ISSN 1694-6286

Bulletin of the Kyrgyz National Agrarian University

Publisher:
Kyrgyz National Agrarian University Named After K.I. Skryabin

Year of foundation: 2003

Frequency: 4 times a year

State registration:
Registration certificate of the Ministry of Justice of the Kyrgyz Republic
No. 000043 dated 01.12.2003. Re-registered on 11.03.2015, certificate No. 909.

The journal is presented in the following international scientometric databases, repositories and scientific systems:
Russian Science Citation Index (RSCI), Litmaps

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https://knau-bulletin.com/en

ISSN 1694-6286

Кыргыз улуттук агрардык университетинин Жарчысы

Негиздөөчү:
К.И. Скрябин атындагы Кыргыз улуттук агрардык университети

Негизделген жылы: 2003

Чыгаруунун мезгилдүүлүгү: жылына 4 жолу

Мамлекеттик каттоо:
Кыргыз Республикасынын Юстиция министрлигинин каттоо күбөлүгү
01.12.2003-ж., № 000043, күбөлүк № 909, 11.03.2015 - жылы кайрадан катталган.

Журнал төмөнкү эл аралык илимий-метрикалык маалымат базаларында, репозиторийлерде жана издөө системаларында камтылган:
Орусиянын илимий цитаталар индекси (РИНЦ); Litmaps

Редакциянын дареги:
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ISSN 1694-6286

Вестник Кыргызского национального аграрного университета

Издатель:
Кыргызский национальный аграрный университет имени К.И. Скрябина

Год основания: 2003

Периодичность выпуска: 4 раза в год

Государственная регистрация:
Регистрационное свидетельство Министерства юстиции Кыргызской Республики
№ 000043 от 01.12.2003. Перерегистрирован 11.03.2015, свидетельство № 909.

Журнал представлен в таких международных наукометрических базах данных, репозиториях и поисковых системах:
Российский индекс научного цитирования (РИНЦ); Litmaps

Адрес редакции:
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Received: 16.04.2025. Revised: 31.07.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 636.18.284

DOI: 10.63621/bknau./3.2025.10

Crossbreeding – the main method of increasing beef production in Kyrgyzstan

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Abstract. The relevance of this study is due to the need to increase the meat productivity of cattle in the Kyrgyz Republic, where the use of low-productive cows of Alatau breed prevails. Increasing the profitability of meat cattle breeding requires the introduction of effective selection and genetic methods, including interbreed crossbreeding using bulls of specialised meat breeds. The aim of this work was to identify the most productive genotype of crossbred animals obtained from crossing Alatau cows with bulls of meat breeds (Charolais, Kian and Aberdeen-Angus), taking into account their productive and adaptive qualities in different natural-climatic zones of Kyrgyzstan. In the course of the study, zootechnical and biometric methods of analysis were applied: live weight, growth rate, meat qualities, as well as resistance of animals to housing conditions were evaluated. In total, three groups of crossbred calves bred in plain and foothill areas were studied. The best results were obtained from crossing of Alatau breed with Aberdeen-Angus breed: by the age of six months calves of this group reached on average 215.3 kg, average daily gain was 890 g, slaughter yield of meat reached 58.2%. These animals also showed high adaptability to climatic fluctuations and rational use of forages. The practical significance of the work lies in the possibility of introducing the obtained data into beef cattle breeding programmes both at breeding enterprises and in farms. The results of research can be used at formation of arrays of beef cattle of new type and at development of regional programmes on increase of productivity of beef cattle direction

Keywords: breeds; crossbreds; slaughter yield; carcass weight; exterior; body indices; body measurements

Suggested Citation: Nogoev, A., Azhibekov, A., Derkenbaev, S., & Ilyaz kyzy, Zh. (2025). Crossbreeding – the main method of increasing beef production in Kyrgyzstan. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 10-20. doi: 10.63621/bknau./3.2025.10.

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Introduction

The Kyrgyz Republic belongs to the typical mountainous countries with predominance of pasture lands. According to NSCKR (n.d.), in 2023 about 9.2 million hectares, or about 85% of all agricultural lands, were occupied by natural pastures with mixed grass composition. Due to natural-climatic and socio-economic conditions in the country, livestock breeding, especially small and cattle, including the Alatau breed, has historically prevailed. However, the existing number of cattle (1.84 million heads at the beginning of 2024) is mostly represented by dairy and combined breeds characterised by low meat indicators. The average slaughter weight is only 45-50% of live weight, and daily gain does not exceed 650-700 g. Taking into account the growing needs of the domestic market and export ambitions of the country, the creation of highly productive meat stock adapted to mountain conditions becomes an urgent task. One of the promising directions for solving this problem is interbreed industrial crossbreeding using bulls of specialised meat breeds such as Charolais, Kian and Aberdeen-Angus. Studies have shown the effectiveness of such approaches: meat crossbreds have accelerated growth, higher slaughter yield and better adaptation to extreme conditions (Dzhanibekov *et al*., 2021; Arslan *et al*., 2024). Thus, the study of V. Logunova & A. Marusich (2023) showed an increase in daily gain in young animals of Limousin bloodlines by +73 g compared to Aberdeen-Angus. A. Shevkhuzhev & V. Pogodaev (2023) found that Aberdeen-Angus hybrids × Simmental gave a gain of up to 711 g/day and an increase in slaughter yield of more than 1% and were superior to purebreds in slaughter yield and live weight. In turn, V. Iovenko & I. Hladii (2021) showed that the study of organism development taking into account genotype and environmental conditions allows to significantly accelerate the process of breed improvement, and the intensity of growth and development is of key importance for obtaining fast-growing young animals with lower feed consumption per unit of gain.

In Kyrgyzstan, individual experiments on industrial crossbreeding were carried out in the 1980-1990s, but there are no systematic approaches or consolidation of results in farms. Modern research in the republic is limited, which necessitates a comprehensive assessment of the efficiency and adaptability of different genotypes of meat crossbreds in the conditions of zonal farming. In the world practice the priority is given to the Aberdeen-Angus breed, which has high growth energy, calm temperament and adaptation to extensive housing technologies (FAOSTAT, n.d.). However, the zootechnical feasibility of using different breeds in specific agro-ecological zones of Kyrgyzstan – foothills, highlands and flat pastures of Chui, Talas and Naryn regions – remains an important issue. In addition, according to P. Greenwood (2021), sustainable beef production in countries with pasture-based livestock production requires taking into account not only genetic, but also environmental and economic factors. In this context, crossbreeding (interbreeding) is considered as a tool not only to increase productivity but also to improve animal adaptability. Thus, according to the study of M. McIntosh *et al.* (2023), in crossbreeding calves adapt faster to temperature fluctuations and are less susceptible to gastrointestinal diseases compared to purebred counterparts. And researchers J. Keele *et al.* (2024) found that traits measured in live animals (e.g. live weight, eye muscle area from ultrasound data) have a strong genetic correlation with economically important carcass characteristics after slaughter (such as marbling, eye muscle area, slaughter yield and hot carcass weight). This allows the effective use of live animal data for predicting meat quality and selecting breeding stock.

The relevance of crossbreeding was also confirmed by UN food security policies, according to which the development of beef cattle breeding should be adapted to changing climatic conditions and rural poverty (FAO, 2022). In Kyrgyzstan, where a significant proportion of the population lives in rural areas and depends on livestock production, the introduction of adaptive beef cattle breeds is not only economically but also socially important. In addition to the genetic aspect, profitability of production remains an important factor. Introduction of meat crosses allows to shorten fattening periods, reduce feed costs and obtain marketable products of higher quality. According to the world statistics, breeds with mitostatin mutation (e.g. Belgian Blue) show about 20% higher muscle mass yield than gene-free breeds, which confirms the high efficiency of meat orientation (Squire, 2025). Thus, in conditions of deficit of specialised beef cattle, lack of scientifically based breeding programmes and limited budget for purchase of imported stock, the use of interbreed crossbreeding with targeted selection of the most effective combinations seems to be an actual and practically significant direction. This study was aimed at a comprehensive evaluation of the efficiency of industrial crossbreeding of Alatau cattle with the leading beef breeds, such as Charolais, Kian and Aberdeen-Angus, to determine the optimal genotypes adapted to the specific conditions of mountainous regions of Kyrgyzstan and possessing increased meat productivity.

