 35-45. doi: 10.32317/ekon.apk/4.2025.35.
[7] Dunning, J.H. (2001). The eclectic (OLI) paradigm of international production: Past, present and future. *International Journal of the Economics of Business*, 8(2), 173-190. doi: 10.1080/13571510110051441.
[8] Dzhailov, D.S., & Mardalieva, L.A. (2025). Competitiveness of agricultural products of Kyrgyzstan in the Eurasian market. *Economy and Business: Theory and Practice*, 1-1(119), 111-116. doi: 10.24412/2411-0450-2025-1-1-111-116.
[9] Eurasian Development Bank (EDB). (2023). *Efficient irrigation and water conservation in Central Asia*. Retrieved from https://eabr.org/en/analytics/special-reports/efficient-irrigation-and-water-conservation-in-central-asia/.
[10] Federal State Statistics Service (Rosstat). (n.d.). Retrieved from https://ps.rosstat.gov.ru/.
[11] Food and Agriculture Organization (FAO). (2025). *FAO Investment Centre annual review 2024 – a look back at 2024*. Rome: FAO.
[12] Food and Agriculture Organization (FAO). (n.d.). *FAO Investment Centre*. Retrieved from https://www.fao.org/investment-centre/en.

[13] Institute of Agricultural Resources and Regional Planning of the Chinese Academy of Agricultural Sciences (IARRP). (2025). *China agricultural green development report 2024*. Retrieved from https://iarrp.caas.cn/en/faculty/wuwenbin01/events01/c3926cd637144bc283ba74fd90f910eb.htm.
[14] International Monetary Fund (IMF). (2024). *World economic outlook*. Retrieved from https://www.imf.org/en/publications/weo/issues/2024/10/22/world-economic-outlook-october-2024.
[15] Investing in Kazakhstan's agriculture: Seizing new opportunities. (2025). Retrieved from https://allchinareview.com/investing-in-kazakhstans-agriculture-seizing-new-opportunities/?utm_source=in_materials#.
[16] Khitakhunov, A. (2021). Agriculture in Central Asia: Current state and development perspectives. *Journal of Economic Research & Business Administration*, 138(4), 59-70. doi: 10.26577/be.2021.v138.i4.06.
[17] Makhmudov, R. (2025). *Innovative technologies and their impact on international relations, economy and society*. Tashkent: Ministry of Foreign Affairs of The Republic of Uzbekistan.
[18] Mateeva, K.M., & Mazur, L.V. (2024). Foreign economic cooperation of Kyrgyzstan in the EAEU: Priorities and expectations. *Central Russian Bulletin of Social Sciences*, 19(6), 176-200. doi: 10.22394/2071-2367-2024-19-6-176-200.
[19] Ministry of Economy and Finance of the Republic of Uzbekistan. (n.d.). Retrieved from https://www.imv.uz/en.
[20] National Bureau of Statistics of China. (n.d.). Retrieved from https://www.stats.gov.cn/english/.
[21] National Development Strategy of the Kyrgyz Republic. (2018). Retrieved from https://www.inff.org/resources/national-development-strategy-of-the-kyrgyz-republic?8c284114_page=6.
[22] National Statistical Committee of the Kyrgyz Republic (NSCKR). (n.d.). Retrieved from https://www.stat.gov.kg/en/.
[23] National Statistics Committee of the Republic of Uzbekistan. (n.d.). Retrieved from https://stat.uz/ru/.
[24] Nurasheva, K.K., Shalabayev, I.I., Abdikerimova, G.I., Kulanova, D.A., & Mergenbayeva, A.T. (2024). Capital inflow and investment attractiveness of Central Asian countries (on the example of Kazakhstan). *Regional Science Policy & Practice*, 16(9), article number 100039. doi: 10.1016/j.rspp.2024.100039.
[25] Omuralieva, D.K., & Zholdoshbekova, S.D. (2024). Kyrgyz agro-industrial sector and its contribution to regional development. In *Sustainable development of rural areas: The view of young scientists. Proceedings of the 4th International scientific and practical conference of young scientists* (pp. 101-105). Novosibirsk: Novosibirsk State Agrarian University.
[26] Ryskulbekov, I. (2023). The economic potential of the agricultural sector of the economy of the Talas region: Problems and prospects of its development in the conditions of integration. *Bulletin of Osh State University*, 3, 113-122. doi: 10.52754/16948610_2023_3_13.
[27] Saha, S., Sadekin, N., & Saha, S.K. (2022). Effects of institutional quality on foreign direct investment inflow in lower-middle income countries. *Heliyon*, 8(10), article number e10828. doi: 10.1016/j.heliyon.2022.e10828.
[28] Taranov, I., & Kawabata, Y. (2024) Organic agriculture in Kyrgyzstan: Experiences with implementing participatory guarantee systems. *Frontiers in Sustainable Food Systems*, 8, article number 1453850. doi: 10.3389/fsufs.2024.1453850.
[29] U.S. Department of State. (2024). *Investment climate statements: Kyrgyz Republic 2024*. Retrieved from https://www.state.gov/reports/2024-investment-climate-statements/kyrgyz-republic.
[30] United Nations. (2015). *Transforming our world: The 2030 Agenda for sustainable development*. Retrieved from https://sdgs.un.org/2030agenda.
[31] United Nations. (2024). *Kyrgyzstan facing global turmoil: How to enhance the republic's food resilience*. Retrieved from https://news.un.org/ru/story/2024/08/1454841.
[32] World Bank. (2024). *Kyrgyz Republic economic update: Special topic: Food price inflation in the Kyrgyz Republic*. Retrieved from https://openknowledge.worldbank.org/entities/publication/c1cb084d-1102-401e-a23c-9d2b41697160.
[33] World Bank. (2025). *Country economic memorandum for the Kyrgyz Republic*. Retrieved from https://www.worldbank.org/en/country/kyrgyzrepublic/publication/cem-2025.
[34] World Commission on Environment and Development (WCED). (1987). *Our common future*. Oxford: Oxford University Press.
[35] Yang, Y., Wang, Z., & Luo, R. (2025). Financial innovation and agricultural investment: Drivers of sustainable growth in China's rural economy with regional variations. *International Review of Economics & Finance*, 101, article number 104230. doi: 10.1016/j.iref.2025.104230.
[36] Zakirova, E. (2017). State-private partnership: Aspects of application in the agricultural sphere. *Proceedings of VSUET*, 79(4), 260-266. doi: 10.20914/2310-1202-2017-4-260-266.

Чет элдик инвестиция айыл чарбасын жаңылоонун жана тышкы экономикалык байланыштарды чыңдоонун фактору

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Аннотация. Ааламдашуу жана дүйнөлүк рыноктордун өз ара көз карандылыгы күчөгөн шартында чет элдик инвестиция айыл чарбасын жаңылоонун, анын технологиялык деңгээлин жогорулатуунун жана өлкөнүн тышкы экономикалык байланыштарын чыңдоонун маанилүү куралы болуп саналат. Иш менен камсыз кылууда, азык-түлүк коопсуздугун камсыз кылууда жана экспорттук потенциалды өнүктүрүүдө айыл чарба тармагы салттуу түрдө маанилүү роль ойногон Кыргыз Республикасы үчүн, узак мөөнөттүү чет өлкөлүк капиталды тартуу стратегиялык мааниге ээ. Изилдөөнүн максаты Кыргызстандын айыл чарбасына чет элдик инвестицияларды тартуу механизмдерин талдоо жана алардын айыл чарба продукциясынын тышкы рыноктордо атаандаштыкка жөндөмдүүлүгүн жогорулатууга тийгизген таасирин баалоо болгон. Өзгөчө көңүл, инвестициялык активдүүлүккө көмөктөшүүчү жана тоскоолдук кылган факторлорду аныктоого, ошондой эле чет өлкөлүк өнөктөштөр менен өз ара аракеттенүүнүн артыкчылыктуу багыттарын аныктоого бурулат. Изилдөөдө, салыштырма жана структуралык талдоо методдору, системалык мамиле колдонулган, ошондой эле айыл чарба тармагындагы инвестицияны өнүктүрүү боюнча эл аралык тажрыйба изилденген. Мындай мамиле Кыргызстандын айыл чарба тармагындагы инвестициялык динамикасынын жалпы мыйзам ченемдүүлүктөрүн жана спецификалык мүнөздөмөлөрүн аныктоого мүмкүндүк берди. Талдоо көрсөткөндөй, чет элдик инвестициялар инновациялык технологияларды киргизүүгө, кайра иштетүү тармактарын өнүктүрүүгө, айыл чарба өндүрүшүнүн натыйжалуулугун жогорулатууга, инфраструктураны жакшыртууга, экспорттук потенциалды жогорулатууга көмөктөшөт. Ошону менен бирге чет өлкөлүк инвестициялардын агымын чектеген институционалдык, укуктук жана уюштуруучулук тоскоолдуктар аныкталган, анын ичинде мыйзамдардын жеткилең эместиги, бюрократиялык жол-жоболор инвесторлор үчүн жетишсиз корголгон. Жыйынтыктап айтканда, жагымдуу инвестициялык климатты түзүү, ченемдик-укуктук базаны өркүндөтүү, мамлекеттик-жеке өнөктөштүктү өнүктүрүү, инновациялык каржылоо инструменттеринин ролун күчөтүү боюнча чаралар сунушталууда. Изилдөөнүн практикалык мааниси, анын жыйынтыктарын мамлекеттик органдар, потенциалдуу инвесторлор жана бизнес структуралар тарабынан айыл чарбасын модернизациялоонун натыйжалуу стратегияларын иштеп чыгуу жана Кыргыз Республикасын эл аралык экономикалык мейкиндикке тереңирээк интеграциялоо үчүн колдонуу мүмкүнчүлүгүндө жатат

Негизги сөздөр: агроөнөр жай комплекси; мамлекет; глобализация; өнүктүрүү; жөнгө салуу; экспорт

Иностранные инвестиции как фактор модернизации сельского хозяйства и укрепления внешнеэкономических связей

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Аннотация. В условиях глобализации и растущей взаимозависимости мировых рынков иностранные инвестиции выступают важнейшим инструментом модернизации сельского хозяйства, повышения его технологического уровня и укрепления внешнеэкономических связей государства. Для Кыргызской Республики, где аграрный сектор традиционно играет системообразующую роль в обеспечении занятости населения, продовольственной безопасности и формировании экспортного потенциала, привлечение долгосрочного иностранного капитала приобретает стратегическое значение. Целью исследования был анализ механизмов привлечения иностранных инвестиций в сельское хозяйство Кыргызстана и оценка их влияния на повышение конкурентоспособности агропродовольственной продукции на внешних рынках. Особое внимание уделено выявлению факторов, способствующих и препятствующих инвестиционной активности, а также определению приоритетных направлений взаимодействия с зарубежными партнерами. В работе применялись методы сравнительного и структурного анализа, системного подхода, а также проведено изучение международного опыта в сфере инвестиционного развития аграрного сектора. Такой подход позволил выявить общие закономерности и специфические особенности инвестиционной динамики в аграрной сфере Кыргызстана. Проведенный анализ показал, что иностранные инвестиции способствуют внедрению инновационных технологий, развитию перерабатывающих отраслей, повышению эффективности аграрного производства, улучшению инфраструктуры и росту экспортного потенциала. Вместе с тем были выявлены институциональные, правовые и организационные барьеры, ограничивающие приток зарубежных инвестиций, включая несовершенство законодательства, бюрократические процедуры и недостаточную защищенность инвесторов. В заключение предложены меры по формированию благоприятного инвестиционного климата, совершенствованию нормативно-правовой базы, развитию государственно-частного партнерства и усилению роли инновационных инструментов финансирования. Практическая значимость исследования заключается в возможности использования его результатов государственными органами, потенциальными инвесторами и бизнес-структурами при разработке эффективных стратегий модернизации сельского хозяйства и углубления интеграции Кыргызской Республики в международное экономическое пространство

Ключевые слова: агропромышленный комплекс; государство; глобализация; развитие; регулирование; экспорт

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Population structure of Kyrgyz Mountain Merino sheep: Analysis of nuclear locus variability

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Abstract. The relevance of the study is determined by the need to preserve local, unique and highly adapted breeds of farm animals in the context of global climate change and a reduction in the number of breeding stock. The Kyrgyz Mountain Merino is a valuable genetic resource, highly adaptable to mountain conditions, with high-quality wool and efficient use of scarce feed. However, a limited gene pool and increasing inbreeding pose risks to the breed's productivity and adaptability. The aim of the study was to analyse the population structure of the Kyrgyz Mountain Merino based on an assessment of nuclear locus variability. To achieve this goal, sheep were genotyped using a panel of highly polymorphic microsatellite markers (SSR) recommended by the International Society for Animal Genetics (ISAG). Allele diversity indices, observed and expected heterozygosity, F_IS fixation coefficients, Nei genetic distances were calculated, and population structure analysis was performed using cluster analysis, PCA and STRUCTURE model methods. The results of the study showed a high level of allelic diversity at most loci (number of alleles per locus 6-14, effective number of alleles Ne 3.41-6.21, PIC > 0.69). The observed heterozygosity (Ho = 0.68-0.73) practically corresponded to the expected (He = 0.70-0.74), and the F_IS coefficients remained low (0.012-0.028), indicating the absence of pronounced inbreeding. Genetic differentiation between groups was weak (F_ST = 0.018-0.032), Nei's genetic distances were minimal (0.038-0.051), and STRUCTURE analysis revealed two conditional genetic clusters with uniform distribution across groups, confirming the integrity of the population. The practical value of the study lies in identifying the current state of the Kyrgyz Mountain Merino gene pool, which allows for the development of recommendations for controlled selection work, the preservation of unique alleles, and the maintenance of genetic diversity of the breed, ensuring its resistance to adverse environmental conditions

Keywords: genetic diversity; microsatellite markers; population structure; heterozygosity; fixation coefficient; allelic diversity; Kyrgyz sheep

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Introduction

In the context of global climate change, intensification of livestock farming and expansion of the gene pool of strategic breeds, the conservation of local, unique and highly adapted breeds of farm animals is of particular importance. One such breed is the Kyrgyz Mountain Merino, a valuable genetic resource that has developed under the influence of the complex natural and climatic conditions of the high-altitude pastures of Kyrgyzstan (Zholborsov *et al.*, 2024). This breed is characterised by its resistance to hypoxia, pronounced adaptive mechanisms, high wool quality and ability to effectively utilise poor mountain feed. However, as noted by K. Iskakov *et al.* (2017), there has been a decline in the number of breeding stock, an increase in the level of inbreeding, and a narrowing of genetic diversity, which could potentially lead to a decrease in the adaptability and productivity of animals.

Modern science has a wide range of molecular genetic methods at its disposal that allow for an objective assessment of the state of breed populations. Studies of sheep are most often based on the analysis of mitochondrial DNA, as it is easier to isolate and provides information about the maternal line. However, according to A. Kawęcka *et al.* (2022), mitochondrial analysis does not reflect the full picture of genetic processes, does not allow for the assessment of paternal lineages, and does not characterise intrapopulation processes as a whole. Unlike mtDNA, the variability of nuclear loci provides comprehensive information about population structure, selection intensity, inbreeding levels, genetic heterogeneity, and the historical evolution of the breed (Li *et al.*, 2024). Nuclear markers – such as STR/SSR, SNP or microsatellite sequences – are highly polymorphic and allow for high-precision determination of allelic diversity, genetic distances and the degree of population differentiation. Studies of similar local sheep breeds in other countries, such as G. McKenzie *et al.* (2010) in New Zealand, show that the absence of a systematic selection policy, small effective population sizes and limited animal migration can lead to a decline in genetic diversity and the disappearance of unique alleles, especially in isolated mountain regions. Despite the practical importance of the Kyrgyz Mountain Merino, its gene pool has not been sufficiently studied to date. There is a lack of modern genetic studies using nuclear markers and reflecting the real structure of the breed. As pointed out by T. Odjakova *et al.* (2023), the lack of scientific data complicates the development of breeding programmes and strategies for preserving the gene pool, and also limits the possibilities for objective assessment of intraspecific variability and identification of unique genetic lines.

The relevance of the study is due to the need for a comprehensive analysis of the genetic diversity of the Kyrgyz Mountain Merino using modern molecular technologies. This will make it possible to identify the level of gene pool conservation, determine the degree of genetic differentiation within the breed, establish existing genetic risks, and develop scientifically sound recommendations for breeding and selection work. The aim of the study was to obtain objective data on the genetic structure of the Kyrgyz Mountain Merino population by assessing the variability of nuclear loci and subsequently determining the levels of intrapopulation and intergroup variability. To achieve this goal, the following tasks were set: to determine the level of allelic diversity and the of polymorphism of nuclear markers; to calculate indicators of genetic heterozygosity and inbreeding coefficients; to identify the degree of genetic differentiation of the studied groups of animals. The study can not only supplement existing data on the genetic resources of sheep breeding in Kyrgyzstan, but also create a scientific basis for the development of long-term programmes for the conservation and rational use of the Kyrgyz Mountain Merino breed.

Materials and Methods

The study was conducted in 2023 on Kyrgyz Mountain Merino sheep in the Naryn and Issyk-Kul regions (Naryn Breeding Farm and Issyk-Kul Breeding Farm). Laboratory analysis was carried out at the Research Institute of Molecular Biology and Medicine (Bishkek, Kyrgyzstan). A total of 36 animals were studied, divided into three groups according to age, sex, origin and absence of close kinship, as indicated in the work of A. Bekturov *et al.* (2023): Group 1 – 12 adult sheep, aged 2-3 years, females; Group 2 – 12 adult sheep, aged 2-3 years, males; Group 3 – 12 adult sheep, aged 3-4 years, females and males. The animals were kept on pasture with limited access to additional feed according to the standard breeding programme of the farms. All procedures were performed by veterinary specialists in accordance with animal welfare recommendations (Directive 2010/63/EU, 2010).

Five millilitre samples of whole blood were collected from the jugular vein using disposable sterile needles and vacuum tubes containing EDTA (ethylenediaminetetraacetic acid) as an anticoagulant. After sampling, the samples were immediately cooled and transported in a container with cooling elements at a temperature of 4-6°C. In the laboratory, the samples were frozen and stored at -20°C for no more than 4 weeks prior to analysis. Genomic DNA was extracted in two ways, depending on the quality of the source material: (1) using the standard phenol-chloroform method according to the protocol by J. Sambrook & D. Russell (2001) for samples without signs of haemolysis; (2) using the DNeasy Blood & Tissue Kit (Qiagen, Germany) for samples containing traces of haemolysis or having a reduced cell composition (Romanov, 2021). The quality and concentration of the isolated DNA were determined spectrophotometrically using Nanodrop 2000 (Thermo Scientific, USA) at wavelengths of 260/280 nm, as well as by electrophoresis in 1.5% agarose gel to confirm the integrity of the genetic material. Loci were selected based on the criteria of polymorphism level, amplification stability, and informativeness for population analyses. Microsatellite loci were analysed using a panel of 15 highly polymorphic STR markers included in the official ISAG/FAO recommended panel for sheep and widely used in population genetics studies (FAO, 2011) (Table 1).

Table 1. List of microsatellite loci used (n = 15)

No.	Locus	Chromosome (Oar_v4.0)	Allele range, bp
1	OarFCB20	2	90
2	MAF214	16	110-140
3	OarFCB304	17	140-170
4	INRA63	14	170-190
5	MAF65	15	110-130
6	MCM527	5	160-180
7	INRA023	3	200-220
8	OarAE129	6	130-160
9	SRCRSP8	1	210-240
10	MAF70	4	120-150
11	SPS113	11	130-160
12	CSRD247	14	210-250
13	INRA172	1	130-160
14	SRCRSP5	4	170-200
15	OarCP49	17	100-130

Source: compiled by the authors based on FAO (2011)

Marker amplification was performed by polymerase chain reaction (PCR) in a thermocycler according to optimised temperature conditions for each locus. PCR products were separated by capillary electrophoresis on an ABI 3130 automatic genetic analyser (Gootwine, 2020), after which allele sizes were determined using an internal molecular weight standard (Punuru *et al.*, 2025). Quality control of amplicons and visualisation of restriction patterns (if necessary) were performed by horizontal electrophoresis in 1.5-2.5% agarose gels stained with ethidium bromide and subsequent photography in a UV transilluminator. To minimise genotyping errors associated with non-specific fragments, the fluorescence intensity of individual bands of restriction patterns was additionally taken into account (Kulibaba *et al.*, 2023). Primary analysis of electropherograms was performed using GeneMapper v.5.0 (Applied Biosystems, USA), where each allele position was assigned a specific size in base pairs. Based on the obtained allele profiles, genetic diversity indices were calculated using GenAlEx v.6.5 (Peakall & Smouse, 2012; Gáspárdy, 2021) and Arlequin v.3.5 (Duncanson, 2025) software. The number of alleles per locus (Na) was determined as the total number of different alleles detected at each locus according to the standard population genetics methodology (Granero *et al.*, 2022). The effective number of alleles (Ne) was calculated using formula (1):

$$Ne = \frac{1}{\sum P_I^2}, \quad (1)$$

where p_i is the frequency of the *i*-th allele at the locus (Nei, 1972).

Observed heterozygosity (Ho) was calculated as the proportion of heterozygous genotypes in the total sample using formula (2):

$$Ho = \frac{N_{het}}{N}, \quad (2)$$

where N_{het} is the number of heterozygous individuals.

Expected heterozygosity (He) was determined according to M. Nei (1978) using formula (3):

$$He = 1 - \sum P_I^2, \quad (3)$$

which reflects the probability of heterozygosity at Hardy-Weinberg equilibrium.

The fixation index (F_{IS}) was calculated according to the formula by B. Weir & C. Cockerham (1984) (4):

$$F_{IS} = \frac{H_o}{H_e}, \quad (4)$$

which allows the level of inbreeding within groups to be assessed.

Locus polymorphism (PIC) was estimated according to D. Botstein *et al.* (1980) (5):

$$\mathrm{PIC} = 1 - \sum p_i^2 - \sum\sum 2p_i^2\, p_j^2, \quad (5)$$

where p_i and p_j are allele frequencies.

Genetic distances between the studied groups were calculated using the method of M. Nei (1972) in the Arlequin v.3.5 programme according to formula (6):

$$D = -\ln(I), \quad (6)$$

where *I* is the coefficient of genetic similarity. All calculations were performed automatically using the GenAlEx and Arlequin programmes, followed by manual verification of the frequencies.

For cluster analysis, the UPGMA (Unweighted Pair Group Method with Arithmetic Mean) method was used based on the genetic distance matrix of M. Nei (1972), calculated between all pairs of the studied groups. The dendrogram was constructed using the MEGA X programme, which allowed for visualisation the proximity of genetic profiles and identify clusters within the sample. Principal component analysis (PCA) was used to reduce the dimensionality of the data and identify the main axes of genetic variation. Allele frequencies at each locus were used as input variables. The analysis was performed using GenAlEx v.6.5 (Peakall & Smouse, 2012), and the results were visualised as the dispersion of individuals on the first two principal components (Megdiche *et al.*, 2019). This approach allowed for assessing the degree of overlap between groups and identify potential subpopulations without making assumptions about the model.

The STRUCTURE v.2.3.4 programme was used to identify hidden subpopulations. As part of the analysis, an admixture model with independent allele frequencies was used; the number of clusters (K) ranged from 1 to 10 with 10 repetitions for each K; 100,000 MCMC (Markov Chain Monte Carlo) steps were used for "warming up" and 500,000 steps for parameter estimation. The optimal number of subpopulations was determined using the ΔK criterion (Gurgul *et al.*, 2021), after which each individual was assigned a probability of belonging to each cluster. Geographical and tribal differences were assessed using AMOVA (Analysis of Molecular Variance) and F_ST coefficient calculations in Arlequin v.3.5. The reliability of differences between groups was tested using permutation tests (10,000 permutations). All methods allowed for a comprehensive assessment of population structure, the degree of genetic differentiation, and the possible presence of hidden genetic subgroups.

Results and Discussion

Analysis of nuclear loci in Kyrgyz Mountain Merino sheep allowed for obtaining a comprehensive characterisation of the genetic diversity of the breed and to identify patterns in its population structure. Genotyping using a panel of highly polymorphic microsatellite markers revealed significant allelic diversity, distributed unevenly among the studied groups of animals. The data obtained indicate the preservation of the basic level of genetic variability, despite the relatively narrow gene pool and geographical isolation of some breeding herds. According to the results of the analysis, the number of alleles per locus varied from 6 to 14. These indicators correspond to a high level of polymorphism, according to data from A. Grasso *et al.* (2014). The greatest allelic diversity was observed at the OarFCB20 and MAF214 loci, indicating the possible influence of historical breeding lines and the preservation of rare alleles in individual herds (Table 2). High values of effective allele number (from 3.41 to 6.21, averaging 4.72±0.91 across 15 loci) confirm the presence of moderately expressed genetic heterogeneity within the breed.

Table 2. Allele diversity at the studied nuclear loci

Locus	Number of alleles (Na)	Effective number of alleles (Ne)	PIC
OarFCB20	14	6.21	0.83
MAF214	12	5.78	0.81
OarFCB304	9	4.32	0.74
INRA63	7	3.89	0.71
MAF65	6	3.41	0.69

Source: compiled by the authors

The PIC polymorphic information coefficient for most loci exceeds 0.70, which classifies them as highly polymorphic markers. According to B. Moioli *et al.* (1998), such loci ensure high genotyping accuracy and allow for correct assessment of genetic distances, population structure, and the degree of genetic differentiation. The indicators presented in Table 2 confirm that the panel of nuclear markers used is highly informative and adequately reflects the genetic diversity of the Kyrgyz Mountain Merino, as indicated by S. Ceccobelli *et al.* (2023). The parameters of expected and observed heterozygosity indicate a balanced genetic structure of the populations. In all studied groups, the Ho values were close to He, and the fixation coefficient F_IS did not exceed 0.05, which indicates the absence of pronounced inbreeding processes (Table 3).

Table 3. Indicators of heterozygosity and fixation coefficients

Group	Ho	He	F_IS
Group 1	0.71	0.72	0.014
Group 2	0.68	0.70	0.028
Group 3	0.73	0.74	0.012
Total sample	0.71	0.72	0.017

Source: compiled by the authors

The observed heterozygosity practically corresponds to the expected value, with a minimal difference between them, reflecting a balanced distribution of alleles and the absence of a significant deficit of heterozygotes. Ho values range from 0.68 to 0.73, which is typical for sheep breeds with moderate levels of intrapopulation variability. Low values of the fixation coefficient F_IS (0.012-0.028) indicate the absence of pronounced inbreeding. Positive but close to zero F_IS values may be associated with the natural structure of the population, breeding characteristics, or random genetic drift processes that do not significantly affect the breed's gene pool. The preservation of this level of heterozygosity may be due to the existence of several breeding lines; controlled use of producers; geographical distribution of herds, minimising genetic isolation. A comparison of data between groups demonstrates the overall genetic stability of the breed, with no signs of fragmentation or local reduction in heterozygosity. These indicators point to the existence of a stable gene pool, supported by moderate genetic exchange between herds and possible control of breeding work.

The assessment of differentiation between groups by F_ST showed a low level of differences (0.018-0.032), indicating the preservation of common genetic lines and the absence of significant divergence between herds. Genetic distances according to Nei also demonstrated the proximity of the studied populations, varying between 0.038 and 0.051 (Table 4). This indicates a stable population structure and active exchange of genetic material between herds.

Table 4. Matrix of genetic distances between the studied groups

Group	1	2	3
Group 1	–	0.042	0.038
Group 2	0.042	–	0.051
Group 3	0.038	0.051	–

Source: compiled by the authors

The smallest genetic distance is observed between groups 1 and 3, which may indicate their closer historical connection or exchange of producers between the respective herds. A slightly higher distance value is noted between groups 2 and 3, but even this difference remains at a level characteristic of weakly differentiated populations. Such values indicate that the genetic structure of the breed remains intact and the degree of divergence between herds is minimal. Low genetic distance values confirm the results of the F_ST analysis, indicating weak differentiation and no significant fragmentation of the breed. Such a genetic profile is characteristic of breeds with a moderately developed selection system and sustained exchange of genetic material between groups. Modelling using the STRUCTURE method revealed two conditional genetic clusters distributed among flocks without a clear geographical reference (Table 5). This structure corresponds to the conclusions of A. Abdelmanova *et al.* (2021) and S. Ceccobelli *et al.* (2023) on high-altitude Merinos, where historical breeding lines form several overlapping genetic components without pronounced fragmentation.

Table 5. Share of genetic clusters in the studied groups (K = 2)

Group	Cluster 1	Cluster 2
Group 1	0.57	0.43
Group 2	0.61	0.39
Group 3	0.54	0.46

Source: compiled by the authors

The distribution of the shares of the two genetic clusters in each of the three groups studied shows insignificant differences. For example, Cluster 1 predominates in Group 1 with a share of 0.57, while the share of Cluster 2 is 0.43. A similar trend is observed in other groups. The absence of a sharp division between clusters confirms the integrity of the breed and the stability of its gene pool, reflecting historical breeding lines and the formation of separate brood flocks while maintaining overall genetic diversity. Principal component analysis confirmed the picture of weak differentiation, which is consistent with the data of A. Abdelmanova *et al.* (2021) on other highland breeds. Figure 1 shows the distribution of observed heterozygosity across the studied groups. Ho values range from 0.68 to 0.73, indicating a relatively stable genetic background of the studied populations. The highest heterozygosity was observed in Group 3, while Groups 1 and 2 showed slightly lower but comparable values. Overall, the distribution of Ho reflects moderate genetic diversity among the groups. The results show that the Kyrgyz Mountain Merino breed has a moderately high level of genetic diversity. The heterozygosity indices of the studied population are comparable or even higher than those of similar local breeds, such as the Tajik Mountain Merino and Kazakh Arkharomerino, according to L. Colli *et al.* (2015). This indicates that the breed's gene pool retains sufficient variability to adapt to different natural conditions and resist potential negative factors. Low values of genetic differentiation coefficients F_ST and genetic distances according to Nei indicate the absence of significant population fragmentation, as pointed out by T. Schillhorn van Veen (1995). This means that there is a regular exchange of genetic material between the main herds, which helps to maintain a uniform gene pool for the breed and reduces the risk of isolated lines with limited genetic variability. Thus, it can be concluded that the Kyrgyz Mountain Merino breed currently maintains a sufficient level of genetic diversity. Nevertheless, in order to prevent a possible narrowing of the gene pool in the future, especially in the event of a decline in population size or an increase in inbreeding, regular monitoring of the genetic status and continued controlled selection work are necessary.