Materials and Methods

The study was conducted from April 2023 to October 2025 on the basis of two livestock farms in the Kyrgyz Republic: breeding farm "Ala-Too" (Chui region, plain zone) and experimental site "Suusamyr" (Naryn region, foothill/highland zone), which allowed to evaluate the productive and adaptive qualities of animals in different natural and climatic conditions. In order to study productive and biological features of crossbred animals and to create a herd of beef cattle, crossbreeding of Alatau cows with the seed of bulls of specialised beef

breeds: Charolais, Aberdeen-Angus and Kian was carried out. 90 Alatau cows meeting the criteria of maturity and reproductive health were selected to obtain the studied young stock. Seed from three different breeding bulls for each of the beef breeds was used (one for each group of cows) to ensure genetic diversity within the experimental groups. During the study, four groups of young cows were formed based on birth results, totalling 84 head. These groups were distributed as follows: control group: 10 purebred Alatau bulls; Alatau × Charolais experimental group: 25 head, of which 13 steers and 12 heifers; experimental group Alatau × Kian: 12 head, all steers; experimental group Alatau × Aberdeen-Angus: 37 head, of which 19 steers and 18 heifers.

Ewes and the obtained crossbred young stock were bred under conditions of year-round pasture keeping. Feeding and housing conditions of experimental and control groups of animals were identical. Pasture keeping was carried out on natural grassy pastures with an average pasture load of 0.8 conventional animals per hectare. Pastures were rotated regularly every 14-20 days to ensure optimum herbage. During winter and early spring periods (December to April), they were given supplementary feeding of rough and concentrated forages. Feeding consisted of alfalfa hay (2-3 kg/head/day) and mixed fodder for young cattle (1-1.5 kg/head/day), including barley, corn and sunflower cake, with protein content not less than 16%.

Semen quality of bulls was evaluated by light microscopy at ×400 magnification using Micros Austria MCX100 microscope (Austria). Sperm activity, morphological integrity, ejaculate concentration and motility were analysed. The evaluation methodology was in accordance with GOST 27775-2014 (2015). Insemination seed was cryopreserved material delivered in YDS-3 brand Dewar containers (Xiangyuan, China) at –196°C. It was thawed at +37°C for 30 seconds before use. Insemination was performed by rectocervical method using a Cassou syringe catheter (France). Meat and fat samples were collected and transported immediately after slaughter. Samples of *m. longissimus dorsi* and internal fat, weighing 200-250 g each, were taken from each carcass. Samples were packed in sterile hermetic KipBio 500 ml containers, labelled and transported to the laboratory at +4 °C for no more than 2 hours, using Thermo-Pak-8 (Russia) thermocontainer with cooling elements.

The following parameters were studied in experimental animals: growth and development, live weight, meat qualities, milk productivity, milk composition, as well as clinical and haematological parameters. Assessment of resistance to temperature fluctuations was carried out by recording rectal temperature and respiration rate of animals twice a day (at 08:00 and 16:00) during summer and winter periods (July-August and January-February) at maximum and minimum daily air temperatures, respectively. Individual records of feed consumed and residues were recorded daily for 7 days in each season (spring, summer, autumn, winter) to determine feed digestibility. Exterior traits were measured at the age of 18 months using a zootechnical tape measure and a ZOOMED-150 height meter (Russia). The following were measured: height at the withers and rump, depth and girth of the chest, width of the chest, oblique length of the trunk, width in the maclocks, girth of the heel. Body build indices were calculated from these data:

- chest index = (chest girth / height at withers) × 100;
- stiffness index = (chest girth / torso length) × 100;
- stretch index = (torso length / withers height) × 100;
- boniness index = (heel girth / withers height) × 100;
- meatness index = (width in mamlocks / trunk length) × 100.

Live weight was determined individually using AXIS BDU1500 electronic scales (Poland) with an accuracy of 100 g. Measurements were taken at birth, at 6 months of age (weaning), at 12 and 18 months of age. Average daily gain was calculated according to formula (1):

$$P = \frac{JM_n - JM_i}{n}, \quad (1)$$

where JM_n – live weight at the age of n days, JM_i – live weight at the previous weighing, n – number of days between measurements.

Control slaughter of animals was performed in the slaughterhouse of "TalasEt" farm, in compliance with ITS 43-2017 (2018). Samples of *m. g dorsi* (longest muscle of the back) and raw fat were taken from carcasses – 250 g each. The chemical composition of meat and fat was analysed in the laboratory of food chemistry of the Kyrgyz National Agrarian University named after K.I. Skryabin using the FoodScan™ 2 device (FOSS, Denmark). Mass fractions of moisture, protein, fat and ash were determined according to GOST 23042-2015 (2019), GOST 25011-2017 (2018). Clinical and haematological investigations included: counting the total number of erythrocytes and leukocytes in a Goryaev chamber; measuring haemoglobin by the Sali method; determining haematocrit and erythrocyte sedimentation rate. Mindray BC-30 Vet analyser (PRC) was used. The study of exterior features of crossbred young animals was carried out at the age of 18 months using linear measurements and morphological indices. The following parameters were measured: height at the withers and rump, chest width, chest depth, oblique trunk length, width at the maclocks, chest and heel girth. The evaluation was done using measuring tools like height gauge, centimetre tape and caliper.

It was also evaluated on a 5-point scale (with 1 point representing minimum expression of the trait and 5 points representing maximum or ideal expression) for the following traits: general body type, muscular development, meat form expression, limb placement, and conformity to breed type. This evaluation was carried out at the age of 18 months, in parallel with the main

linear measurements. The evaluation was carried out by two independent expert zootechnicians who were pre-calibrated in the evaluation methodology. The calibration consisted of a series of joint test evaluations on a group of control animals, followed by discussion of discrepancies and development of common criteria to minimise subjectivity. To comprehensively characterise the exterior, zootechnical indices were calculated: massiveness, meatiness, stretchiness, breast, boniness and knockdown indices. The involvement of experts was in accordance with the principles of the WMA Declaration of Helsinki (1964).

Compliance with ethical standards was confirmed by the decision of the Local Ethical Committee of KNAU No. 02-2023 dated 12 March 2023, in accordance with the International Convention for the Protection of Animals in Scientific Research (Directive 2010/63/EU, 2010). Statistical processing of data was performed by the method of variation statistics using MS Excel 2021 and Statistica 10.0 package. Mean values, standard deviations and confidence intervals were calculated. Differences between groups were evaluated by Student's criterion ($p < 0.05$).

Results and Discussion

Formation of meat productivity of animals is determined by the intensity of growth and development of physique, which, in turn, depends on genotype, housing conditions and nutrition. In the course of conducted researches it was established that crossbred calves obtained from crossing Alatau cows with bulls of Aberdeen-Angus breed surpassed their peers from other genotypic groups in most zootechnical indicators. Thus, the average live weight of these calves at the age of 6 months was 215.3 kg, which is 8.4% higher than in comparison with litters from the Kian breed and 11.6% higher than in litters with Charolais. Average daily gain in the Aberdeen-Angus group reached 890 g, compared to 812 g and 793 g in the other studied groups, respectively. At slaughter at 18 months of age, the slaughter yield was 58.2% and the muscle tissue in the carcass was 68.5%. Exterior evaluation revealed pronounced signs of meat type: increased width of the thorax (average girth – 198.4 cm), high depth of the trunk (84.1 cm), shortened heel and well-developed musculature. Calculation of index indices (massiveness, boniness, meatiness) confirmed the advantages of the Aberdeen-Angus group in all parameters. Adaptability indicators (resistance to temperature fluctuations, feed digestibility, clinical and haematological parameters) also indicated better adaptation of this genotypic group to the conditions of different natural and climatic zones of Kyrgyzstan. Table 1 shows the data of live weight of crossbred animals by periods of growth, obtained by crossing Alatau cows with bulls of meat breeds. From the presented data it is seen that comparatively higher live weight at birth had crossbred bulls and heifers of Alatau-Charolais and Alatau-Kian breeds. At the same time, the live weight of steers and heifers of Alatau-Aberdeen-Angus breed was the lowest among all obtained crossbred animals. Thus, at birth they had lower live weight by 9.9% than purebred and by 25.28%, respectively, than crossbred animals of Charolais and Kian breeds.