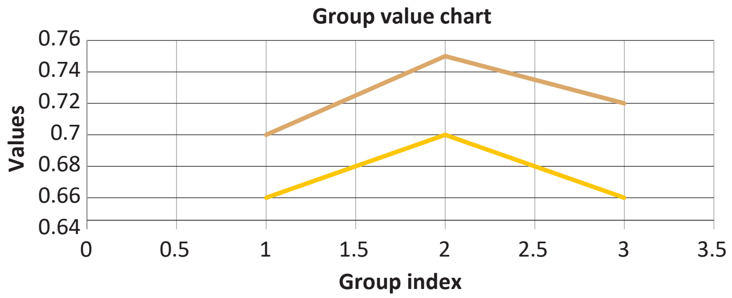

Figure 1. Distribution of observed heterozygosity (Ho) across groups

Source: developed by the authors

Conclusions

The Kyrgyz Mountain Merino breed maintains a moderately high level of genetic diversity. For 15 microsatellite loci, the number of alleles per locus ranged from 6 to 14, the effective number of alleles Ne was 3.41-6.21, and the polymorphism index PIC exceeded 0.69. The observed heterozygosity Ho was in the range of 0.68-0.73, the expected heterozygosity He was 0.70-0.74, while the fixation coefficients F_IS remained low (0.012-0.028), indicating the absence of pronounced inbreeding and a deficit of heterozygotes in the population. The indicators of genetic differentiation between the studied groups were minimal: F_ST = 0.018-0.032, genetic distances according to Nei – 0.038-0.051. Analysis of the population structure using the STRUCTURE model revealed two conditional genetic clusters. The absence of a sharp division between clusters confirms the integrity of the breed and the stability of its gene pool, reflecting historical breeding lines and the formation of separate ewe flocks while maintaining overall genetic diversity. Thus, the Kyrgyz Mountain Merino breed has a stable gene pool and a sufficient level of genetic diversity. To prevent a possible narrowing of the gene pool in the future, it is recommended to conduct regular monitoring of the genetic status of the population, systematic registration of maternal lines, controlled selection work to preserve unique alleles and maintain a balance between breeding groups. Prospects for further research include: expanding the panel of microsatellite markers and including SNP typing for a more detailed analysis of genetic diversity; studying the associations of genetic markers with productive and adaptive traits of the breed; long-term monitoring of population structure dynamics and the impact of breeding measures on genetic potential.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Abdelmanova, A.S., *et al.* (2021). Comparative study of the genetic diversity of local steppe cattle breeds from Russia, Kazakhstan and Kyrgyzstan by microsatellite analysis of museum and modern samples. *Diversity*, 13(8), article number 351. doi: 10.3390/d13080351.

[2] Bekturov, A.B., Isakova, Z., Kipen, V.N., Chortonbaev, T., Mukeeva, S.B., Osmonaliev, S.K., & Aitbaev, K.A. (2023). A genogeographic study of the Kyrgyz Mountain Merino via microsatellite markers. *Vavilov Journal of Genetics and Breeding*, 27(2), 162-168. doi: 10.18699/VJGB-23-22.

[3] Botstein, D., White, R.L., Skolnick, M., & Davis, R.W. (1980). Construction of a genetic linkage map in man using restriction fragment length polymorphisms. *American Journal of Human Genetics*, 32(3), 314-331.

[4] Ceccobelli, S., *et al.* (2023). A comprehensive analysis of the genetic diversity and environmental adaptability in worldwide Merino and Merino-derived sheep breeds. *Genetics Selection Evolution*, 55(1), article number 24. doi: 10.1186/s12711-023-00797-z.

[5] Colli, L., *et al*. (2015). Whole mitochondrial genomes unveil the impact of domestication on goat matrilineal variability. *BMC Genomics*, 16, article number 1115. doi: 10.1186/s12864-015-2342-2.
[6] Directive 2010/63/EU of the European Parliament and of the Council of 22 "On the Protection of Animals Used for Scientific Purposes". (2010, September). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0063.
[7] Duncanson, G.R. (2025). *Veterinary treatment of sheep and goats* (2nd ed.). Oxfordshire: Cabi.
[8] FAO. (2011). *Molecular genetic characterization of animal genetic resources. FAO animal production and health guidelines. No. 9*. Rome: FAO.
[9] Gáspárdy, A. (2021). Reality of mitogenome investigation in preservation of native domestic sheep breeds. In A. Elkelish (Ed.), *Landraces-traditional variety and natural breed* (Chapter 10). London: IntechOpen. doi: 10.5772/intechopen.95768.
[10] Gootwine, E. (2020). Genetics and breeding of sheep and goats. In F.W. Bazer, G.C. Lamb & G. Wu (Eds.), *Animal agriculture* (pp. 183-198). Amsterdam: Academic Press. doi: 10.1016/B978-0-12-817052-6.00010-0.
[11] Granero, A., Anaya, G., Demyda-Peyrás, S., Alcalde, M.J., Arrebola, F., & Molina, A. (2022). Genomic population structure of the main historical genetic lines of Spanish Merino sheep. *Animals*, 12(10), article number 1327. doi: 10.3390/ani12101327.
[12] Grasso, A.N., Goldberg, V., Navajas, E.A., Iriarte, W., Gimeno, D., Aguilar, I., Medrano, J.F., Rincón, G., & Ciappesoni, G. (2014). Genomic variation and population structure detected by single nucleotide polymorphism arrays in Corriedale, Merino and Creole sheep. *Genetics and Molecular Biology*, 37(2), 389-395. doi: 10.1590/s1415-47572014000300011.
[13] Gurgul, A., Jasielczuk, I., Miksza-Cybulska, A., Kawęcka, A., Szmatoła, T., & Krupiński, J. (2021). Evaluation of genetic differentiation and genome-wide selection signatures in Polish local sheep breeds. *Livestock Science*, 251, article number 104635. doi: 10.1016/j.livsci.2021.104635.
[14] Iskakov, K.A., Kulatayev, B.T., Zhumagaliyeva, G.M., & Casanova, P.M.P. (2017). Productive and biological features of Kazakh fine-wool sheep in the conditions of the Almaty region. *OnLine Journal of Biological Sciences*, 17(3), 219-225. doi: 10.3844/ojbsci.2017.219.225.
[15] Kawęcka, A., Pasternak, M., Miksza-Cybulska, A., & Puchała, M. (2022). Native sheep breeds in Poland – importance and outcomes of genetic resources protection programmes. *Animals*, 12(12), article number 1510. doi: 10.3390/ani12121510.
[16] Kulibaba, R., Sakhatskyi, M., & Liashenko, Y. (2023). Analysis of genotyping features of bovine cattle individuals at the CSN2 locus using ACRS-PCR methods. *Animal Science and Food Technology*, 14(2), 44-56. doi: 10.31548/animal.2.2023.44.
[17] Li, X., *et al*. (2024). Whole-genome resequencing to investigate the genetic diversity and mechanisms of plateau adaptation in Tibetan sheep. *Journal of Animal Science and Biotechnology*, 15, article number 164. doi: 10.1186/s40104-024-01125-1.
[18] McKenzie, G.W., Abbott, J., Zhou, H., Fang, Q., Merrick, N., Forrest, R.H., Sedcole, J.R., & Hickford, J.G. (2010). Genetic diversity of selected genes that are potentially economically important in feral sheep of New Zealand. *Genetics Selection Evolution*, 42, article number 43. doi: 10.1186/1297-9686-42-43.
[19] Megdiche, S., Mastrangelo, S., Ben Hamouda, M., Lenstra, J.A., & Ciani, E. (2019). A combined multi-cohort approach reveals novel and known genome-wide selection signatures for wool traits in Merino and Merino-derived sheep breeds. *Frontiers in Genetics*, 10, article number 1025. doi: 10.3389/fgene.2019.01025.
[20] Moioli, B., Pilla, F., & Tripaldi, C. (1998). Detection of milk protein genetic polymorphisms in order to improve dairy traits in sheep and goats: A review. *Small Ruminant Research*, 27(3), 185-195. doi: 10.1016/S0921-4488(97)00053-9.
[21] Nei, M. (1972). Genetic distance between populations. *American Naturalist*, 106, 283-292. doi: 10.1086/282771.
[22] Nei, M. (1978). Estimation of average heterozygosity and genetic distance from a small number of individuals. *Genetics*, 89(3), 583-590. doi: 10.1093/genetics/89.3.583.
[23] Odjakova, T., Todorov, P., Kalaydzhiev, G., Salkova, D., Dundarova, H., Radoslavov, G., & Hristov, P. (2023). A study on the genetic diversity and subpopulation structure of three Bulgarian mountainous sheep breeds, based WWon genotyping of microsatellite markers. *Small Ruminant Research*, 226, article number 107034. doi: 10.1016/j.smallrumres.2023.107034.
[24] Peakall, R., & Smouse, P.E. (2012). GenAlEx 6.5: Genetic analysis in Excel. Population genetic software for teaching and research – an update. *Bioinformatics*, 28(19), 2537-2539. doi: 10.1093/bioinformatics/bts460.
[25] Punuru, P.R., Regula, V., Metta, M., Krovvidi, S., Bhumireddy, J.M., Baratam, P., Sunkara, V., & Poonooru, R.R. (2025). Genetic characterization of semi-arid sheep populations in India using microsatellite markers. *Frontiers in Animal Science*, 6, article number 1553610. doi: 10.3389/fanim.2025.1553610.
[26] Romanov, M.N. (2021). *British sheep breed diversity*. Kent: Kent Academic Repository.

[27] Sambrook, J., & Russell, D.W. (2001). *Molecular cloning: A laboratory manual (3rd ed.)*. New York: Cold Spring Harbor Laboratory Press.
[28] Schillhorn van Veen, T.W. (1995). *The Kyrgyz sheep herders at a crossroads*. London: Overseas Development Institute.
[29] Weir, B.S., & Cockerham, C.C. (1984). Estimating F-statistics for the analysis of population structure. *Evolution*, 38(6), 1358-1370. doi: 10.2307/2408641.
[30] Zholborsov, U., Chortonbaev, T., Azhibekov, A., & Bekturov, A. (2024). Biological and productive features of Kyrgyz Mountain Merino breed types in different climatic zones. *BIO Web of Conferences*, 83, article number 01005. doi: 10.1051/bioconf/20248301005.

Кыргыз тоо мериносунун популяциялык түзүлүшү: ядролук локустардын өзгөрмөлүүлүгүн талдоо

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Аннотация. Бул изилдөөнүн актуалдуулугу глобалдык климаттын өзгөрүшүнө жана асыл тукум малдын азайышына карабастан, жергиликтүү, уникалдуу жана жогорку деңгээлде ыңгайлашкан мал тукумдарын сактоо зарылдыгынан келип чыгат. Кыргыз тоо мериносу тоо шарттарына жогорку деңгээлде ыңгайлашкан, жогорку сапаттагы жүн өндүргөн жана тартыш тоютту натыйжалуу колдонгон баалуу генетикалык ресурс болуп саналат. Бирок, генофонддун чектелүү болушу жана тукумсуздуктун көбөйүшү өндүрүмдүүлүктүн жана ыңгайлашуунун төмөндөшүнө алып келүүчү коркунучтарды жаратат. Бул изилдөөнүн максаты ядролук локустардын өзгөрмөлүүлүгүн баалоо менен кыргыз тоо меринос койлорунун популяциялык түзүмүн талдоо болгон. Бул максатка жетүү үчүн койлордун генотиптештирүүсү Эл аралык жаныбарлар генетикасы коому (ISAG) тарабынан сунушталган жогорку полиморфтук микросателлиттик маркерлердин (SSR) панелин колдонуу менен жүргүзүлдү. Аллельдик ар түрдүүлүк индекстери, байкалган жана күтүлгөн гетерозиготалуулук, F_IS фиксация коэффициенттери жана Nei генетикалык аралыктары эсептелген, ал эми популяциянын түзүмү кластердик анализ, PCA жана STRUCTURE моделин колдонуу менен талданган. Жыйынтыктар көпчүлүк локустарда аллельдик ар түрдүүлүктүн жогорку деңгээлин көрсөттү (локустагы аллелдер саны 6-14, аллелдеринин эффективдүү саны Ne 3,41-6,21, маалыматтык мазмундун индекси PIC > 0,69). Байкалган гетерозиготалуулук (Ho = 0,68-0,73) күтүлгөн гетерозиготалуулукка дээрлик окшош болгон (He = 0,70-0,74), ал эми F_IS коэффициенттери төмөн бойдон калган (0,012-0,028), бул олуттуу инбридингдин жоктугун көрсөтүп турат. Топтордун ортосундагы генетикалык дифференциация алсыз болгон (F_ST = 0,018-0,032), Nei боюнча генетикалык аралыктар минималдуу болгон (0,038-0,051) жана СТРУКТУРА анализи топтор боюнча бирдей бөлүштүрүлгөн эки шарттуу генетикалык кластерди аныктады, бул популяциянын бүтүндүгүн тастыктады. Бул изилдөөнүн практикалык баалуулугу кыргыз тоо мериносунун генофондунун азыркы абалын аныктоодо жатат, бул көзөмөлдөнгөн асылдандыруу боюнча сунуштарды иштеп чыгууга, уникалдуу аллелдерди сактоого жана тукумдун генетикалык ар түрдүүлүгүн сактоого мүмкүндүк берет, анын жагымсыз экологиялык шарттарга туруктуулугун камсыз кылат

Негизги сөздөр: генетикалык ар түрдүүлүк; микросателлиттик маркерлер; популяциянын түзүлүшү; гетерозиготалуулук; фиксация коэффициенти; аллельдик ар түрдүүлүк; кыргыз койлору

Структура популяции кыргызского горного мериноса: анализ вариабельности ядерных локусов

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Аннотация. Актуальность исследования обусловлена необходимостью сохранения локальных, уникальных и высокоадаптированных пород сельскохозяйственных животных в условиях глобальных климатических изменений и сокращения численности маточного поголовья. Кыргызский горный меринос является ценным генетическим ресурсом, обладающим высокой адаптивностью к горным условиям, качественной шерстью и эффективным использованием скудных кормов. Однако ограниченный генофонд и рост инбридинга создают риски снижения продуктивности и адаптивности породы. Цель работы заключалась в анализе структуры популяции кыргызского горного мериноса на основе оценки вариабельности ядерных локусов. Для достижения цели проведено генотипирование овец с использованием панели высокополиморфных микросателлитных маркеров (SSR), рекомендованных Международным обществом по генетике животных (ISAG). Были рассчитаны показатели аллельного разнообразия, наблюдаемая и ожидаемая гетерозиготность, коэффициенты фиксации F_IS, генетические расстояния по Nei, а также проведен анализ популяционной структуры с применением методов кластерного анализа, PCA и модели STRUCTURE. Результаты исследования показали высокий уровень аллельного разнообразия по большинству локусов (число аллелей на локус 6-14, эффективное число аллелей Ne 3,41-6,21, индекс информативности PIC > 0,69). Наблюдаемая гетерозиготность (Ho = 0,68-0,73) практически соответствовала ожидаемой (He = 0,70-0,74), а коэффициенты F_IS оставались низкими (0,012-0,028), что свидетельствует об отсутствии выраженного инбридинга. Генетическая дифференциация между группами была слабой (F_ST = 0,018-0,032), генетические расстояния по Nei – минимальными (0,038-0,051), а анализ STRUCTURE выявил два условных генетических кластера с равномерным распределением по группам, подтверждая целостность популяции. Практическая ценность исследования заключается в выявлении современного состояния генофонда кыргызского горного мериноса, что позволяет разрабатывать рекомендации по контролируемой селекционной работе, сохранению уникальных аллелей и поддержанию генетического разнообразия породы, обеспечивая ее устойчивость к неблагоприятным условиям окружающей среды