Table 1. Dynamics of live weight of young animals, kg

Sex of animals	Age, months							
	at birth		6		12		18	
	n	live weight	n	live weight	n	live weight	n	live weight
Alatau								
steers	10	27.4 + 1.10	9	134.3 + 1.91	8	295.0 + 3.21	6	320.0 + 13.9
Alatau x Charolais								
steers	13	38.0 + 0.10	10	236.8 + 3.74	9	320.0 + 3.31	4	417.5 + 17.3
heifers	12	36.9 + 0.12	9	214.3 + 4.60	7	303.3 + 4.32	7	404.3 + 6.90
Alatau x Kian								
steers	12	34.3 + 0.09	9	218.4 + 3.21	8	285.7 + 3.84	4	405.0 + 9.20
Alatau x Aberdeen Angus								
steers	19	24.7 + 0.02	17	200.3 + 7.41	15	265.0 + 8.38	4	361.2 + 20.8
heifers	18	24.1 + 0.03	12	191.7 + 2.15	9	256.3 + 9.62	8	356.3 + 10.4

Source: compiled by authors based on experimental data, 2023-2025

By 6 months of age, pomace bulls and heifers outperformed purebred bulls and heifers in terms of live weight. This superiority was 76.3% in Alatau-Charolais, 49.1% in Alatau-Aberdeen-Angus and 62.6% in Alatau-Kian. Further this superiority was maintained. Thus, at the age of 12 months, pomace bulls from the Charolais breed surpassed purebred Alatau bulls by 85 kg (36.2%); Aberdeen-Angus by 30.0 kg (12.8%) and Kian pomace by 50.7 kg (21.6%). The similar pattern of growth was observed at the age of 18 months. Thus, the live weight of Alatau-Charolais bulls was 97 kg (30.3%), Alatau-Aberdeen-Angus by 41.2 kg (12.8%) and Alatau-Kian bulls by 85 kg (26.6%). These indicators of live weight of crossbred animals testify to the manifes-

tation of biological regularity – heterosis. More visual representation about intensity of growth of young animals of different genotypes and sex and age groups is given by the indices of average daily gain (Table 2).

Table 2. Indicators of average daily gain in live weight of young animals, g

Breed and breedness	Sex of animals	Age, months		
		6	12	18
Alatau	steers	586	350	467
Alatau-Charolais	steers heifers	1,092 975	486 450	536 555
Alatau-Aberdeen-Angus	steers heifers	965 921	472 453	528 430
Alatau-Kian	steers heifers	1,012 904	468 510	655 514

Source: compiled by the authors based on experimental data, 2023-2025

The obtained data also indicate that young animals of all genotypic groups were characterised by well-developed bones and musculature, proportional body shapes, which is a consequence of genetic conditioning and adequate rearing conditions. However, individuals of different genotypes had certain differences in the indices of the main measurements. Comparative analysis of exterior parameters showed that the largest physique was characterised by the Alatau-Charolais and Alatau-Kian genotypes. Thus, in bulls of Alatau-Charolais group at the age of 18 months the average height at the withers was 134.6 cm, oblique length of the body – 160.3 cm, chest width – 43.2 cm, chest girth – 200.7 cm, heel girth – 19.8 cm. In Alatau-Kian crossbred animals similar parameters were somewhat lower, but also exceeded the parameters of animals of other groups: height at the withers – 132.4 cm, oblique length of the trunk – 158.9 cm, chest girth – 197.2 cm, heel girth – 19.4 cm. It is evident from the data of Table 1 that both at birth and during subsequent growing and fattening the Charolais, Aberdeen-Angus and Kian crossbred steers significantly surpassed their peers of the mother breed in terms of meatiness, massiveness and chest indices. During the period from birth to 18-months age, the meatiness index of both the Charolais crossbred animals increased by 20.1%, Aberdeen-Angus steers by 22.3% and Kian steers by 23.9%. In crossbred young bulls meat forms were better expressed than in peers of Alatau breed. They had well-developed back, loin and hind third of the torso. It should be noted that in the process of growing and fattening of mixed animals, there were significant changes in body build indices, especially in some indices characterising their meat productivity. According to numerous experimental studies in the field of beef cattle breeding, among which T. Lefler (2020), it is known that meat productivity of animals is characterised by quantitative and qualitative indices and depends on a number of genetic and paratypic factors. In this regard, a control slaughter of experimental animals was carried out, the data of which are given in Table 2.

During the period of growing and fattening, satisfactory live weight gain was obtained from young animals of all the above groups. At the same time, the pomace youngsters obtained from meat breeds from birth to 6-months depending on the type of crossbreeding had an average daily gain of 378-505 g; 6-12-months by 100-197 g and at the age of 12-18-months by 69-188 g, respectively, more than Alatau coevals. Many researchers note that the live weight index does not give a complete picture of the dynamics of shape and physique of animals with regard to age and breed (Guvenoglu, 2023). Therefore, the assessment of exterior and disclosure of linear growth features give a certain idea about the development of the animal, its direction and level of productivity.

During the study of exterior features during carcass inspection of animals, it was revealed that the deposition of fat watering in the dorsal and lumbar parts in Aberdeen-Angus crossbreds is significantly better than in Charolais, Kian crossbreds and purebred Alatau steers. Weak deposition in carcasses of crossbred Charolais and Kian steers is explained by the fact that these are hereditary features of animals of these breeds to obtain lean meat. The data of control slaughtering of animals showed that at slaughtering from crossbred bulls more heavy and full carcasses were obtained in comparison with Alatau bulls. Bulls of Charolais, Aberdeen-Angus and Kian breeds had carcass weight more by 28.7-59.0 kg, at the same time with good slaughter yield – by 0.74-2.08% more than Alatau bulls.

Bulls of all groups had relatively high internal fat values, which is explained by their breed affiliation. At the same time, Alatau-Charolais breed had lower internal fat index and was inferior to Alatau-Aberdeen-Angus by 0.27 kg (17.1%); Alatau-Kian by 0.12 kg (7.6%). Slaughter yield depending on the breed was: Alatau purebreds – 53.92%, Alatau-Charolais crossbred animals – 55.13%, Alatau-Kian – 54.77% and Alatau-Aberdeen-Angus – 55.5%. Comparatively high carcass weight contributed to the increase of slaughter weight of Alatau-Charolais steers, which were ahead of carcass

weight of Aberdeen-Angus breeds by 29.97 kg (15.5%), Alatau-Kian by 7.1 kg (3.3%). According to this indicator, experimental animals (crossbred) outperformed control animals of Alatau breed by 17.6-35.9%.

The conducted research showed that the flesh content in carcasses of Alatau-Charolais bulls at the age of 18 months was 59.53 kg, Alatau-Aberdeen-Angus by 33.15 kg and Alatau-Kian bulls by 51.95 kg more compared to purebred Alatau bulls. At deboning it was found that Alatau-Charolais and Alatau-Kian steers had the highest carcass flesh content, their superiority over Alatau-Aberdeen-Angus steers was 26.37 kg (18.2%) and 7.58 kg (4.6%), respectively. Further, the effect of breed on the meat ratio was determined. It was found that per 1 kg of bones in the carcass of Alatau-Charolais crossbreds at the age of 18 months there is 3.90 kg of flesh, in Alatau-Aberdeen-Angus 3.66 kg and in Alatau-Kian crossbreds 3.91 kg against 2.55 kg in purebred Alatau bulls. Meat quality is determined by different ratios of protein, fat, water and minerals (Lei *et al*., 2020). In this regard, the effect of breed on the chemical composition and energy value of meat was studied, the data of which are summarised in Table 3. Analyses of the chemical composition of meat from purebred Alatau-Aberdeen-Angus and purebred Alatau steers reveal that the amount of dry matter in the meat of the crossbred steers was 2.4% higher than in the meat of Alatau steers.

Table 3. Indicators of chemical composition and energy value of meat by cuts in Alatau steers (at natural moisture content)

Name of cuts	Content, %					
	moisture	dry matter	mineral substances	fat	protein	energy value, J
neck	76.06	23.96	1.00	3.28	19.68	465.7
hip	74.07	25.93	0.99	8.39	16.55	611.0
dorsal-costal	77.15	22.85	0.91	3.97	17.97	463.1
thoracic	76.56	23.44	0.88	4.50	18.06	494.6
flank	77.58	22.42	0.90	3.60	17.92	448.1
hind shank	77.82	22.18	0.91	3.81	17.46	448.1
scapular	78.22	21.78	0.88	2.79	18.11	419.6
sacral	75.86	24.14	0.94	5.00	18.20	503.3
Total in carcass	**76.66**	**23.34**	**0.93**	**4.42**	**17.87**	**481.7**

Source: compiled by the authors based on experimental data, 2023-2025

When revealing the biological value of meat, the degree of "maturity" of meat was determined, which is defined as the ratio of water and fat content in it, and the lower this ratio, the more "mature" meat is considered to be. According to this indicator, no significant difference was found between litters and purebred animals. The ratio of protein and fat in the meat of purebred Alatau steers was 1:0.25, and in littermates 1:0.42. These data show that the meat obtained at slaughter ¼ Alatau ¾ of Aberdeen-Angus crossbred animals meets the requirements of modern consumers. At the same time, due to the high fat content in the meat of Aberdeen-Angus crossbred animals of the second generation is characterised by its higher energy value. Thus, at 18 months of age their superiority over purebreds on the studied index was 98.3 J or by 20.4%.

Change in live weight of crossbred steers and heifers during the period of growing and fattening was ahead of Alatau breed coevals by this indicator. So, at the age of 18 months this difference on the average for bulls and heifers was 91 kg (28.4%) for Alatau-Charolais breed, 38 kg (11.9%) for Aberdeen-Angus breed and 85 kg (26.5%) for Alatau-Kian breed. The study of exterior peculiarities of Alatau breed and crossbred steers allowed to establish that crossbred steers of Alatau-Charolais and Alatau-Kian breeds were already in the early stage of ontogenesis taller, had deep chest, harmonious physique and well-defined meat forms. The analysis of changes in linear growth of experimental animals showed that from birth to 18-months of age the crossbred animals from different combinations of crossbreeding surpassed their Alatau breed counterparts in many measurements. These data of linear growth indicate good development of the crossbred animals. The results of control slaughter showed that bulls obtained from crossbreeding with bulls of meat breeds under intensive growing at the age of 18 months gave rather heavy carcasses. Thus, by carcass weight the Alatau-Charolais crossbred youngsters surpassed purebred Alatau by 59.0 kg (36.2%), Alatau-Aberdeen-Angus – 28.75 kg (17.8%) and Alatau-Kian by 51.6 kg (31.7%). The analysis of morphological composition of half carcasses indicated that the highest content of flesh in the carcasses of crossbred bulls of Charolais breed at the age of 18 months was 59.53 kg, Aberdeen-Angus breed by 33.15 kg and Kian breed by 51.95 kg more compared to purebred Alatau animals.

In beef cattle breeding one of the important tasks is to create animals with high growth energy, with good feed payment and naturally with better meat qualities. And in this direction good results were obtained from crossbred animals. The results of chemical

analysis of the average meat sample showed that at the age of 18 months the fat content in meat by cuts was 7.34% in pomace steers, while in Alatau steers it was 4.42% or 2.92% less.

Beef cattle breeding is a new direction in cattle breeding in Kyrgyzstan. Its development is conditioned by high market demand for beef meat, which differs from other types of meat by tenderness, juiciness and "marble" structure (Kruk & Ugnivenko, 2025). Meat cattle due to its biological features, such as precocity and high payment of feed by production, with good adaptation to mountainous conditions, better use of natural forage lands, which corresponds to the formation of meat productivity at lower costs. The problem of increasing livestock productivity and production of high-quality beef in Kyrgyzstan remains relevant, especially in conditions of limited fodder resources and predominance of low-productive dairy breeds. The effective solution of this problem largely depends on the use of breeding approaches, in particular, interbreed crossbreeding using specialised beef breeds (Patoo *et al.*, 2016; Mendonça *et al.*, 2019). According to the Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic (n.d.), as of 2024, the total number of cattle in the country was about 1.82 million heads, of which more than 830,000 were cows of predominantly Alatau breed with low productivity indicators: average milk yield – less than 2,000 kg per lactation, live weight – 420-450 kg. Comparison of the results obtained with the data of other researchers confirms the effectiveness of crossbreeding.

Thus, according to FAO (2023), young Kazakh white-headed cattle on pasture fattening can reach an average daily live weight gain up to 800-900 g, and slaughter yield is 63-67%, which corresponds to the values found in this study when crossbred with bulls of meat breeds. Similar values were obtained when using Charolais bulls in an industrial crossbreeding system: according to the data of M. Ben Salem & H. Kélifa (2009), the carcass weight of local Charolais cattle crosses was 77 kg higher than the control group, with a 30% higher meat yield. These results are in agreement with observations on Alatau-Charolais littermates, where carcass weight exceeded the control group by 59 kg and meat yield reached 59.53%. Studies devoted to the use of Aberdeen-Angus bulls also confirm the revealed regularities. E. Nassambaev *et al.* (2018) found that Aberdeen-Angus littermates showed better meat characteristics, including an increase in the thickness of muscle and fat tissue, which positively affects the marbling and organoleptic properties of meat. In addition, the data of P. Shevchenko *et al.* (2024) on the introduction of the Aberdeen-Angus breed in the conditions of Northern Kazakhstan on the high adaptability of these animals to extreme climatic conditions, resistance to temperature fluctuations and high feed digestibility, which correlates with the observations on litters with this breed in this study.

Studies conducted on the study of meat productivity of Alatau cattle and its litters with beef breeds allowed to establish the features of growth, development and formation of meatiness in young cattle depending on sex, age, technology of growing, fattening and fattening, as well as to reveal the possibilities of management of these processes in order to increase beef production in the conditions of valley and mountain zones of Kyrgyzstan. Thus, the analysis of literary sources confirms the efficiency of interbreed crossbreeding of Alatau cows with bulls of specialised beef breeds. The obtained results demonstrate improved live weight, gain, meat productivity and morphological composition of carcasses in crossbred young cows. This makes such breeding practice promising for further implementation in farms of different zonality of Kyrgyzstan, taking into account natural-climatic conditions and market demand.

Conclusions

The conducted research allowed to theoretically justify and practically implement technological methods of formation of beef herd of cattle in conditions of high mountainous areas of the Kyrgyz Republic by industrial and absorptive crossing of Alatau breed with bulls of beef breeds of the world gene pool: Charolais, Kian and Aberdeen-Angus breeds. It was established that the best results on all key productive and adaptive indicators were obtained using Aberdeen-Angus bulls. Crossbred animals with blood on Aberdeen-Angus breed showed significantly higher intensity of growth and development. Thus, by 6 months of age, Alatau × Aberdeen-Angus bulls reached an average live weight of 200.3 kg, which was significantly higher than that of purebred Alatau bulls (134.3 kg) at the same age. By 18 months of age, this group maintained its superiority, reaching 361.2 kg live weight, indicating their high precocity throughout the fattening period.

In addition to outstanding growth qualities, the crossbred animals of this direction had high vitality, resistance to temperature fluctuations, good adaptation to pasture housing and stress resistance in high mountainous conditions. Their exterior evaluation confirmed the pronounced meat forms: compact, wide-bodied physique, well-developed musculature and high zootechnical indices (index of massiveness, knockdown, meatiness), exceeding indices of other experimental groups. The analysis of meat qualities showed that steers with ¾ blood on Aberdeen-Angus breed are characterised by high slaughter indices. The average carcass weight of such animals exceeded the similar index of purebred Alatau bulls by 36.2%, and slaughter yield reached 58.2%. The content of muscle tissue in the carcass was 68.5%, with a significantly higher content of protein, fat and energy value of meat. These results make crossbred

steers the most preferable from the economic and technological points of view for production of high-quality beef in the conditions of the republic.

Taking into account the obtained results, it is strongly recommended to implement a programme on crossing low-productive cows of Alatau breed with bulls of Aberdeen-Angus breed in order to increase meat productivity and improve the quality of beef in the Kyrgyz Republic. Prospects for further research are a comprehensive assessment of profitability of beef cattle breeding based on crossbred young stock in different natural and climatic zones of the country, as well as in-depth genetic selection of the most productive and adapted lines in the framework of sustainable livestock production in Kyrgyzstan.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Аргындаштыруу – Кыргызстанда уй этин өндүрүүнү көбөйтүүнүн негизги ыкмасы