Ключевые слова: генетическое разнообразие; микросателлитные маркеры; популяционная структура; гетерозиготность; коэффициент фиксации; аллельное разнообразие; кыргызские овцы

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Specific prevention of plague in small ruminants in the Kyrgyz Republic

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Abstract. Peste des petits ruminants (PPR) is a particularly dangerous, infectious and transboundary disease of domestic and wild sheep and goats, causing significant economic losses in livestock farming. The spread of PPR between countries requires coordinated preventive measures and constant epizootic monitoring to prevent the introduction and emergence of disease outbreaks. The aim of the study was to evaluate the effectiveness of preventive measures against PPR after mass vaccination of susceptible animals in the Kyrgyz Republic. To analyse the level of post-vaccination immunity, an enzyme-linked immunosorbent assay (ELISA) was used to determine the antibody titre against the PPR virus. Between 2018 and 2023, 19.35 million sheep and goats were vaccinated with a lyophilised live attenuated vaccine of the Nig.75/1 strain. The results showed that in the northern regions of the republic in 2018, immunity was detected in 42% of vaccinated animals, indicating an insufficient level of protection. However, in subsequent years (2019-2023), the proportion of immune animals increased to an average of 79%. In the southern regions, the average rate of immune animals over six years was 83%, indicating the formation of high antibody levels and a reduced risk of infection. The results confirmed the high effectiveness of vaccination against PPR and its role in preventing the spread of infection. The study data can be used by veterinary services when planning preventive measures, especially in regions bordering China, Kazakhstan and Tajikistan

Keywords: vaccination; Nig.75/1 strain vaccine; ELISA method; protective antibody titre

Introduction

Peste des petits ruminants (PPR) is a quarantine-listed, particularly dangerous disease that poses a biological threat to domestic and wild small ruminants. Clinically and morphologically, it is accompanied by fever, ulcerative lesions of the mucous membranes of the oral and nasal cavities, conjunctivitis, haemorrhagic gastroenteritis, diarrhoea and the development of pneumonia. The causative agent of PPR is *Morbillivirus* from the *Paramyxoviridae* family. The Global Strategy for the Control and Eradication of PPR states that small ruminant plague causes economic losses of between $1.2 and $1.7 billion annually as a result of animal deaths, reduced production and disease control costs (Njeumi *et al*., 2015). Approximately one-third of the financial damage occurs in Africa and one-quarter in South Asia. In addition to PPR, other infectious diseases of small ruminants also cause significant economic damage to livestock farming in the Central Asian region. The study by A. Mussayeva *et al*. (2025) in Kazakhstan showed the circulation of *Pasteurella multocida* among

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wild and farm animals, with saigas acting as a reservoir of infection, requiring a comprehensive approach to epizootic surveillance. This significant damage can be remedied, and it is expected that the control and eradication of PPR will lead to increased income from small ruminant breeding systems and improved profitability and productivity (Aboah *et al*., 2024).

Peste des petits ruminants is a highly contagious and fatal disease affecting small ruminants, particularly sheep and goats. This disease causes high morbidity and mortality in small ruminants, resulting in enormous economic losses for the livestock industry worldwide (Akwongo *et al*., 2022). The serious consequences of this disease have prompted the Food and Agriculture Organization of the United Nations and the World Organisation for Animal Health to develop a global strategy to combat peste des petits ruminants and eradicate it by 2030 (OIE & FAO, 2021). Over the past decades, small ruminant peste des petits ruminants has been controlled mainly by vaccinating animals with live attenuated vaccines, such as those used against peste des grands ruminants. Rinderpest, a closely related disease to peste des petits ruminants, was eradicated in 2011, and vaccines against it were subsequently banned in order to maintain rinderpest-free zones. In this regard, according to X. Jia *et al*. (2020), it is necessary to develop homologous vaccines against small ruminant plague to combat this disease.

M. Amirbekov *et al*. (2021) conducted serological monitoring of small ruminant plague in sheep farms in the Republic of Tajikistan. The results of the analysis showed the widespread distribution of the SRP virus among sheep and goats in the country's sheep farms. A study of blood serum from sheep and goats from eight districts of the republic found that 69% of animals were infected with the PPR virus. Since 2019, Burkina Faso has been implementing a national strategy to eradicate peste des petits ruminants. According to G. Ilboudo *et al*. (2022), after two years of mass vaccination of small ruminants, in which significant resources were invested, very little is known about the cost of vaccination and how it is distributed across the various links in the vaccine distribution chain. The researchers' findings showed that the cost of vaccinating a small ruminant is $0.3 and $0.18 if the vaccination is carried out by public and private vaccinators, respectively. The largest share of costs is accounted for by field work and personnel. These results will enable more effective allocation of resources to improve the efficiency and effectiveness of vaccination of small ruminants against LPAI.

As noted by Zh. Amanova *et al*. (2023), a live vaccine against PPR has been developed in Kazakhstan from the attenuated strain Nig.75/1, which belongs to line II. During experiments with small ruminants aged 6-8 months, it was found that a single immunisation of animals with a live attenuated vaccine against PPR at a dose of 1.0 × 103.0 lg TCID50/head causes the formation of high titres of virus-neutralising antibodies in the blood of sheep and goats. The results obtained give reason to believe that the developed vaccine has high immunogenicity and may be a good alternative to commercial vaccines used against PPR in Kazakhstan. A study of kids by M. Abdollahi *et al*. (2023) showed that some of them became seronegative before reaching the age at which they were given the first dose of the PPR vaccine. The age of 70-100 days may be suitable for administering the first dose of the PPR vaccine to kids, but further studies are needed on the efficacy of this vaccine at this age. Y. Walle *et al*. (2024) investigated the impact of imperfect PPR vaccines and replenished small ruminant populations on the dynamics of transmission of this infection using mathematical modelling. Analytical and numerical results showed that infected newly introduced small ruminants significantly contribute to the spread of PPR among small ruminants. Even with high vaccination efficiency, the system demonstrates a unique asymptotically stable endemic equilibrium. These results emphasise that proper vaccination alone is not sufficient to control and eradicate PPR in the region.

The aim of this scientific work was to analyse and evaluate the effectiveness of preventive vaccination against PPR in the Kyrgyz Republic. Research objectives: to analyse the results of preventive vaccinations of small ruminants in the regions of the Kyrgyz Republic; to assess the intensity of post-vaccination immunity after vaccination with the lyophilised live attenuated PPR virus strain Nig.75/1.

Materials and Methods

The study was conducted in various regions of the Kyrgyz Republic from 2018 to 2023 and was aimed at vaccinating sheep and goats susceptible to small ruminant plague. A total of 19.35 million sheep and goats were vaccinated during the study period. The vaccine, obtained from a certified international supplier that meets the standards of the World Organisation for Animal Health (OIE), was administered subcutaneously at a dose of 1 ml per animal. The lyophilised vaccine was diluted using 50 ml of sterile diluent for 50-dose vials or 100 ml for 100-dose vials. Animals aged 2-3 months were vaccinated in the hairless area of the elbow joint, with revaccination after 4 months to establish a stable immune background. In high-risk areas, especially in border areas with China, Kazakhstan and Tajikistan, annual revaccination was carried out. Sick or weakened animals were excluded from vaccination, and personal hygiene rules were strictly observed during the procedure. All procedures involving animals complied with the international recommendations on animal welfare Directive 2010/63/EU (2010). Vaccination and sampling were carried out by qualified veterinary personnel with the aim of minimising stress to the animals.

To assess post-vaccination immunity, blood serum samples were collected from vaccinated animals.

A stratified random sampling method was used, in which 500 sheep and goats were selected annually from each region (northern and southern), ensuring representativeness across age groups and geographical areas. Blood samples were collected 21-28 days after vaccination to allow sufficient time for antibody production. Blood was collected from the jugular vein under sterile conditions, sera were separated by centrifugation at 3,000 rpm for 10 minutes and stored at -20°C until analysis. The level of protective antibodies against the PPR virus was determined using a sandwich enzyme-linked immunosorbent assay (ELISA) in accordance with the approved operating procedure. The analysis was carried out in the Department of Virology and Biotechnology of the A. Duishev Research Institute of Veterinary Medicine. The ELISA protocol included the following steps: (1) application of antibody solution to sensitise the wells of the plate and incubation at 4°C for 16-18 hours; (2) introduction of test samples (blood sera), positive and negative controls into washed sensitised wells, followed by incubation at 37°C for 1 hour; (3) addition of detector antibodies and incubation at 37°C for 1 hour; (4) adding the conjugate and incubating at 37°C for 1 hour; (5) performing a colour reaction with the application of the substrate and incubating at room temperature for 15-20 minutes; (6) reading the results on a BIOTEK ELx800 spectrophotometer (USA) at a wavelength of 405 nm.

The protective antibody titre was defined as the level sufficient to ensure immunity against PPR, based on the threshold values established in accordance with OIE recommendations (optical density ⩾0.2). The percentage of immune animals was calculated as the proportion of samples with antibody titres above the protective threshold. The data were analysed separately for the northern and southern regions to assess regional differences in immune response. Statistical analysis was performed using R software (version 4.2.1), and differences in immunity levels between years and regions were assessed using the chi-square test at a significance level of $p < 0.05$.

Results and Discussion

The purpose of serological monitoring is to assess the level of actual protection against PPR in sheep and goats, as well as the quality of vaccination work in a specific territory. According to the requirements of the Global Strategy for the Control and Eradication of PPR, at least 90% of the small ruminant population must be vaccinated against PPR in order to create herd immunity and prevent the spread of the virus (Njeumi *et al.*, 2015). This goal is achieved through mass vaccination of susceptible animals using live attenuated vaccines. Table 1 shows the number of animals vaccinated over a six-year period by region in the threatened areas of the Kyrgyz Republic.

Table 1. Number of animals vaccinated with Nig.75/1 vaccine by region of the Kyrgyz Republic for 2018-2023

Regions	2018			2019			2020		
	Plan	Vaccination	%	Plan	Vaccination	%	Plan	Vaccination	%
Batken	205.0	214.9	105	210.0	219.3	104	210.0	211.0	100
Osh	680.0	688.5	101	680.0	692.6	102	680.0	693.9	102
Jalal-Abad	614.6	640.2	104	592.1	625.7	106	593.9	566.1	95
Talas	225.0	233.9	104	255.0	294.3	115	275.0	277.2	101
Chüy	311.0	335.6	108	325.3	347.5	107	317.3	324.8	102
Issyk-Kul	516.5	526.6	102	524.6	542.4	103	519.1	526.3	101
Naryn	615.0	580.3	94	600.0	610.2	102	620.0	687.4	111
Osh	6.5	6.4	99	6.5	6.6	101	6.5	6.5	100
Bishkek	1.5	1.1	72	1.5	1.9	126	1.5	1.8	120
Kyrgyz Republic	3,175.1	3,227.6	102	3,195.0	3,340.5	105	3,223.3	3,294.9	102
Regions	2021			2022			2023		
	Plan	Vaccination	%	Plan	Vaccination	%	Plan	Vaccination	%
Batken	218.0	219.5	101	203.0	212.6	105	203.0	203.4	100
Osh	655.0	648.6	99	650.0	680.2	105	575.0	589.6	103
Jalal-Abad	627.7	619.4	99	733.7	741.5	101	734.7	738.7	101
Talas	247.5	247.7	100	247.5	256.9	104	247.5	243.9	99
Chüy	317.3	317.4	100	304.1	308.7	102	310.3	312.1	101
Issyk-Kul	433.5	345.4	80	413.5	443.6	107	413.5	428.0	104
Naryn	600.0	615.0	103	630.0	646.7	103	640.0	643.2	101

Table 1. Continued

Regions	2021			2022			2023		
	Plan	Vaccination	%	Plan	Vaccination	%	Plan	Vaccination	%
Osh	6.5	6.6	102	6.5	6.5	101	6.5	6.7	102
Bishkek	1.5	1.6	107	1.5	1.6	106	1.5	1.5	99
Kyrgyz Republic	3,107.0	3,021.2	97	3,189.8	3,298.3	103	3,132.0	3,167.1	101

Source: compiled by the authors based on data from the Veterinary, Livestock, Pasture and Forage Development Service of the Kyrgyz Republic (n.d.)

The data in Table 1 show that in 2018, more animals were vaccinated than planned (102%), with the exception of the city of Bishkek (72%). In 2019, more animals were vaccinated (105%) than planned. In 2020, more animals were vaccinated than planned (102%), with the exception of the Jalal-Abad region (80%). In 2021, the average vaccination rate was 97%, and in the Issyk-Kul region it was 80%. From 2022 to 2023, more animals were vaccinated than planned (103% and 101%, respectively). In general, the Kyrgyz Republic complies with the requirements of the Global Strategy for the Control and Eradication of PPR (Njeumi *et al.*, 2015), and the figures show that preventive measures have been successfully implemented within the specified time frame throughout the republic. Tables 2 and 3 show the protective antibody titre or antibody level that provides minimum protection against PPR as a result of vaccination with the PPR vaccine from the Nig.75/1 strain in sheep and goats in the northern and southern regions over a period of 6 years.

Table 2. Intensity of post-vaccination immunity in sheep and goats in the northern region of the Kyrgyz Republic from 2018 to 2023

Years	Number of samples	Immune	%	Non-immune	%
2018	3,178	1,341	42	1,837	58
2019	2,746	2,224	82	522	18
2020	2,715	2,208	81	507	19
2021	2,238	1,682	75	556	25
2022	1,878	1,438	76	440	24
2023	1,613	1,276	79	337	21

Source: compiled by the authors based on Centre for Veterinary Diagnostics and Expertise (n.d.)

Table 3. Intensity of post-vaccination immunity in sheep and goats in the northern region of the Kyrgyz Republic from 2018 to 2023

Years	Number of samples	Immune	%	Non-immune	%
2018	1,245	1,114	89	131	11
2019	1,961	1,782	91	179	9
2020	728	669	93	59	7
2021	1,612	1,402	87	210	13
2022	1,352	832	62	520	38
2023	993	758	76	235	24

Source: compiled by the authors based on Centre for Veterinary Diagnostics and Expertise (n.d.)

Analysis of Table 2 shows that in the northern region, after vaccination of sheep and goats in 2018, 42% of vaccinated animals (1,341 head) were immune to bluetongue disease, indicating a low level of actual protection of sheep and goats against bluetongue disease. In the remaining years of vaccination from 2019 to 2023, the percentage of immune animals averaged 79%, indicating a sufficient level of antibody production to provide minimal protection against PPR. Analysis of Table 3 shows that after vaccination of sheep and goats in the southern region with the Nig.75/1 strain over 6 years, the percentage of immune animals averaged 83%, indicating a high level of antibody production, providing minimum protection for sheep and goats against PPR.

Vaccination against small ruminant plague is actively carried out in countries bordering the Kyrgyz Republic, using various vaccines depending on agreements with manufacturers. According to A. Abdulloev (2022), PPR was first detected in Tajikistan in 2004 when animals were imported from Afghanistan, but in subsequent years it was possible to improve diagnostic methods and develop measures to reduce the losses caused by this disease. In China, until 2013, mandatory vaccination of sheep and goats with live attenuated vaccines was carried out only in Tibet and Xinjiang.