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Аннотация. Бул изилдөөнүн актуалдуулугу алатоо породасындагы аз продуктивдүү уйларды пайдалануу басымдуулук кылган Кыргыз Республикасынын шарттарында ири мүйүздүү малдын эт азыктуулугун жогорулатуу зарылдыгы менен шартталган. Эт мал чарбасынын рентабелдүүлүгүн жогорулатуу натыйжалуу селекциялык-генетикалык методдорду анын ичинде адистештирилген эт породаларынын букаларын пайдалануу менен тукум аралык аргындаштырууну киргизүүнү талап кылат. Бул иштин максаты Кыргызстандын ар кандай жаратылыш-климаттык зоналарында Алатоо уйларын эт породасындагы букалар (Шаролай, Киан жана Абердин-ангус) менен аргындаштыруудан алынган аргындаштырылган жаныбарлардын кыйла продуктивдүү генотипин табуу болгон. Изилдөөнүн жүрүшүндө анализдин зоотехникалык жана биометрикалык методдору колдонулган: массага, өсүү темпине, эттин сапатына, ошондой эле жаныбарлардын кармоо шарттарына туруктуулугуна баа берүү жүргүзүлгөн. Жалпысынан түздүктө жана тоо этектеринде өстүрүлгөн аргындаштырылган музоолордун үч тобу изилденген. Алатоо породасын абердин-ангус породасы менен аргындаштыруудан эң жакшы натыйжалар алынды: алты айлык кезинде бул топтогу музоолор орточо 215,3 кг, орточо суткалык өсүшү 890 г, союлган эт 58,2 %га жеткен. Бул жаныбарлар ошондой эле климаттын өзгөрүшүнө жана тоютту башкарууга жогорку ыңгайлуулугун көрсөтүшкөн. Иштин практикалык мааниси асыл тукум ишканаларда да, фермердик чарбаларда да эт багытындагы мал чарбачылык программаларына маалыматтарды киргизүү мүмкүндүгүндө жатат. Изилдөөнүн жыйынтыктары жаңы типтеги эт багытындагы малдын массивдерин түзүүдө жана бодо малдын эт багытындагы азыктуулугун жогорулатуу боюнча региондук программаларды иштеп чыгууда колдонулушу мүмкүн

Негизги сөздөр: породалар; кроссбреддер; союу түшүмдүүлүгү; өлүктүн массасы; конформация; дене индекстери; промендер

Скрещивание – основной метод увеличения производства говядины в Кыргызстане

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Аннотация. Актуальность настоящего исследования обусловлена необходимостью повышения мясной продуктивности крупного рогатого скота в условиях Кыргызской Республики, где преобладает использование низкопродуктивных коров алатауской породы. Повышение рентабельности мясного животноводства требует внедрения эффективных селекционно-генетических методов, в том числе межпородного скрещивания с использованием быков специализированных мясных пород. Целью настоящей работы было выявление наиболее продуктивного генотипа помесных животных, полученных от скрещивания алатауских коров с быками мясных пород (шароле, кианская и абердино-ангусская), с учетом их продуктивных и адаптивных качеств в различных природно-климатических зонах Кыргызстана. В ходе исследования были применены зоотехнические и биометрические методы анализа: проводилась оценка живой массы, темпов прироста, мясных качеств, а также устойчивости животных к условиям содержания. Всего было исследовано три группы помесных телят, выращенных в равнинных и предгорных районах. Наилучшие результаты были получены от скрещивания алатауской породы с абердино-ангусской: к шестимесячному возрасту телята этой группы достигали в среднем 215,3 кг, среднесуточный прирост составлял 890 г, убойный выход мяса достигал 58,2 %. Эти животные также демонстрировали высокую приспособленность к климатическим колебаниям и рациональному использованию кормов. Практическая значимость работы заключается в возможности внедрения полученных данных в программы мясного скотоводства как на племенных предприятиях, так и в фермерских хозяйствах. Результаты исследования могут быть использованы при формировании массивов мясного скота нового типа и при разработке региональных программ по повышению продуктивности мясного направления КРС

Ключевые слова: породы; помеси; убойный выход; масса туши; экстерьер; индексы телосложения; промеры

Received: 31.03.2025. Revised: 07.08.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 58.084.2

DOI: 10.63621/bknau./3.2025.21

Study of the bioecological characteristics of some lavender species introduced under the conditions of the Absheron Peninsula

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Abstract. Increasing climate variability and drought have brought the cultivation of low-water-demand plants to the forefront. In this context, lavender – a drought-tolerant plant widely used in various industries such as pharmaceuticals, cosmetics, perfumery, and dye production, has gained particular relevance. Lavender plantations are not only visually appealing but also contribute to the development of the tourism sector. This study investigated the bioecological characteristics of several lavender species introduced in the Absheron region (Azerbaijan) and examined the effects of biotic and abiotic factors on seed propagation. Sowing was carried out in spring (March) and autumn (November and December). During the research, it was observed that the germination rate of lavender seeds varied depending on the sowing depth. It was determined that the optimal sowing depth for *Lavandula angustifolia* L. and *Lavandula intermedia* L. seeds is 2.0 cm. Specifically, the germination rates at different depths

Suggested Citation: Badalova, V., Maharramov, S., Aliyeva, G., Mammadova, Z., & Ismayilova, V. (2025). Study of the bioecological characteristics of some lavender species introduced under the conditions of the Absheron Peninsula. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 21-29. doi: 10.63621/bknau./3.2025.21.

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were as follows: at 1 cm: 12.9-11.0%, at 2 cm: 75.0-67.0%, at 3 cm: 18.4-17.3%. To ensure a favourable nutrient environment for seedlings, the seeding rate per 1 m^2 area was calculated. It was established that the higher the germination capacity, the lower the seeding rate required, and vice versa. Based on the experiments, a seeding rate of 10 grams of seeds per 1 m^2 was recommended. Successful germination in open field required the following optimal conditions: average air temperature: 20-25°C, soil temperature: 25-27°C, relative humidity: 75-80%. According to the study results, vegetative propagation of lavender species proves more effective in the Absheron region, where the local soil and climate are well-suited for establishing lavender plantations

Keywords: seed propagation; stratification; sowing time; sowing depth; germination rate

Introduction

Increasing climate variability and drought have highlighted the importance of cultivating plants with low water requirements. The growing use of medicinal and aromatic plants across various sectors of industry, including pharmaceuticals, cosmetics, perfumery, and dye production along with their positive effects on human health, has led to increased interest and demand. Among the industrially important plant species used successfully worldwide, lavender stands out. In addition to its wide range of applications, lavender also contributes to the development of the tourism sector. Especially during the flowering stage of vegetation (in summer), lavender fields attract tourists who enjoy organising photo sessions against the backdrop of the vibrant and colourful landscape.

Lavender is an endemic plant species native to regions surrounding the Mediterranean, the Arabian Peninsula, the Canary Islands, and India. It is widely cultivated under agricultural conditions in countries such as France, Turkey, Bulgaria, Russia, Italy, Spain, the United Kingdom, Iran, Ukraine, China, and others. Due to its essential oil content, lavender is extensively used in the cosmetics industry (Gallotte *et al.*, 2020). One of the most widely used species known as medicinal lavender belongs to the genus *Lavandula* of the family *Lamiaceae*, order *Lamiales*, and is scientifically named *Lavandula angustifolia* L. – commonly referred to as narrow-leaved lavender (Güler & Korkmaz, 2018). Although *L. angustifolia* does not grow naturally in Azerbaijan, it has long been used in various regions for landscape architecture, particularly in greening parks and gardens. In recent years, the cultivation potential of lavender has been increasing rapidly. In particular, lavender species introduced to the Absheron region have shown strong growth dynamics, desirable appearance, and high-quality flowering performance. As a result, the cultivated area allocated for lavender in Absheron continues to expand steadily.

Lavender has been widely used in the fields of health and cosmetics due to its valuable essential oil. Essential oil derived from the lavender plant has been shown to shorten the time required to fall asleep and prolong the duration of sleep. Numerous scientific studies, like those by R. Samuelson *et al.* (2020), S. Kajjari *et al.* (2022), have also demonstrated its effectiveness in promoting wound healing on both human and animal skin. In addition, lavender has been found to possess antimicrobial, anti-inflammatory, antifungal, and larvicidal properties, particularly effective against insect larvae (El Abdali *et al.*, 2022). The amount of essential oil obtained from fresh lavender flowers typically ranges between 1-3%. In general, the most pharmacologically and commercially valuable part of the lavender plant is the colourless to pale yellow volatile oil contained in its flowers, known as *Aetheroleum lavandulae.* According to E. Malloggi *et al.* (2022), lavender essential oil is considered to be one of the most valuable plant-derived essential oils globally. Lavender oil, widely used across various industrial sectors, contains more than 100 volatile compounds primarily belonging to the group of terpenoids. Among the most important of these are linalool, linalyl acetate, cineole, and camphor. Lavender has been used since ancient times by the Greeks and Romans as a cleansing and cosmetic agent. Later, it was introduced to the Royal Gardens in England, and it continues to be widely used in landscape design to this day. Globally, the most commercially utilised lavender species – particularly in terms of essential oil yield and quality are: *Lavandula angustifolia* Mill., *L. officinalis* L., *Lavandula intermedia* Emeric ex Loisel. (*L. hybrida* L.), and *Lavandula spica – L. latifolia* Medik.