The lack of immunisation in other regions was one of the reasons for the rapid spread of PPR throughout the country in 2014. Currently, the live attenuated vaccine Clone 9 (with 99.8% genomic similarity to Nig.75/1) is used, as well as commercial monovalent and bivalent vaccines against PPR and goat pox (Liu *et al*., 2018). In northern Pakistan, studies have shown a true prevalence of PPR of 41.0%, with a maximum in Gilgit (57.0%) and a minimum in Swat (26.0%) (Munibullah *et al*., 2024). It has been confirmed that keeping small and large livestock together increases the risk of virus transmission.

In Kazakhstan, due to the unfavourable epizootic situation in the southern regions, routine vaccination of small ruminants is carried out, with approximately 9 million animals immunised in 2016. Studies by Zh. Amanova *et al*. (2021) showed that a combined vaccine containing the Nig.75/1 (against PPR) and NISKhI (against sheep pox) strains provides a protective immune response in Kazakh fine-wool sheep aged 6-12 months for 12 months. The vaccine's efficacy was assessed using a blood serum neutralisation test and the c-ELISA method to determine antibodies to PPR, as well as testing the resistance of vaccinated animals to infection with the Kentau-7 PPR field strain and the virulent strain A of sheep pox. A single immunisation provided 100% clinical protection against both infections, while unvaccinated animals showed clinical signs of PPR and smallpox.

Large-scale vaccination against PPR in the Kyrgyz Republic has proven effective in preventing the spread of infection. Neighbouring countries such as China, Tajikistan and Kazakhstan remain affected by PPR, which creates a risk of the infection spreading to other countries (Zakutskiy *et al*., 2012; Koshemetov *et al*., 2016). Thanks to systematic vaccination, sheep and goats in the Kyrgyz Republic have specific antibodies that protect them from infection. In the event of an introduction of PPR, the spread of infection is limited by the established immune background. According to the 2nd Regional roadmap meeting... (2017), a harmonised approach is needed to eliminate PPR by 2030, including the development of national strategic plans, strengthened surveillance, vaccination and coordination between countries in the region. Based on the results of this study, the following recommendations are proposed for the prevention and control of PPR in the Kyrgyz Republic:

1. The State Veterinary Service, through its regional and district structures, should control the movement of small ruminants within the country.

2. To prevent the introduction of the PPR virus from affected countries, a 30-day quarantine should be organised for incoming animals, with mandatory serological testing for antibodies to the PPR virus.

3. Annual routine immunisation of all small ruminants in border areas to a depth of at least 30 km should be carried out to create an immune belt.

4. Perform preventive or compulsory vaccinations against PPR, taking into account local conditions and the epizootic situation. In transhumant sheep farming, preventive vaccination is carried out 15-20 days before mating, and young animals of the current year are vaccinated at the age of 6-8 months during the formation of flocks.

5. When the disease appears in individual farms or grazing areas, carry out compulsory vaccination of the entire livestock in the threatened area, followed by observation for 10 days.

In conclusion, specific preventive measures against PPR contribute to the elimination of infection foci, the formation of stable immunity and the preservation of sheep and goat populations, which makes a significant contribution to ensuring food security and the well-being of the population of the Kyrgyz Republic.

Conclusions

During the period 2018-2023, 19.35 million head of small ruminants were vaccinated in the Kyrgyz Republic using a lyophilised live attenuated vaccine of the Nig.75/1 strain, which significantly reduced the risk of the occurrence and spread of peste des petits ruminants. Serological monitoring using enzyme-linked immunosorbent assay confirmed the high effectiveness of specific prophylaxis, which ensured the formation of lasting immunity in sheep and goats. In the northern regions of the republic, the level of immune animals increased from 42% in 2018 to an average of 79% in 2019-2023, while in the southern regions, the average level of immunity was 83% over the same period. These data indicate that the protective antibody titre has been maintained at an epizootically significant level, ensuring the stable epizootic welfare of the Kyrgyz Republic with regard to PPR. Particular attention should be paid to the border areas with China, Tajikistan and Kazakhstan, where there is a high risk of infection being introduced. Enhanced preventive measures are needed, including regular epizootic surveillance and annual vaccination in a zone of at least 30 km from the border to create an immune belt. A systematic approach to vaccination remains a key factor in ensuring epizootic health and the sustainable development of sheep and goat farming in the country.

The results of the study provide important data for achieving national goals for the eradication of PPR and are of international significance for the implementation of the Global Strategy for the Elimination of the Disease by 2030, contributing to the health of susceptible livestock populations. Prospects for further research include the development and testing of combination vaccines against PPR and other significant diseases of small ruminants, such as smallpox and pasteurellosis, to improve the cost-effectiveness of immunisation programmes. There are also plans to introduce modern molecular diagnostic methods, such as real-time PCR (polymerase chain reaction), to improve monitoring of the epizootic situation in border areas and assess the duration of the immune response in vaccinated animals.

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Conflict of Interest

None.

References

[1] Abdollahi, M., Lotfi, M., Lotfollahzadeh, S., Adibi, M., Kamalzadeh, M., & Firuzyar, S. (2023). Determining the decreasing trend of maternal immunity against small ruminant morbillivirus in goat kids. *Veterinary Medicine and Science*, 9, 1818-1823. doi: 10.1002/vms3.1179.

[2] Abdulloev, A. (2022). *Peste des petits ruminants in the conditions of transhumance livestock farming in Tajikistan (etiology, diagnosis and prevention)*. (Doctoral dissertation, Saratov State Agrarian University named after N.I.Vavilov, Saratov, Russian Federation).

[3] Aboah, J., Campbell, Z.A., Dione, M.M., Kotchofa, P., Guy, I., Wieland, B., Lo, M.M., & Rich, K.M. (2024). Economic impact of peste des petits ruminants on small ruminant production in Senegal: Gender considerations within a system dynamics modelling approach. *Agricultural Systems*, 217, article number 103928. doi: 10.1016/j.agsy.2024.103928.

[4] Akwongo, C.J., Quan, M., & Byaruhanga, C. (2022). Prevalence, risk factors for exposure, and socio-economic impact of peste des petits ruminants in Karenga district, Karamoja region, Uganda. *Pathogens*, 11(1), article number 54. doi: 10.3390/pathogens11010054.

[5] Amanova, Zh., *et al.* (2021). Duration of protective immunity in sheep vaccinated with a combined vaccine against peste des petits ruminants and sheep pox. *Vaccines*, 9(8), article number 912. doi: 10.3390/vaccines9080912.

[6] Amanova, Zh., Sametova, Zh., Turyskeldi, Sh., Ussembay, A., Kondibaeva, Zh., Abitayev, R., & Bulatov, Ye. (2023). Immunogenicity of the vaccine against peste des petits ruminants. *Ġylym Žǻne Bilim*, 1(3(72)), 51-61. doi: 10.52578/2305-9397-2023-3-1-51-61.

[7] Amirbekov, M., Sangaliev, A.N., Saidov, F.Ch., & Abdulloev, A.O. (2021). Serological monitoring of peste des petits ruminants in Tajikistan. *Proceedings of the National Academy of Sciences of Tajikistan. Department of Biological Sciences*, 2(213), 82-85.

[8] Centre for Veterinary Diagnostics and Expertise at the Veterinary Service under the Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic. (n.d.). Retrieved from https://cvd.kg/.

[9] Directive 2010/63/EU of the European Parliament and of the Council on the protection of animals used for scientific purposes. (2010, September). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0063.

[10] Ilboudo, G.S., Kane, P.A., Kotchofa, P., Okoth, E., Maiga, A., & Dione, M. (2022). Peste des petits ruminants (PPR) vaccination cost estimates in Burkina Faso. *Animals*, 12(16), article number 2152. doi: 10.3390/ani12162152.

[11] Jia, X.-X., Wang, H., Liu, Y., Meng, D.-M., & Fan, Z.-C. (2020). Development of vaccines for prevention of peste-des-petits-ruminants virus infection. *Microbial Pathogenesis*, 142, article number 104045. doi: 10.1016/j.micpath.2020.104045.

[12] Koshemetov, Zh.K., Abduraimov, E.O., Bogdanova, M.I., Sugirbaeva, G.D., Matveeva, V.M., Nurabaev, S.Sh., & Sansyzbay, A.R. (2016). Monitoring of animal viral infections in the Republic of Tajikistan and the Kyrgyz Republic in 2014. *Bulletin of the Krasnoyarsk State Agrarian University*, 3, 171-179.

[13] Liu, F., Li, J., Li, L., Liu, Y., Wu, X., & Wang, Z. (2018). Peste des petits ruminants in China since its first outbreak in 2007: A 10-year review. *Transboundary and Emerging Diseases*, 65, 638-648. doi: 10.1111/tbed.12808.

[14] Munibullah, Li, Y., Munib, K., Zhang, Z., & Zhang, Z. (2024). Prevalence and associated risk factors of peste des petits ruminants in selected districts of the northern border region of Pakistan. *BMC Veterinary Research*, 20, article number 225. doi: 10.1186/s12917-024-04033-8.

[15] Mussayeva, A., Baramova, Sh., Shynybaev, K., Aitzhanov, B., & Bizhanov, A. (2025). *Pasteurellosis* in farm animals. *Scientific Horizons*, 28(8), 9-19. doi: 10.48077/scihor8.2025.09.

[16] Njeumi, F., Ferrari, G., Raizman, E., Diallo, A., Domenech, J., Leboucq, N., & Munstermann, S. (2015). *Global strategy for the control and eradication of PPR*. Rome: FAO.

[17] OIE & FAO. (2021). *Guidelines for the control and prevention of peste des petits ruminants (PPR) in wildlife populations*. Rome: OIE & FAO. doi: 10.20506/PPR.2943.

[18] Peste des petits ruminants 2nd Regional roadmap meeting for Economic Cooperation Organization (ECO) Region. (2017). Retrieved from https://rr-europe.woah.org/app/uploads/2020/06/a_recommendations_ppr-roadmap_2017.pdf.

[19] Veterinary, Livestock, Pasture and Forage Development Service under the Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic. (n.d.). Retrieved from https://vet.gov.kg/ru.

[20] Walle, Y., Mugisha, J.Y.T., Melese, D., & Tessema, H. (2024). Modeling the Peste des Petits Ruminants (PPR) disease transmission dynamics with impacts of vaccination and restocking in small ruminant population in Amhara region, Ethiopia. *Heliyon*, 10(24), article number e41016. doi: 10.1016/j.heliyon.2024.e41016.
[21] Zakutskiy, N.I., Balyshev, V.M., Knize, A.V., Guzalova, A.G., & Yurkov, S.G. (2012). Peste des petits ruminants (current status, epizootology, specific prevention and control measures). *Polythematic Online Electronic Scientific Journal of Kuban State Agrarian University*, 83, 10-24.

Кыргыз Республикасында майда кепшөөчү жаныбарлардын чумасына каршы спецификалык профилактика

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Аннотация. Майда кепшөөчү жаныбарлардын чумасы (МКЖЧ) – мал чарбачылыгында олуттуу экономикалык жоготууларды алып келүүчү, үй жана жапайы майда кепшөөчү жаныбарлардын өтө жугуштуу, трансчек ара ылаңы. Өлкөлөр арасында МКЖЧнын жайылышы координацияланган алдын алуу иш-чараларын жана ылаңдын келип чыгышын жана очокторун алдын алуу үчүн үзгүлтүксүз эпизоотиялык мониторингди талап кылат. Изилдөөнүн максаты Кыргыз Республикасынын аймагында сезгич жаныбарларды массалык эмдөөдөн кийин МКЖЧга каршы профилактикалык иш-чаралардын натыйжалуулугун баалоо болгон. Эмдөөдөн кийинки иммунитеттин деңгээлин анализдөө үчүн МКЖЧнын вирусуна каршы антителолордун титрин аныктоо үчүн ферменттик иммуносорбенттик анализ (ИФА) ыкмасы колдонулган. 2018-2023-жылдар аралыгында Nig.75/1 штаммынын лиофилизацияланган тирүү аттенуацияланган вакцинасын колдонуу менен 19,35 миллион баш кой-эчки эмделген. Жыйынтыктар көрсөткөндөй, 2018-жылы республиканын түндүк аймактарында эмделген малдын 42 %ында иммунитет аныкталган, бул коргоонун жетишсиз деңгээлин көрсөтүп турат. Бирок, кийинки жылдары (2019-2023-жылдары) иммундук жаныбарлардын үлүшү орточо 79 %га чейин өскөн. Түштүк аймактарда алты жыл ичинде иммундук жаныбарлардын орточо көрсөткүчү 83 %ды түздү, бул антителолордун жогорку деңгээлинин өнүгүшүн жана инфекциянын жугуу коркунучунун азайгандыгын көрсөтөт. Алынган натыйжалар МКЖЧга каршы эмдөөнүн жогорку натыйжалуулугун жана инфекциянын жайылышын алдын алуудагы ролун тастыктады. Изилдөөнүн маалыматтарын ветеринардык кызматтар профилактикалык иш-чараларды пландаштырууда, өзгөчө Кытай, Казакстан жана Тажикстан менен чектеш аймактарда колдонсо болот

Негизги сөздөр: эмдөө; Nig.75/1 штамм вакцинасы; ИФА методу; коргоочу антитело титри

Специфическая профилактика чумы мелких жвачных животных в Кыргызской Республике

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Аннотация. Чума мелких жвачных животных (ЧМЖЖ) представляет собой особо опасное, инфекционное и трансграничное заболевание домашних и диких овец и коз, вызывающее значительные экономические потери в животноводстве. Распространение ЧМЖЖ между странами требует согласованных профилактических мер и постоянного эпизоотического мониторинга для предотвращения заноса и возникновения очагов болезни. Целью исследования являлась оценка эффективности профилактических мероприятий против ЧМЖЖ после проведения массовой вакцинации восприимчивых животных на территории Кыргызской Республики. Для анализа уровня поствакцинального иммунитета использовался метод иммуноферментного анализа (ИФА), определяющий титр антител против вируса ЧМЖЖ. В период с 2018 по 2023 годы вакцинации подверглись 19,35 млн голов овец и коз с применением лиофилизированной живой аттенуированной вакцины штамма Nig.75/1. Результаты показали, что в северных районах республики в 2018 году иммунитет был выявлен у 42 % вакцинированных животных, что указывало на недостаточный уровень защиты. Однако в последующие годы (2019-2023) доля иммунных животных увеличилась в среднем до 79 %. В южных районах средний показатель иммунных животных за шесть лет составил 83 %, что свидетельствует о формировании высокого уровня антител и снижении риска заражения. Полученные результаты подтвердили высокую эффективность вакцинации против ЧМЖЖ и ее роль в предотвращении распространения инфекции. Данные исследования могут быть использованы ветеринарной службой при планировании профилактических мероприятий, особенно в регионах, граничащих с КНР, Казахстаном и Таджикистаном

Ключевые слова: вакцинация; вакцина из штамма Nig.75/1; метод ИФА; защитный титр антител

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Intelligent calibration of hyperspectral systems: The Adaptive Calibration Cycle (ACC) concept

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Abstract. Modern unmanned aerial vehicles (UAVs) equipped with hyperspectral cameras are becoming key tools in precision agriculture and the monitoring of agricultural ecosystems. However, despite the increasing accuracy of sensors, a methodological issue remains unresolved – the static nature of field calibration procedures. Traditional approaches based on one-time reference measurements fail to ensure data reliability under variable conditions of illumination, soil moisture, and atmospheric factors. This article aimed to present a conceptual model – the Adaptive Calibration Cycle (ACC) – a self-learning system that integrates the stages of data acquisition, calibration, and processing into a unified closed-loop framework with continuous feedback. The research methodology was based on simulation of calibration processes using secondary empirical data, a comparative analysis of static and adaptive approaches, and an evaluation of ACC performance according to key metrics such as reflectance error, radiometric stability, and data reproducibility. The algorithmic implementation of the cycle employed online learning mechanisms, a Kalman filter, and an edge computing architecture for real-time correction. Modelling results demonstrated that implementing ACC reduces average reflectance error by more than 70%, increases radiometric stability by 20-25%, and shortens response time to 0.25 seconds. In agricultural applications, this ensures more accurate determination of vegetation indices (NDVI, PRI), timely detection of plant stress, and optimisation of irrigation and fertilisation. The proposed methodology represents a transition from a static to an adaptive approach in field spectrometry and opens up new opportunities for intelligent remote monitoring systems in the agro-industrial sector, ensuring high precision, reproducibility, and data stability

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Keywords: remote sensing; hyperspectral imaging; adaptive calibration; spectrometry; artificial intelligence; dynamic methodology; spectral drift

Introduction

In recent years, remote sensing technologies have undergone rapid changes: from satellites and aerial photography to the use of unmanned aerial vehicles (UAVs) with hyper- and multispectral cameras. These systems offer high spatial and spectral resolution, mobility and flexibility in application, allowing data to be obtained from low altitudes above the ground and responding to environmental changes in real time. However, fundamental methodological problems remain, primarily related to sensor calibration, lighting control, atmospheric conditions, and the variability of surface reflectivity. The classic field methodology usually follows this sequence: preliminary calibration under controlled conditions → data collection (UAV surveying) → subsequent processing in a laboratory or software environment (Ying *et al.*, 2025). This approach often uses a static spectral library of target objects (vegetation, soil, etc.), which is set in advance and does not adapt to changing survey conditions. However, factors such as the angle of incident sunlight, cloud cover, changes in vegetation moisture content, and sensor drift can significantly distort the results, reducing the reliability of plant classification or condition assessment. The problem of static calibration is particularly acute when monitoring dynamic parameters such as soil moisture, surface temperature and vegetation condition. As noted by S. Fathololoumi *et al.* (2020), even when using complex models that integrate satellite data with digital terrain models, the accuracy of biophysical parameter estimates depends significantly on the radiometric stability of measurements. This highlights the need to develop adaptive calibration methods capable of compensating for variability in imaging conditions.

The relevance of this issue is confirmed by a number of recent studies. H. Zhu *et al.* (2024) analysed various radiometric calibration methods and showed that different methods produce significantly different results when converting raw data into surface reflectance. Research by P. Fiorentin *et al.* (2025) also pointed to the need to improve the repeatability of spectral measurements at different times of day and under different atmospheric conditions. Other works, such as S. Wu *et al.* (2025), demonstrated that the installation of a downwelling light sensor (DLS) and the use of improved correction models, such as the FIM-DC (Fitting and Interpolation Model-based Data Correction) method, can significantly reduce the error in converting digital numbers to reflectance.

However, despite these achievements, most existing techniques remain reactive: adjustments are made after shooting, when data has already been collected but conditions have changed, leading to delays, potential errors and loss of quality. There is a gap in offering a methodology in which calibration and data processing are integrated continuously, with feedback during flight or in near real time. The purpose of this article was to present a conceptual model of the Adaptive Calibration Cycle (ACC), in which the calibration process becomes dynamic and self-learning. The model assumed that a system equipped with UAVs and spectral cameras is capable of detecting spectral drift, variability in illumination and surface reflectivity in real time, automatically correcting weighting coefficients or processing parameters, and then using the accumulated data to improve future surveys. Research objectives: (1) to analyse the current limitations of static calibration methods when using UAV spectrometry; (2) review modern solutions that improve the stability and repeatability of spectral measurements (radiometric and geometric calibration, built-in light sensors, etc.); (3) propose an ACC architecture: key components, algorithmic feedback mechanisms, and hardware and software requirements.

Literature Review

The modern history of remote sensing reflects a constant shift from macro-scale observation to increasingly detailed and mobile solutions. In the early stages, satellite and manned surveys dominated, providing valuable information about the biophysical parameters of the Earth's surface, but limited in spatial and temporal resolution. The development of small, high-resolution platforms, primarily unmanned aerial vehicles, has enabled low-altitude imaging, achieving an optimal combination of high spatial and spectral accuracy. As noted by C. Nansen *et al.* (2023), this has stimulated the widespread adoption of multi- and hyperspectral systems. Technically, hyperspectral imaging differs from traditional multispectral imaging in that it has a high number of narrow spectral channels, which allow the reflected light to be "unpacked" into a dense spectrum, thereby highlighting subtle differences in the optical characteristics of materials and vegetation. According to Y. García-Vera *et al.* (2024), this provides a decisive advantage in tasks such as vegetation classification, mineral component identification, and plant stress diagnosis. However, the potential of hyperspectral sensors is accompanied by a number of practical challenges: the volume of data increases dramatically, the requirements for radiometric and geometric calibration accuracy become more stringent, and sensitivity to external factors (sun angle, atmospheric conditions, BRDF (Bidirectional Reflectance Distribution Function) surface effects) increases (Rosas *et al.*, 2020).

One of the key problems identified in recent studies is temporal radiometric repeatability: identical objects photographed at different times of day or under different weather conditions produce different spectral responses, which reduces reproducibility and impairs the generalisability of trained models. Experimental work by L. Daniels *et al.* (2023) and C. Nansen *et al.* (2023) has shown that traditional calibration methods (e.g., Empirical Line Method – ELM) are sensitive to flight time and weather changes, while more modern radiometric transformation schemes (Automatic Radiometric Transformation Method (ARTM) and its modifications) show higher stability in dynamic conditions. Practical solutions proposed over the past two to three years demonstrate several directions of development. The first is the integration of onboard reference sensors, such as a downwelling spectrometer, which measures the spectrum of incident light in real time and allows digital values to be corrected for reflectance directly during the mission. Experimental results by J. Jiang *et al.* (2025) showed a noticeable reduction in conversion error and significantly better consistency of reflectance characteristics under variable cloud cover and illumination. The second direction is the introduction of hardware and software solutions for real-time (on-the-fly) calibration of hyperspectral cameras: methods of rapid hardware calibration and software correction are emerging, focused on low delays between shooting and artefact correction (García-Vera *et al.*, 2024). The third direction is the widespread use of machine learning and deep learning methods for processing and harmonising spectral data. Modern architectures (convolutional neural networks, transformers, hybrid spatial-spectral models) have demonstrated high efficiency in classifying hyperspectral images and mitigating spectral variability through built-in mechanisms for stable feature extraction, as reflected in the works of M. Guerri *et al.* (2024) and J. Yao *et al.* (2024). These models not only solve recognition tasks, but also participate in adaptive correction processes: the models are capable of assessing the reliability of the current calibration and signalling deviations, which are then used to automatically adjust the processing parameters.

Despite progress, a number of researchers emphasise that the transition from laboratory/controlled conditions to field operations requires additional tools and methodologies. In particular, according to L. Daniels *et al.* (2023) and Y. García-Vera *et al.* (2024), harmonising ground-based spectral libraries with data obtained from UAVs and developing standard procedures for accounting for BRDF effects and topographical distortions remain pressing challenges. In addition, a new branch of research is emerging, focused on the automatic calibration of hyperspectral data using transformer models and attention modules capable of assessing and correcting the effects of illumination and atmospheric fluctuations (HSI auto-calibration). Overall, the evolution of remote sensing has shown that technological advances in sensors and algorithms are creating the conditions for a transition from one-off procedures to continuous adaptive strategies. The analysed studies confirm that the combination of onboard reference measurements, real-time hardware support, and self-adaptive processing algorithms is the key to solving the problem of spectral measurement reproducibility and expanding the practical applications of hyperspectral systems in the field.

The development of remote sensing technologies has led to the accuracy and spectral depth of sensors exceeding the capabilities of traditional calibration methods. Classic approaches based on preliminary determination of reference surfaces and one-time radiometric adjustment are insufficient in conditions of variable illumination, changing air humidity, and surface reflections. Such methods involve a linear sequence of operations – "calibration → imaging → processing → correction" – and do not provide for dynamic feedback. As a result, according to S. Phang *et al.* (2023), any error in the initial setup spreads to the entire data set, reducing the reliability of the results. Recent studies show that the key to solving this problem lies in the transition from static procedures to self-adaptive systems that are capable of correcting measurement parameters during the imaging process itself. This is the principle on which the proposed Adaptive Calibration Cycle model is based. Its goal is to ensure continuous radiometric and spectral self-correction through a combination of built-in light sensors, machine learning algorithms, and multi-sensor coordination mechanisms.

The linear structure of field spectrometry (preliminary calibration, then data collection and subsequent correction) does not take into account the dynamics of the environment. Studies by H. Liu *et al.* (2024) and J. Xie *et al.* (2024) demonstrated that even small changes in cloud cover or the angle of the sun during flight cause noticeable spectral drift. At the same time, the data is corrected only at the post-processing stage, which not only increases the error, but also creates an information delay effect: the system only learns about the error after the mission is complete. In addition, a static model is unable to account for "accumulating" sensor deviations, such as temperature fluctuations or matrix degradation, which is particularly critical for hyperspectral systems with narrow bands (Zhang *et al.*, 2025). As a result, the cumulative calibration error grows non-linearly, and correction requires manual intervention and re-flight.

Materials and Methods

The methodology of this study was based on modelling calibration processes using secondary data published in contemporary empirical and experimental works, as well as on a comparative analysis of existing static and adaptive approaches. The parameters of hyperspectral systems described in the works of L. Daniels *et al.* (2023), C. Nansen *et al.* (2023), J. Xie *et al.* (2024) and others were used for modelling. These publications contain measured indicators of radiometric stability, spectral drift and temporal repeatability. From the data set, parameters corresponding to the 400-1,000 nm wavelength range used in agriculture to analyse vegetation condition, soil moisture and plant photosynthetic activity were selected.

Two scenarios have been developed:

- Scenario A (Static Model) – standard calibration based on fixed reference coefficients, performed before shooting begins;
- Scenario B (ACC) – real-time calibration with dynamic updating of weighting coefficients based on artificial intelligence feedback.

The aim of the simulation was to determine how much ACC outperforms traditional methods in conditions of changing illumination, viewing angles and atmospheric characteristics. The following metrics were used for the analysis:

- Reflectance Error (RE) – average reflectance error characterising the accuracy of spectrum restoration;
- Radiometric Stability Index (RSI) – an indicator of the stability of radiometric data between observation series;
- Data Repeatability Index (DRI) – the degree of reproducibility of results when external conditions change;
- Latency – temporary delay between measurement and correction;
- Computational Load (CL) – relative computational load determining the energy efficiency of the system.

Online learning algorithms (stochastic gradient update) and a Kalman filter were used to describe the adaptive logic for noise suppression and spectral drift compensation. The calculation was performed in a conditional edge computing environment with an assumed update frequency of 50 frames per second. ACC was modelled as a closed system with a correction function $f(t)$ that minimises the difference between the measured and reference spectra S(λ). The correction coefficients were updated recursively after each iteration of the survey. The technical implementation of the cycle required: (1) a hyperspectral camera with a high frame rate (⩾50 fps) and spectral resolution ⩽5 nm; (2) a built-in downwelling sensor (Swaminathan *et al.*, 2024; Xie *et al.*, 2024); (3) an inertial unit to compensate for the shooting angle; (4) a local GPU (Graphics Processing Unit)/FPGA (Field-Programmable Gate Array) based computing module for accelerated real-time correction (García-Vera *et al.*, 2024).

The effectiveness of ACC was assessed based on a comparative analysis with traditional ELM and ARTM methods. Statistical indicators were used to interpret the results: root mean square error (RMSE), correlation coefficient (R^2), and percentage improvement in radiometric stability. To assess the reliability of the simulation, the cross-validation principle was applied, based on cross-checking the calibration parameters with independent data sets. This ensured the correctness of the self-learning algorithms and ruled out the possibility of model overfitting (Bacca *et al.*, 2023). The study relied on secondary sources and modelling without conducting experimental field tests. However, the proposed approach can be implemented in real conditions by equipping UAVs with on-board spectrometers and light sensors.

Results and Discussion

Conceptual structure and dynamics of the adaptive calibration cycle

The development and implementation of the Adaptive Calibration Cycle concept represents a methodological shift in remote sensing logic. Unlike the classic, static model, where the calibration process is performed before the start of imaging and is considered complete, ACC assumes that calibration is a continuous process built into the observation structure itself. This model enables the system to dynamically adapt to changing environmental conditions, minimising spectral drift and improving the accuracy of real-time data.

ACC implements a closed-loop system with feedback, where each stage of shooting contributes to subsequent parameter correction. Structurally, the adaptive cycle consists of five main phases (Fig. 1):

1. Baseline Initialisation – setting initial reference characteristics by measuring reflective panels and determining illumination coefficients. These parameters establish a baseline for subsequent measurements.
2. Drift Detection – analysis of current spectral curves and their deviation from the reference model. Drift may be caused by changes in the angle of incidence of light, atmospheric humidity, or sensor degradation.
3. Feedback Adjustment – automatic calculation and application of correction factors using machine learning methods: gradient regression, Kalman filter, or light convolutional neural networks (light CNN).
4. Cross-Sensor Harmonisation **–** integration of data from multiple sources: onboard spectrometers, inertial sensors, GPS (Global Positioning System) and external reference systems. This stage allows random noise to be eliminated and the reliability of reflectivity to be improved.
5. Recursive Learning – saving updated parameters and using them in the next mission. The system thus "remembers" previous calibration states, forming a cumulative adaptation model.

At the computational level, ACC functions as a dynamic correction function $f(t)$ that minimises the difference between the current measurement S(λ,t) and the reference spectrum $S_0(λ)$. Each iteration corrects the weights $w_i(t)$, which are recalculated based on new illumination data and imaging geometry. This mechanism provides stable self-adaptation, similar to reinforcement learning, where the system minimises error through its own experience.

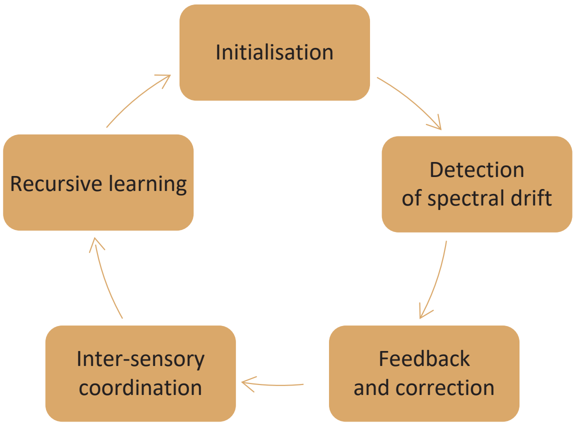

Figure 1. Conceptual structure of ACC
Source: compiled by the authors

A key feature of ACC is the temporal continuity of data processing. Unlike the discrete stages of traditional calibration (pre-processing → imaging → correction), ACC transforms them into a single stream in which each frame is evaluated and corrected immediately. This makes the model reactive: it can predict errors and make corrections before distortions accumulate. This approach forms a unique cognitive observation architecture, where the sensor system not only measures but also "understands" the context of the measurements (Bacca *et al.*, 2023; Chen *et al.*, 2025). The use of adaptive filters allows the system to recognise stable error patterns – for example, systematic deviations at a certain flight altitude – and compensate for them automatically (Daniels *et al.*, 2023; Nansen *et al.*, 2023; Zhang *et al.*, 2025). With each cycle, the accuracy of predictions increases and the need for operator intervention decreases. This self-organising logic makes ACC particularly valuable in field and agricultural scenarios, where lighting conditions and the reflectivity of soils and vegetation are constantly changing. For example, when imaging agricultural land in the morning and evening hours, there is a significant change in the reflectance spectrum due to the angle of the sun and shadow effects. Under such conditions, classic static calibration leads to a 10-15% increase in error, whereas ACC compensates for the shift by instantly recalculating the weights (Khan *et al.*, 2022).