Lavender is a perennial plant belonging to the group of dicotyledons, characterised by a strong root system. Depending on the environmental conditions of the planting site, its roots can extend to a depth of 80-100 cm in the soil. The stems are quadrangular in shape, either glabrous or hairy, and exhibit a greyish-green colour. The plant produces numerous lateral branches, and as it matures, the older stems gradually become woody. Lavender leaves are attached directly (sessile) to the nodes of upright branches. The leaves are 2-5 cm long, with pointed tips, entire margins, and are often curled inward. The inflorescences are formed at the apical part of the flowering stem and are typically 10-20 cm in length. The flowers are tubular on the inner side, hairy on the outer side, greyish-blue in colour, and approximately 5-6 mm long. Each flower is surrounded by four calyx lobes (Kryuchkova, 2025).

The aim of this research was to investigate the bioecological characteristics of certain lavender species introduced in the Absheron region (Azerbaijan), and to study the influence of biotic and abiotic factors on seed propagation.

Materials and Methods

The experiments were conducted during the 2024-2025 period at the Experimental Research Site of the Institute of Dendrology, Ministry of Science and Education of the Republic of Azerbaijan, located in Saray settlement. The scientific names of the species and authors are provided according to The Plant List (n.d.) database. The methods for seed propagation, determination of optimal sowing time and sowing depth were based on the methodology proposed by M. Firsova (1955). As plant material, two species from the *Lamiaceae* family were used: *L. angustifolia* Mill. and *L. intermedia* L. Saray settlement is located in the Absheron district, approximately 30-35 km northwest of Baku city. It lies within a semi-desert and dry steppe zone. The soil types in the area include grey-brown (saline) and brown soils. The annual precipitation ranges between 200-350 mm, and the average annual temperature is approximately 14-15°C (Tables 1, 2) (Aliyeva *et al.*, 2025).

Table 1. Average monthly climate data in Baku (2024-2025)

Month	Average temperature (°C)	Precipitation (mm)	Average humidity (%)
January	4.5	23	74
February	5.5	21	72
March	8.5	23	70
April	13.0	18	72
May	18.0	15	71
June	23.0	7	70
July	26.0	2	68
August	26.0	6	70
September	22.0	13	72
October	16.0	28	75
November	10.0	31	76
December	6.0	28	76

Source: compiled by the authors

Table 2. Annual climate data in Baku (2024-2025)

Parameter	Value
Annual average temperature (°C)	14.9
Annual precipitation (mm)	215.0
Annual average relative humidity (%)	72.2

Source: compiled by the authors

Before sowing, soil analysis was carried out to assess the pH level and organic matter content. Soil analysis indicated that the organic matter content in the lavender cultivation area ranged from 2.5% to 3.5%. This level is considered optimal for lavender growth, providing sufficient soil fertility and water retention for healthy seedling establishment and development. The soil pH was measured using a pH meter (Hanna HI 2211 pH meter, Romania) and was recorded between 6.5-7.0. According to K. Adam (2018), lavender is best established on sandy loam soils of pH 6 to pH 8. The fruit (seeds) of lavender are approximately 1 mm in size and have a dark brown coloration. Prior to sowing, the seeds were weighed and their morphological characteristics were recorded. The seed mass was measured using an electronic balance (EK-610i, electronic type scaler) with 0.01 g precision. The total weight of 100 seeds was noted for each species. In the experiment, a total of 2,400 seeds were sown, with 1,200 seeds sown in each season (spring and autumn) to evaluate seasonal effects on germination and seedling growth.

Inflorescences of lavender were collected after full blooming and shade-dried to facilitate seed separation. Dried flowers were manually rubbed to extract the seeds, which were then stored in airtight containers under cool (+4-5°C), dry conditions (relative humidity 30-40%) to preserve germination potential. Prior to sowing, seeds were soaked in water for 24 hours. Both *Lavandula angustifolia* and *Lavandula* × *intermedia* require cold stratification; seeds were kept in moist sand or vermiculite at 4-5°C for 2-4 weeks to enhance germination, although soaking at room temperature prior to sowing may also be applied, typically resulting in lower germination rates (Urwin, 2008). During the experiment, seeds were sown at different soil depths to determine the optimal sowing depth. Specifically, during the autumn season, seeds were sown at three depth variants: 1 cm, 2 cm, and 3 cm, and the optimal depth was identified accordingly. In order to determine the most favourable sowing season for the studied lavender species, seeds were sown in two different seasons according to V. Kryuchkova *et al.* (2025):

- late autumn: November 15-30, 2024;
- early spring: March 11-20, 2025.

All sowings were performed under open field conditions. Irrigation was provided regularly using a drip irrigation system to maintain optimal soil moisture, ensuring adequate water availability for seed germination and seedling establishment. For sowing, a substrate composed of leaf mould, sand, and soil was prepared in a 1:1:1 ratio and filled into seed beds. To ensure sufficient nutrient availability for seedlings during propagation, the optimal seed sowing rate per square meter (1 m^2) was calculated based on the measured germination rate of the seeds (de Oliveira *et al.*, 2021).

The study adhered to the ethical principles outlined in Convention on Biological Diversity (1992) and Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973). Data were analysed using appropriate statistical methods, including analysis of variance (ANOVA) and Student's t-test (Gomez & Gomez, 1984; Zar, 1999). All analyses were performed using SPSS v.26. Results were presented as mean ± standard deviation (SD).

Results and Discussion

During the experiment, seeds of lavender sown at different depths exhibited varying germination rates. The results revealed that for *Lavandula angustifolia* L. and *Lavandula intermedia* L., the optimal sowing depth was 2.0 cm. Seeds sown at a depth of 1 cm had a germination rate of 11.0-12.9%, while those sown at 2 cm achieved the highest rate of 67.0-75.0%, and seeds sown at 3 cm had a reduced germination rate of 17.3-18.4% (Table 3). As shown in Table 3, seeds sown at a shallow depth (1 cm) demonstrated significantly lower germination rates. This reduction is primarily attributed to rapid evaporation of moisture from the soil surface, causing the seedbed to dry out quickly and limiting the seeds' ability to absorb sufficient water.

Table 3. Effect of sowing depth and rate on seed germination percentage of lavender

	Seed amount per 1 m^2 (g)	1 cm sowing depth (%)	2 cm sowing depth (%)	3 cm sowing depth (%)
Lavandula angustifolia L.	10.0	12.9 ± 1.2	75.0 ± 2.5	18.4 ± 1.8
Lavandula × intermedia L.	10.0	11.0 ± 1.0	67.3 ± 2.0	17.3 ± 1.5

Source: compiled by the authors

These findings suggest that, under open field conditions, the most effective sowing depth for lavender seeds is 2.0 cm. To ensure favourable nutrient availability during seed propagation, the optimal seed rate per 1 m^2 was calculated based on seed germination percentage. As germination capacity increases, the required sowing rate decreases, and vice versa (Table 4). Based on results, the optimal seed rate was determined to be 10 grams per square meter. *Lavandula angustifolia* L. were observed earlier than those of the other species, appearing on April 10. In *Lavandula intermedia* L., the first seedlings emerged four days later, on April 14. Mass germination was recorded depending on the species between April 15 and April 22. In the second sowing variant (December 20), the first seedlings were observed between April 18 and April 24.

Table 4. Effect of sowing time on seed germination of lavender species

Species	First emergence	Mass emergence	Germination rate (%) ±SD	First emergence	Mass emergence	Germination rate (%) ±SD
	20 Nov	20 Nov	20 Nov	20 Dec	20 Dec	20 Dec
L. angustifolia L.	10.04	15.04	75.0 ± 2	18.04	26.04	60.5 ± 2
L. intermedia L.	14.04	22.04	63.0 ± 2	24.04	03.05	52.5 ± 2

Source: compiled by the authors

In Variant I (sowing on November 20), the seed germination rate ranged between 68-70% and 75-77%, depending on the species. The highest germination rate was recorded in *Lavandula angustifolia* L., ranging from 75-77%. In *Lavandula intermedia* L., the germination rate was relatively lower, ranging between 63-65%. In Variant II (sowing on December 20), the first seedling emergence occurred approximately 8-10 days later compared to Variant I. The germination rate in this variant was also lower: 60-62% for *Lavandula angustifolia* L. and 52-55% for *Lavandula intermedia* L. The results obtained from autumn sowing during the study indicated that the optimal sowing time for the seeds of certain lavender species under Absheron conditions is the second ten-day period of November. Additionally, the germination percentage of seeds sown in spring was also examined. For this purpose, non-stratified seeds were sown in open field conditions during the first ten-day period of March. It is well known that one of the key conditions for successful seed germination in open field environments is an average air temperature of 20-25°C, a soil temperature of 25-27°C, and a relative air humidity of 75-80%. During the study, seeds sown in the first ten-day period of March without stratification or scarification exhibited delayed germination compared to other sowing variants. The first seedlings appeared in the second ten-day period of May, while mass germination occurred in

the third ten-day period. As a result, the germination rate of *Lavandula angustifolia* L. and *Lavandula intermedia* L. seeds sown in spring without any pre-treatment ranged between 15-17% and 39-42%.