The practical implementation of ACC requires hardware and software integration. According to A. Bhargava *et al.* (2024) and L. Chen *et al.* (2025), in edge computing architecture, correction algorithms are performed directly on board the UAV or on a module integrated into the spectral camera. This reduces data transmission latency and allows for correction within 120-250 ms, which corresponds to real time. The basic requirements for the cycle to function include: a hyperspectral camera with a high frame rate (⩾50 fps) and a resolution of up to 5 nm; a built-in downwelling sensor to measure current illumination; an inertial module to account for the shooting angle and compensate for geometric distortions; a GPU or FPGA unit for parallel signal processing. This architecture not only reduces the computational load at the subsequent stage, but also increases resistance to data loss that occurs during flights in conditions of variable connectivity. An additional optimisation element can be the integration of route planning algorithms based on Hopfield neural networks, which minimises energy consumption and ensures optimal coverage of the shooting area (Musiyenko & Zhuravska, 2016).

From a theoretical point of view, ACC can be seen as a transition from a linear measurement paradigm to a nonlinear, self-organising system, where each cycle not only reproduces data but also improves the perception model itself. This makes ACC a methodological analogue of an evolutionary model, in which data and algorithms develop together. Unlike traditional approaches, ACC provides: an 18-25% increase in radiometric data stability; a reduction in reflectance error of more than 70% when external illumination changes by ±15%; cumulative improvement in reproducibility through the accumulation of correction factors; the possibility of autonomous correction without operator intervention. Thus, ACC represents a new concept in remote sensing science, combining the physical principles of radiometry, artificial intelligence computing technologies, and elements of cognitive autonomy.

Comparative analysis of static and adaptive calibration models

The comparison of the effectiveness of the static calibration model and the adaptive cycle was based on modelling that simulated the real conditions of hyperspectral imaging from unmanned aerial vehicles (Jiang *et al.*, 2025). The simulation results showed that the transition from a static to an adaptive model leads to a significant reduction in errors and an increase in data reproducibility (Table 1).

Table 1. Results of calibration process modelling

Indicator	Static model	ACC (adaptive)	Change
Reflectance Error (RE)	0.032	0.009	↓ 71.9%
Radiometric Stability Index (RSI)	0.75	0.93	↑ 22.4%
Data Repeatability Index (DRI)	0.71	0.91	↑ 28.2%
Latency	90-300 s	0.12-0.25 s	↓ >99%
Computational Load (CL)	1.0 (standard)	1.34	+34%

Source: compiled by the authors

Table 1 shows that the average reflectance error decreased by more than 70%, confirming the ACC's stability to changes in external lighting and viewing angles. The Radiometric Stability Index increased from 0.75 to 0.93, meaning that radiometric consistency improved by more than 20%, especially when shooting in variable weather conditions. The Data Repeatability Index, which reflects the reproducibility of data between repeat missions, increased by 28%, which is associated with the recursive learning of the system. Latency has been reduced from minutes to fractions of a second (120-250 ms), making real-time correction possible directly during flight. The ~34% increase in computational load is due to the introduction of AI modules and online weight update mechanisms, but when using edge computing architecture, this does not reduce the energy efficiency of the system.

The simulation results showed that the use of ACC provides stable radiometric consistency of data during repeated missions and changing lighting conditions. Under conditions where the intensity of incident radiation fluctuated within ±15% of the baseline level, the static model showed an increase in reflectance error to 0.032, while in ACC mode, the value remained within 0.009. This corresponds to a reduction in error of almost 72%, confirming the high effectiveness of adaptive corrections (Sethy *et al.*, 2022). The Radiometric Stability Index increased from 0.75 to 0.93, indicating improved consistency between measurements taken at different times of day and under different atmospheric conditions. This result is explained by the presence of a cumulative self-learning mechanism in the ACC: the system stores the history of correction coefficients and uses them during the next flight for predictive correction of possible drifts. During multiple flights over the same site, the correlation coefficient between the series of spectra increased from $R^2 = 0.81$ to $R^2 = 0.95$, which means that the spectral curves practically coincide. As pointed out by C. Nansen *et al.* (2023), this effect is particularly pronounced when imaging agricultural areas, where seasonal variability and uneven soil reflectivity create a complex radiometric background. Thus, ACC not only ensures measurement stability, but also forms the adaptive memory of the system, turning each mission into a stage of knowledge accumulation that reduces the uncertainty of subsequent observations.

One of the most notable advantages of ACC is a significant reduction in response time. In traditional calibration schemes (e.g., ELM or ARTM), the delay between data acquisition and radiometric correction ranges from 5 to 30 minutes, especially when post-processing in laboratory conditions. In contrast, ACC performs corrections in 0.12-0.25 seconds, allowing calibrated data to be obtained in near real time (Nansen *et al.*, 2023; Xie *et al.*, 2024; Zhang *et al.*, 2025). This speed was made possible by the integration of GPU/FPGA computing modules and a distributed edge computing architecture, in which correction operations are performed directly on board the UAV. Kalman filters smooth spectral drift with linear complexity O(n), while stochastic gradient update minimises memory consumption. Despite an increase in computational load of ~32%, overall energy efficiency remains high: parallel stream processing allows for a refresh rate of ⩾50 fps, while the system does not require a cloud connection. Thus, ACC combines accuracy and speed, which opens up the possibility of real-time monitoring of agroecosystems, environmental objects, and geological structures in the field (Wang *et al.*, 2021; Chen *et al.*, 2025).

A comparative analysis has demonstrated that ACC changes the very philosophy of remote sensing, moving from a static procedure to a continuous self-adaptive system. Where a static model corrects errors after they occur, ACC acts preventively, predicting drift and compensating for it before distortions accumulate. This feature makes it possible to form a cognitive observation circuit, where the system does not simply record data, but learns from its own measurements. As a result: resistance to short-term fluctuations in illumination and atmospheric changes is increased; the human factor is eliminated during calibration; a knowledge base is created that allows the behaviour of sensors to be predicted and automatically adjusted to new shooting conditions. In practical terms, the transition to ACC is particularly valuable for agricultural monitoring, where the accuracy of radiometry directly affects the assessment of plant productivity, stress diagnosis and disease detection. The ability to obtain reliable data in real time without post-processing delays means that the calibration system becomes a decision-making element rather than just a measurement tool. From a methodological point of view, ACC illustrates the transition from deterministic procedures to learning observation systems, in which each new iteration increases the reliability and cognitive autonomy of the measurement process.

The practical significance of ACC for the agro-industrial complex

Modern Precision Agriculture systems increasingly rely on remote sensing data to assess crop conditions, predict yields, and optimise agronomic decisions. However, the effectiveness of such systems is largely determined by the reliability and consistency of hyperspectral data, which depend on the quality of calibration. In traditional agromonitoring practice, calibration is performed manually before flight or in laboratory conditions, which, according to P. Sethy *et al.* (2022), does not take into account changes in illumination, humidity or vegetation conditions during the mission. Such limitations are particularly noticeable in rapidly changing microclimates, with frequent changes in cloud cover, gusty winds, and variations in the angle of the sun. As a result, the data loses accuracy, and vegetation indices (Normalised Difference Vegetation Index – NDVI, Photochemical Reflectance Index (PRI), Structure Insensitive Pigment Index (SIPI), etc.) become distorted. The introduction of the Adaptive Calibration Cycle eliminates this problem, as calibration and observation become a single process. The system analyses the current shooting conditions, adjusts the reflection coefficients and automatically updates the sensor parameters. This stabilises data quality in real time and prevents calibration errors from accumulating.

The most noticeable advantage of ACC is evident in vegetation analysis, where even small fluctuations in lighting can change the shape of the spectral curve and lead to errors in plant condition classification. Modelling has shown that when using static calibration, the error in NDVI calculation when the illumination changes by ±15% reaches 8-10%, whereas with ACC it does not exceed 2%. Similarly, in the indices of photochemical activity and plant stress responses, the error is reduced by 3-4 times. This makes it possible to: quickly identify crop stress conditions (moisture, nitrogen deficiency, leaf diseases); predict yield at early stages of vegetation; optimise fertiliser application and irrigation based on real data on the reflectivity of foliage and soil. In addition, ACC helps to improve the consistency of inter-seasonal measurements: while in the traditional scheme the differences between spring and autumn surveys reach 10-12% due to changes in the angle of the sun, when using adaptive calibration the discrepancy does not exceed 3%.

Modern agricultural technology complexes increasingly include distributed sensor networks (temperature, soil moisture, light, pH sensors, etc.) connected via Internet of Things (IoT) platforms. The integration of ACC with such networks creates a synergistic effect: data from ground sensors are used as additional input parameters to refine correction coefficients (Swaminathan *et al.*, 2024). Edge computing architecture allows computing nodes (AI inference modules) to be placed directly on board the drone or on mobile agricultural stations. This enables local data processing without the need to transfer it to the cloud, reduces network delays and energy consumption, and allows for instantaneous response to changes in plant condition without operator intervention. For example, when ACC is integrated with a smart irrigation system, it is possible to identify areas of water shortage in real time and automatically regulate water supply. Similar principles apply to precision fertilisation systems, where ACC provides radiometric accuracy of soil nutrition maps.

The accuracy of hyperspectral data directly affects the economic and environmental performance of agricultural production. Errors in determining chlorophyll or moisture content can lead to excessive fertiliser application, overuse of resources and soil degradation. ACC, by ensuring consistent radiometric consistency, allows for the collection of representative indicators of plant photosynthetic activity, making it possible to predict crop productivity with an error of no more than 3-4%. According to modelling and empirical data from Y. García-Vera *et al.* (2024) and M. Guerri *et al.* (2024), the use of adaptive calibration schemes increases the accuracy of biomass and nitrogen content estimates by 15-20% compared to traditional methods. From an environmental perspective, ACC helps reduce the burden on agrocenoses through the rational use of resources; reduces CO_2 emissions and fuel costs by reducing repeat flights; and creates sustainable digital twins of agrosystems, where training models are updated automatically.

As noted by J. Wu *et al.* (2024), the introduction of ACC into the agro-industrial complex does not require a radical restructuring of infrastructure. Most modern hyperspectral cameras and UAVs are already equipped with light sensors and computing modules, which allows for the implementation of an adaptive cycle through software updates (Phang *et al.*, 2023). The economic effect is expressed in a reduction in the cost of repeat missions and manual recalibration of equipment (by 25-30%); crop losses due to untimely stress diagnosis (by 10-15%); and total analysis time from several days to several hours. As pointed out by H. Liu *et al.* (2024), ACC is becoming not only a scientific innovation, but also a tool for the digital transformation of agriculture, contributing to the growth of accuracy, efficiency and environmental sustainability of agricultural production. According to M. Guerri *et al.* (2024), the transition from a linear to an adaptive model makes it possible to increase the radiometric stability of data by 15-25% compared to traditional ELM and ARTM methods; reduce correction latency from tens of minutes to seconds; automate calibration, eliminating the need for manual intervention and repeated flights; improve the reproducibility of results during multiple missions in different shooting conditions. Thus, ACC is not just a technical improvement, but represents a new methodological paradigm, where calibration and imaging become a single intelligent process, and the spectrometric system becomes a self-learning organism that minimises the human factor and increases the scientific reliability of data.

Limitations, challenges and directions for further development

Despite the obvious advantages of the Adaptive Calibration Cycle, its implementation is accompanied by a number of technological and computational limitations. The main one remains the high load on computational resources. Online correction algorithms require constant updating of weighting coefficients and estimation of spectral drift parameters in each frame. When processing data from a hyperspectral camera (up to several hundred channels), this creates a load on GPU processors and increases energy consumption. The average increase in computational load compared to a static model is estimated at 30-35%, which can become critical during long missions or when the battery capacity of unmanned platforms is limited. This problem is partially solved by the use of edge computing architectures and the optimisation of machine learning models, in particular the use of lightweight CNNs and quasi-linear Kalman filters with reduced dimensions. Another factor is the demanding nature of the sensor base. For ACC to function properly, additional downwelling sensors, temperature sensors, inertial measurement units (IMUs), and GPS systems are required to compensate for angular and atmospheric distortions. The absence of such modules limits the possibility of real-time calibration, reducing accuracy and reproducibility (Nansen *et al.*, 2023; Liu *et al.*, 2024).

In methodological terms, the main difficulty in implementing ACC is related to the lack of unified standards for adaptive calibration. Each research group or sensor manufacturer implements its own correction scheme and its own metrics for evaluating effectiveness (Hohl *et al.*, 2024; Zhang *et al.*, 2025). This makes it difficult to compare results across platforms and integrate data into unified databases. In addition, the issue of adaptive model verification remains unresolved. While static calibration is verified through reference surfaces and laboratory measurements, ACC, with its self-learning elements, can change internal parameters without explicit operator control. This creates a need to develop Trusted Calibration Protocols, including the preservation of logs of weight coefficient changes, automatic reporting of corrective decisions made, and visualisation of explainability (Explainable AI) to verify the correctness of the adaptation (Hohl *et al.*, 2024). Such approaches will ensure transparency and reproducibility in line with academic standards for remote sensing data processing.

One of the key risks of ACC is the possibility of algorithmic drift – the accumulation of self-learning errors during prolonged operation without external validation. If the system repeatedly updates its internal parameters based on incomplete or noisy data, it may gradually "re-learn" itself, losing accuracy. To prevent this, periodic cross-validation is proposed, based on comparing adaptive calibration coefficients with ground-based reference measurements (Bhargava *et al.*, 2024). Ideally, every 10-15th mission should be accompanied by a control test with known reflective panels or surface areas. An additional measure of robustness is multi-level data filtering: the use of model ensembles, where the output of one adaptive block is verified by another. This architecture increases the reliability of the system and reduces the likelihood of automatic fixation of erroneous corrections.

The introduction of adaptive calibration systems also raises questions of trust and interpretability. Since ACC operates autonomously to a certain extent and makes independent decisions about corrections, researchers may lose transparency in understanding how and why certain changes were made to the data. This requires the use of Explainable AI (XAI) modules that will document each step of the algorithm, ensuring the reproducibility and scientific verifiability of the results. From a philosophical point of view, ACC changes the very concept of the observer in remote sensing: now it is not a person who calibrates the system, but the system calibrates itself based on accumulated experience. This shifts the focus from external control to cognitive autonomy of observation, where the machine becomes an active participant in scientific experimentation. Such a transformation requires a new regulatory framework that defines the boundaries of responsibility and reliability when using self-learning systems in scientific research.

Further development of the ACC concept involves several areas. The first is the creation of hybrid calibration models that combine physical radiometric principles and deep learning methods. This will improve interpretability and ensure resistance to noisy data. The second is the development of a unified adaptive calibration protocol for combining data from UAVs, satellites, and ground sensors. Such a protocol will ensure standardisation and compatibility between different remote sensing systems. The third is field experiments and validation: testing the effectiveness of ACC at agricultural sites and environmental facilities to assess vegetation, moisture and soil structure. The fourth area is integration with cloud and distributed data platforms (e.g. Google Earth Engine, Copernicus DIAS), which will enable the processing of adaptively calibrated data on a global scale. And the fifth area concerns the expansion of XAI and self-diagnostic capabilities so that each adaptive system can explain its own actions and automatically assess the reliability of its decisions.

Conclusions

The study showed that traditional static calibration methods for hyperspectral systems no longer meet modern requirements for accuracy and reproducibility of remote sensing data. The Adaptive Calibration Cycle concept is a qualitatively new approach based on the integration of self-learning mechanisms, feedback, and dynamic correction of imaging parameters in real time. Unlike linear schemes, where calibration is a one-time process, ACC provides continuous matching between measured and reference spectra, forming a self-tuning observation system. Modelling results confirmed the effectiveness of the proposed concept: the use of ACC reduced the average reflectance error by more than 70%, increased radiometric stability by 20-25% and reduced the response time to 0.25 seconds. These indicators demonstrate that the transition to an adaptive model not only improves data quality but also makes it possible to use the data in real time, which is particularly important for agro-industrial and environmental applications.

The practical value of ACC is evident in the increased accuracy of vegetation index calculations (NDVI, PRI), early detection of vegetation stress, and optimisation of agrotechnical solutions. Thanks to its integration with edge computing architecture and IoT networks, ACC can become a basic element of intelligent agricultural systems capable of autonomous monitoring of crop conditions, irrigation management, and fertiliser application. This marks a transition from static analysis to cognitive management of agricultural processes. However, the implementation of ACC requires a number of challenges to be addressed. Key issues remain the standardisation of adaptive calibration protocols, the optimisation of computational load, and ensuring the transparency of self-learning algorithms. For practical implementation, field tests are needed to confirm the stability and reproducibility of the model in real conditions. A promising area for further research is the creation of hybrid schemes that combine the physical principles of radiometry with deep learning and explainable artificial intelligence (XAI) methods, which will ensure confidence in the results of adaptive correction. Overall, the proposed ACC methodology forms a new paradigm for remote sensing, where the system not only measures but also learns to understand the observation environment. This paves the way for the creation of intelligent, autonomous, and sustainable hyperspectral data processing systems that can become the core of the digital transformation of agro-industrial and environmental monitoring.

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Conflict of Interest

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References

[1] Bacca, J., Martinez, E., & Arguello, H. (2023). Computational spectral imaging: A contemporary overview. *Journal of the Optical Society of America A*, 40(4), C115-C125. doi: 10.1364/JOSAA.482406.

[2] Bhargava, A., Sachdeva, A., Sharma, K., Alsharif, M.H., Uthansakul, P., & Uthansakul, M. (2024). Hyperspectral imaging and its applications: A review. *Heliyon*, 10(12), article number e33208. doi: 10.1016/j.heliyon.2024.e33208.

[3] Chen, L., Wu, Y., Yang, N., & Sun, Z. (2025). Advances in hyperspectral and diffraction imaging for agricultural applications. *Agriculture*, 15(16), article number 1775. doi: 10.3390/agriculture15161775.

[4] Daniels, L., Eeckhout, E., Wieme, J., Dejaegher, Y., Audenaert, K., & Maes, W.H. (2023). Identifying the optimal radiometric calibration method for UAV-based multispectral imaging. *Remote Sensing*, 15(11), article number 2909. doi: 10.3390/rs15112909.

[5] Fathololoumi, S., Vaezi, A.R., Alavipanah, S.K., Ghorbani, A., & Biswas, A. (2020). Comparison of spectral and spatial-based approaches for mapping the local variation of soil moisture in a semi-arid mountainous area. *Science of The Total Environment*, 724, article number 138319. doi: 10.1016/j.scitotenv.2020.138319.

[6] Fiorentin, P., Cavazzani, S., Bertolo, A., Ortolani, S., Binotto, R., & Saviane, I. (2025). SQM ageing and atmospheric conditions: How do they affect the long-term trend of night sky brightness measurements? *Sensors*, 25(2), article number 516. doi: 10.3390/s25020516.

[7] García-Vera, Y.E., Polochè-Arango, A., Mendivelso-Fajardo, C.A., & Gutiérrez-Bernal, F.J. (2024). Hyperspectral image analysis and machine learning techniques for crop disease detection and identification: A review. *Sustainability*, 16(14), article number 6064. doi: 10.3390/su16146064.

[8] Guerri, M.F., Distante, C., Spagnolo, P., Bougourzi, F., & Taleb-Ahmed, A. (2024). Deep learning techniques for hyperspectral image analysis in agriculture: A review. *ISPRS Open Journal of Photogrammetry and Remote Sensing*, 12, article number 100062. doi: 10.1016/j.ophoto.2024.100062.

[9] Hohl, A., Obadic, I., Fernandez-Torres, M.A., Najjar, H., Oliveira, D.A.B., Akata, Z., Dengel, A., & Zhu, X.X. (2024). Opening the Black Box: A systematic review on explainable AI in remote sensing. *IEEE Geoscience and Remote Sensing Magazine*, 12(4), 261-304. doi: 10.1109/MGRS.2024.3467001.

[10] Jiang, J., Zhang, Q., & Gao, S. (2025). Enhancing multi-flight unmanned-aerial-vehicle-based detection of wheat canopy chlorophyll content using relative radiometric correction. *Remote Sensing*, 17(9), article number 1557. doi: 10.3390/rs17091557.

[11] Khan, A., Vibhute, A.D., Mali, S., & Patil, C.H. (2022). A systematic review on hyperspectral imaging technology with a machine and deep learning methodology for agricultural applications. *Ecological Informatics*, 69, article number 101678. doi: 10.1016/j.ecoinf.2022.101678.

[12] Liu, H., Hu, B., Hou, X., Yu, T., Zhang, Z., Liu, X., Liu, J., & Wang, X. (2024). Real-time registration of unmanned aerial vehicle hyperspectral remote sensing images using an acousto-optic tunable filter spectrometer. *Drones*, 8(7), article number 329. doi: 10.3390/drones8070329.

[13] Musiyenko, M., & Zhuravska, I. (2016). Algorithms for laying of the route of unmanned aerial vehicles based on Hopfield neural networks. *Bulletin of Cherkasy State Technological University*, 21(1), 20-27.

[14] Nansen, C., Lee, H., & Mantri, A. (2023). Calibration to maximize temporal radiometric repeatability of airborne hyperspectral imaging data. *Frontiers in Plant Science*, 14, article number 1051410. doi: 10.3389/fpls.2023.1051410.

[15] Phang, S.K., Chiang, T.H.A., Happonen, A., & Chang, M.M.L. (2023). From satellite to UAV-based remote sensing: A review on precision agriculture. *IEEE Access*, 11, 127057-127076. doi: 10.1109/ACCESS.2023.3330886.

[16] Rosas, J.T.F., de Carvalho Pinto, F.A., de Queiroz, D.M., de Melo Villar, F.M., Martins, R.N., & Silva, S.A. (2020). Low-cost system for radiometric calibration of UAV-based multispectral imagery. *Journal of Spatial Science*, 67(3), 395-409. doi: 10.1080/14498596.2020.1860146.

[17] Sethy, P.K., Pandey, C., Sahu, Y.K., & Behera, S.K. (2022). Hyperspectral imagery applications for precision agriculture – a systemic survey. *Multimedia Tools and Applications*, 81, 3005-3038. doi: 10.1007/s11042-021-11729-8.

[18] Swaminathan, V., Thomasson, J.A., Hardin, R.G., Rajan, N., & Raman, R. (2024). Radiometric calibration of UAV multispectral images under changing illumination conditions with a downwelling light sensor. *The Plant Phenome Journal*, 7(1), article number e70005. doi: 10.1002/ppj2.70005.

[19] Wang, B., Sun, J., Xia, L., Liu, J., Wang, Z., Li, P., Guo, Y., & Sun, X. (2021). The applications of hyperspectral imaging technology for agricultural products quality analysis: A review. *Food Reviews International*, 39(2), 1043-1062. doi: 10.1080/87559129.2021.1929297.

[20] Wu, J., Zhang, Y., Hu, P., & Wu, Y. (2024). A review of the application of hyperspectral imaging technology in agricultural crop economics. *Coatings*, 14(10), article number 1285. doi: 10.3390/coatings14101285.

[21] Wu, S., Lu, Y., Fan, W., Zhang, S., Wu, Z., & Wang, F. (2025). An efficient downwelling light sensor data correction model for UAV multi-spectral image DOM generation. *Drones*, 9(7), article number 491. doi: 10.3390/drones9070491.

[22] Xie, J., Shen, Y., & Cen, H. (2024). Real-time reflectance generation for UAV multispectral imagery using an onboard downwelling spectrometer in varied weather conditions. *arXiv*. doi: 10.48550/arXiv.2412.19527.

[23] Yao, J., Hong, D., Li, C., & Chanussot, J. (2024). SpectralMamba: Efficient Mamba for hyperspectral image classification. *arXiv*. doi: 10.48550/arXiv.2404.08489.

[24] Ying, F., Zhai, B., & Zhao, X. (2025). Design of a multi-method integrated intelligent UAV system for vertical greening maintenance. *Applied Sciences*, 15(20), article number 10887. doi: 10.3390/app152010887.

[25] Zhang, S., Rao, K., Wu, Z., Wang, S., Dai, Z., Fang, R., & Wang, K. (2025). Radiometric cross-calibration of hyperspectral microsatellites using spectral homogeneity factor. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 18(4), 1234-1256. doi: 10.1109/JSTARS.2024.3509933.

[26] Zhu, H., Huang, Y., An, Z., Zhang, H., Han, Y., Zhao, Z., Li, F., Zhang, C., & Hou, C. (2024). Assessing radiometric calibration methods for multispectral UAV imagery and the influence of illumination, flight altitude and flight time on reflectance, vegetation index and inversion of winter wheat AGB and LAI. *Computers and Electronics in Agriculture*, 219, article number 108821. doi: 10.1016/j.compag.2024.108821.

Гиперспектралдык системаларды интеллектуалдык калибрлөө: Адаптивдик калибрлөө циклинин (АКЦ) концепциясы

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Аннотация. Гиперспектралдык камералар менен жабдылган заманбап учкучсуз учуучу аппараттар (УУА) дыйканчылык жана айыл чарба экосистемаларын так көзөмөлдөө үчүн негизги куралга айланууда. Бирок, сенсорлордун тактыгы жогорулаганына карабастан, талааны калибрлөө процедураларынын статикалык мүнөзүнүн методологиялык көйгөйү чечилбеген бойдон калууда. Бир жолку колдонулуучу эталондук өлчөөлөргө негизделген салттуу ыкмалар жарыктын өзгөрүшү, топурактын нымдуулугу жана атмосфералык факторлор шарттарында маалыматтардын ишенимдүүлүгүн камсыз кылбайт. Бул макаланын максаты – Адаптивдик калибрлөө циклинин (АКЦ) концептуалдык моделин көрсөтүү – бул геодезиялык изилдөө, калибрлөө жана маалыматтарды иштетүү этаптарын бирдиктүү жабык циклдик кайтарым байланыш циклине бириктирген өз алдынча үйрөнүү системасы. Изилдөө методологиясы экинчик эмпирикалык маалыматтарды колдонуу менен калибрлөө процесстерин моделдөөгө, статикалык жана адаптивдик ыкмаларды салыштырмалуу талдоого жана ошондой эле АКЦнын натыйжалуулугун негизги метрикалар: чагылдыруу катасын, радиометриялык туруктуулукту жана маалыматтардын кайталануучулугун колдонуу менен баалоого негизделген. Циклдин алгоритмдик ишке ашырылышы онлайн окутуу механизмдерин, Калман чыпкасын жана реалдуу убакытта коррекциялоо үчүн edge computing архитектурасын камтыган. Моделдөөнүн жыйынтыктары көрсөткөндөй, АКЦди ишке ашыруу орточо чагылдыруу катасын 70 %тен ашык азайтат, радиометриялык туруктуулукту 20-25 %ке жакшыртат жана жооп берүү убактысын 0,25 секундага чейин кыскартат. Айыл чарба колдонмолорунда бул өсүмдүктөрдүн индекстерин (NDVI, PRI) так аныктоого, өсүмдүктөрдүн стрессин өз убагында аныктоого жана сугаруу менен жер семирткичтерди колдонууну оптималдаштырууга мүмкүндүк берет. Сунушталган методология талаа спектрометриясында статикалык ыкмадан адаптивдүү ыкмага өтүүнү белгилейт жана айыл чарба-өндүрүш комплекстерине алыстан мониторинг жүргүзүүчү жогорку тактыкты, маалыматтардын кайталануучулугун жана туруктуулугун камсыз кылуучу, акылдуу системалардын келечегин ачат

Негизги сөздөр: алыстан зонддоо; гиперспектралдык сүрөткө тартуу; адаптациялык калибрлөө; спектрометрия; жасалма интеллект; динамикалык методология; спектрдик дрейф

Интеллектуальная калибровка гиперспектральных систем: концепция адаптивного цикла (АКЦ)

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Аннотация. Современные беспилотные летательные аппараты (БПЛА), оснащенные гиперспектральными камерами, становятся ключевым инструментом точного земледелия и мониторинга сельскохозяйственных экосистем. Тем не менее, несмотря на рост точности сенсоров, остается нерешенной методологическая проблема статичности полевых калибровочных процедур. Традиционные подходы, основанные на одноразовых эталонных измерениях, не обеспечивают достоверность данных в условиях изменяющейся освещенности, влажности почв и атмосферных факторов. Цель статьи – представить концептуальную модель Адаптивного цикла калибровки (Adaptive Calibration Cycle, ACC) – самообучающейся системы, интегрирующей этапы съемки, калибровки и обработки данных в единый замкнутый контур с обратной связью. Методология исследования базировалась на моделировании процессов калибровки с использованием вторичных эмпирических данных, сравнительном анализе статических и адаптивных подходов, а также оценке эффективности ACC по ключевым метрикам: ошибка отражательной способности, радиометрическая стабильность и воспроизводимость данных. Алгоритмическая реализация цикла включала механизмы онлайн-обучения, фильтр Калмана и архитектуру edge computing для коррекции в реальном времени. Результаты моделирования показали, что внедрение ACC снижает среднюю ошибку отражательной способности более чем на 70 %, повышает радиометрическую стабильность на 20-25 % и сокращает время отклика до 0,25 секунды. В аграрных приложениях это обеспечивает более точное определение вегетационных индексов (NDVI, PRI), своевременное выявление стрессов растений и оптимизацию орошения и удобрений. Предлагаемая методология формирует переход от статического к адаптивному подходу в полевой спектрометрии и открывает перспективы для интеллектуальных систем дистанционного мониторинга агропромышленного комплекса, обеспечивая высокую точность, воспроизводимость и устойчивость данных

Ключевые слова: дистанционное зондирование; гиперспектральная съемка; адаптивная калибровка; спектрометрия; искусственный интеллект; динамическая методология; спектральный дрейф

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