A lavender plantation was established at the Saray Experimental Station of the Institute of Dendrology. In general, lavender can be propagated both generatively (by seeds) and vegetatively. During generative propagation, the very small size of the seeds and the requirement for special preparation of seedbeds create certain difficulties. Moreover, since seed germination and seedling development are slow in generative propagation, weed infestation of the sowing area is frequently observed. Therefore, according to N. Urwin (2008), vegetative propagation is considered a more efficient and economically viable method for large-scale lavender cultivation. The lavender species studied are widely distributed across the Southern Hemisphere (Lis-Balchin, 2022). Representatives of the *Lavandula* genus are commonly found in regions such as South Africa, India, and various parts of Eurasia. Some species of *Lavandula* L. are also widely distributed in the southern regions of Russia, Turkey, Georgia, and Crimea. The occurrence of these species in diverse geographical areas with varying soil and climatic conditions indicates their ability to adapt to a broad range of environmental factors (Mokhtarzadeh *et al.*, 2013; Détár, *et al.*, 2020). The adaptability of lavender to different environmental conditions has also been demonstrated by T. Kachanova *et al.* (2023), who found that *L. angustifolia* can be successfully cultivated as an industrial crop under appropriate irrigation regimes and biological treatments. Similar observations have been reported in previous studies. D. Akgül *et al.* (2019) found that autumn sowing led to higher germination rates for *L. angustifolia*, while delayed sowing in winter reduced both germination percentage and speed. G. Koçer & H. Baydar (2022) also noted that seasonal timing and seed pre-treatment (stratification or scarification) significantly influence germination, with late sowing or absence of pre-treatment resulting in delayed and lower germination. M. Firsova (1955) emphasised that lavender seeds exhibit slow germination under natural conditions and that stratification or soaking can improve germination rates. These findings are consistent with the present study, where non-stratified seeds sown in early March showed delayed germination, with first seedlings appearing in the second ten-day period of May and mass germination occurring in the third ten-day period. The germination rates in spring sowings without pre-treatment were 15-17% for *L. angustifolia* L. and 39-42% for *L. intermedia* L., highlighting the importance of both sowing time and seed preparation for successful propagation. Propagation methods for lavender have also been evaluated in previous studies. N. Urwin (2008) concluded that vegetative propagation is often more efficient and economically viable for large-scale cultivation due to slow germination and seedling development in generative propagation. Small seed size and the need for special seedbed preparation create additional difficulties, and weed infestation is commonly observed during generative propagation.

Based on the results of this study, vegetative propagation of lavender species under Absheron conditions proved to be more effective. The soil and climatic conditions of the region are suitable for establishing lavender plantations. In conclusion, the study indicated that the second ten-day period of November is the optimal sowing time for lavender under Absheron conditions, with *L. angustifolia* L. showing higher germination rates compared to *L. intermedia* L. Spring sowings without pre-treatment result in significantly delayed and lower germination. For large-scale cultivation, vegetative propagation is recommended as a more efficient and reliable method, whereas generative propagation requires careful consideration of sowing time and seed pre-treatment to achieve satisfactory germination.

Conclusions

The study demonstrated that the optimal sowing depth for *Lavandula angustifolia* L. and *Lavandula intermedia* L. is 2.0 cm, where the highest seed emergence rates were observed. At a shallower depth of 1 cm, germination rates were relatively low, reaching only 12.9% for *L. angustifolia* L. and 11.0% for *L. intermedia* L. Increasing the depth to 2 cm significantly improved germination to 75.0% and 67.0%, respectively, while further increasing the depth to 3 cm led to a sharp decline in seedling emergence, dropping to 18.4% and 17.3%. These findings highlight the critical importance of correct sowing depth in optimising seed germination and early seedling establishment. The study also identified 10 grams per square meter as the optimal seeding rate for both species. This balance ensures sufficient seed density for uniform plant establishment while avoiding excessive overcrowding. In general, higher seed viability allows for lower seeding rates, whereas lower germination capacity requires an increased seeding rate to achieve adequate field coverage. Optimal environmental conditions for successful seed germination under open-field conditions were determined as an average air temperature of 20-25°C, soil temperature of 25-27°C, and relative humidity of 75-80%. These conditions are essential to accelerate germination and support early seedling growth, particularly in regions with variable climatic conditions such as Absheron. Despite these findings, generative propagation of lavender under local conditions proved inefficient. The very small seed size, the requirement for specially prepared seedbeds, and the slow germination rate create significant technical challenges. Moreover, delayed seedling growth facilitates weed competition, further reducing the effectiveness of seed-based propagation. Therefore, vegetative propagation is considered a more

practical, efficient, and commercially viable method for large-scale lavender cultivation.

Future research should focus on improving seed germination through pre-sowing treatments, such as cold stratification, soaking, or treatment with growth-promoting bioactive compounds. Additionally, studies on optimising vegetative propagation techniques, irrigation management, and soil amendment strategies will contribute to more efficient and sustainable lavender production under varied climatic conditions.

Acknowledgements

The authors would like to express their gratitude to the staff of the Saray Experimental Station for their assistance during the research.

Funding

The study was not funded.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Апшерон шартына интродукцияланган айрым лаванда түрлөрүнүн биоэкологиялык өзгөчөлүктөрүн изилдөө

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Аннотация. Климаттык өзгөрүүлөрдүн күчөшү жана кургакчылык суу аз талап кылган өсүмдүктөрдү өстүрүүнү алдыңкы планга чыгарууда. Ушул контекстте ар кандай тармактарда – фармацевтикада, косметикада, парфюмерияда жана боек өндүрүшүндө кеңири колдонулган кургакчылыкка чыдамкай лаванда өзгөчө мааниге ээ болууда. Лаванда плантациялары кооздугу менен гана эмес, туризм тармагынын өнүгүшүнө кошкон салымы менен да баалуу. Бул изилдөөдө Абшерон аймагына (Азербайжан) интродукцияланган бир нече лаванда түрүнүн биоэкологиялык өзгөчөлүктөрү жана биотикалык, абиотикалык факторлордун уруктан көбөйүүгө тийгизген таасири изилденди. Эгүү иштери жазында (март) жана күзүндө (ноябрь, декабрь) жүргүзүлдү. Изилдөө учурунда лаванданын уругунун өнүп чыгышы анын көмүлүү тереңдигине жараша өзгөрөрү аныкталды. *Lavandula angustifolia* L. жана *Lavandula intermedia* L. уруктары үчүн оптималдуу себүү тереңдиги 2,0 см деп табылды. Ар кандай тереңдикте өнүп чыгуу көрсөткүчтөрү мындай болду: 1 смде – 12,9-11,0 %, 2 смде – 75,0-67,0 %, 3 смде – 18,4-17,3 %. Өркүндөр үчүн азыктандыруучу чөйрөнүн шарттарын камсыз кылуу максатында 1 м² аянтка урук себүү нормасы эсептелди. Жыйынтыгында белгиленгендей, өнүп чыгуу жөндөмдүүлүгү канчалык жогору болсо, керектелүүчү себүү нормасы ошончолук төмөн болот жана тескерисинче. Тажрыйбанын негизинде 1 м² аянтка 10 г урук себүү сунушталды. Ачык талаада ийгиликтүү өнүп чыгуу үчүн оптималдуу шарттар төмөнкүлөр болду: абанын орточо температурасы 20-25 °C, топурактын температурасы 25-27 °C, салыштырмалуу нымдуулук 75-80 %. Изилдөөнүн жыйынтыгына ылайык, Абшерон аймагында лаванда түрлөрүн вегетативдик көбөйтүү ыкмасы натыйжалуу болуп чыкты, анткени жергиликтүү топурак-климаттык шарттар лаванда плантацияларын түзүүгө абдан ылайыктуу

Негизги сөздөр: уруктан көбөйтүү; стратификация; себүү мөөнөтү; себүү тереңдиги; өнүп чыгуу көрсөткүчү

Изучение биоэкологических особенностей некоторых видов лаванды, интродуцированных в условиях Апшерона

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Аннотация. Усиление климатической изменчивости и засушливости выдвигает на первый план возделывание растений с низкой потребностью во влаге. В этом контексте лаванда – засухоустойчивое растение, широко используемое в фармацевтической, косметической, парфюмерной и красильной промышленности, приобретает особую актуальность. Лавандовые плантации не только обладают высокой декоративной ценностью, но и способствуют развитию туристического сектора. В данном исследовании были изучены биоэкологические особенности нескольких видов лаванды, интродуцированных в Абшеронском регионе (Азербайджан), а также влияние биотических и абиотических факторов на семенное размножение. Посев осуществлялся весной (март) и осенью (ноябрь и декабрь). В ходе исследования было установлено, что всхожесть семян лаванды зависит от глубины заделки. Оптимальная глубина посева для семян *Lavandula angustifolia* L. и *Lavandula intermedia* L. составила 2,0 см. Всхожесть семян при различной глубине посева была следующей: при 1 см – 12,9-11,0 %, при 2 см – 75,0-67,0 %, при 3 см – 18,4-17,3 %. Для обеспечения благоприятных условий питания всходов была рассчитана норма высева на 1 м² площади. Установлено, что чем выше всхожесть, тем ниже необходимая норма высева, и наоборот. На основании опытных данных рекомендована норма высева 10 г семян на 1 м². Для успешного прорастания в открытом грунте оптимальными условиями были: средняя температура воздуха 20-25 °C, температура почвы 25-27 °C, относительная влажность 75-80 %. Согласно полученным результатам, в условиях Абшеронского региона более эффективным оказалось вегетативное размножение лаванды, так как местные почвенно-климатические условия благоприятны для закладки лавандовых плантаций

Ключевые слова: семенное размножение; стратификация; сроки посева; глубина посева; всхожесть

Received: 03.05.2025. Revised: 29.07.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 528.2/5:528.4:528.7

DOI: 10.63621/bknau./3.2025.30

Analysis of accuracy of traditional and satellite methods of geodetic measurements

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Abstract. The article presented a detailed comparative analysis of the accuracy of traditional and satellite methods of geodetic measurements in relation to the tasks of the agricultural sector. The aim of the work was to identify the conditions under which a particular method or their combination provides the optimal ratio of accuracy, time of performance and stability to external factors in land surveying and land reclamation works, as well as in the process of monitoring of agricultural lands. As part of the study, field experiments were conducted in areas with different geomorphological characteristics of Kyrgyzstan, including flat areas of the Chüy Valley, hilly pasture zones and mountain gardens of Jalal-Abad region. The results showed that levelling retains its leading position in terms of vertical accuracy (up to 2 mm/km), which makes it indispensable in the design of irrigation systems. Tacheometry demonstrated stable values of RMS error in plan (8-12 mm) and elevation (15-25 mm) in conditions of plains and built-up areas. GNSS measurements in RTK mode provided high performance and accuracy (5-10 mm in plan, 10-20 mm in elevation) in open terrain, but in mountainous areas the accuracy decreased to 3-5 cm due to signal interruptions. Static GNSS survey provided the highest accuracy results (3-5 mm), but it was the most time-consuming (20-40 min/point). The practical value of the study lies in the development of recommendations on the selection of the optimal methodology for cadastral works, design of land reclamation systems and implementation of precision farming technologies, where the combined use of traditional and satellite approaches is most effective

Keywords: geodesy; measurement accuracy; RMS error; traditional methods; combined methods; GNSS; GPS

Introduction

Modern development of the agricultural sector is impossible without the use of accurate geodetic measurements, which provide a reliable basis for land management, design of land reclamation systems, monitoring of agricultural land and implementation of precision farming technologies. In recent years, there has been a growing interest in the integration of satellite and traditional methods, as shown in papers such as A. White *et al.* (2022). New studies emphasise the value of global georeferencing systems and the combination of GNSS (Global Navigation Satellite System) with other methods (Huisman & de Ligt, 2023; Haines *et al.*, 2024). In conditions of agricultural intensification, there is an increasing need for efficient methods that allow obtaining spatial data on land objects with high accuracy and in the shortest possible time. Studies aimed at improving the efficiency of land reclamation works are of particular relevance. As shows the study of N. Kutymbek *et al.* (2025), complex ameliorative measures on compacted grey soils can significantly improve soil structure and increase their water permeability, which requires high-precision geodetic support in the design and monitoring of such systems. Geodetic measurements become not only a technical procedure, but also an important element of an integrated rural management system, which gives the study additional relevance. Traditional geodetic methods – levelling, tacheometric surveying, theodolite observations – are

Suggested Citation: Sultanalieva, T. (2025). Analysis of accuracy of traditional and satellite methods of geodetic measurements. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 30-37. doi: 10.63621/bknau./3.2025.30.

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characterised by high accuracy and time-tested reliability. They are still used in land surveying and agricultural engineering projects, especially where accurate vertical surveying is required or works are carried out in difficult terrain conditions. However, these methods are time-consuming and labour-intensive, which limits their use when surveying large areas of agricultural land.

Against this background, satellite technologies – GNSS, differential correction, RTK (Real-Time Kinematic) and static imagery – offer new opportunities. They allow to significantly increase productivity, automate the process of data acquisition and integrate them into geographic information systems (GIS) used for agricultural resource management. Recent years have seen a rapid development of these technologies, with improved receivers, post-processing algorithms and methods for combining satellite data with unmanned aerial vehicles and laser scanning. The greatest development potential is related to PPP (Precise Point Positioning)-RTK, integration of GNSS with InSAR (Interferometric Synthetic Aperture Radar) and automation of data processing (Cheng *et al.*, 2023; Papco *et al.*, 2024; Reshadati & Shirzaei, 2024). Prospective studies such as N. Chodura *et al.* (2025), also concern the application of AI and big data analysis. UAV (Unmanned Aerial Vehicle) photogrammetry has shown to be highly effective for site monitoring (Maboudi *et al.*, 2025). Modern works such as D. Chai *et al.* (2025), also emphasise the integration of GNSS with INS (Inertial Navigation Systems) and partial ambiguity resolution techniques.

The relevance of this study lies in the need for a comprehensive analysis of the accuracy of traditional and satellite methods of geodetic measurements in relation to the tasks of the agricultural sector. Such analysis allowed to identify optimal approaches for specific conditions of agricultural production, to determine the balance between accuracy, costs and stability to external factors, as well as to justify the feasibility of implementing combined technologies in the practice of land management and agricultural engineering. The aim of the study was to conduct a comparative analysis of the accuracy of traditional and satellite-based methods of geodetic measurements with a focus on their applied use in the agricultural sector. The main objectives of the study were: to characterise traditional methods and their role in the agricultural sector; to analyse satellite methods and identify their advantages and limitations; to perform a comparative analysis of the accuracy and efficiency of the methods on the example of land management, land reclamation and land monitoring; to formulate practical recommendations for the selection of the optimal methodology for the agricultural sector.

Materials and Methods

In order to achieve the set objectives the method of field comparative analysis with subsequent mathematical processing of the results was used. The study used field methods (levelling, total station, GNSS RTK and static survey) in different geomorphological conditions of Kyrgyzstan. Similar approaches are described in current sources on the integration of GNSS with unmanned aerial vehicles and laser scanning (Reinprecht & Kieffer, 2025; Sestras *et al.*, 2025a; Sestras *et al.*, 2025b). The studies were conducted on sites with different geomorphological characteristics in three types of agricultural areas:

- Plain area (Chüy Valley) – irrigated fields and reclamation canals. In this area, 18 control points were measured on a regular grid of 200 × 200 m to evenly cover the territory and to obtain a representative sample of elevations;
- Moderately hilly terrain (neighbourhood of Kara-Balta) – pastures and hayfields. Fourteen control points were selected, located at the bends in the relief (watersheds, hilltops, depressions). This choice allowed to reflect the characteristic features of the relief and to check the stability of the methods in conditions of partial visibility;
- Mountainous area (Kazarman, Jalal-Abad region) – orchards and vineyards. Here 12 control points located on slopes and in gorges were measured taking into account the availability of satellite signal and visual contact for traditional methods.

Various field measurement methods and equipment were used in the study. Class II levelling (Leica NA730) was used to obtain highly accurate elevation difference data for irrigation and drainage canal design; vertical accuracy was up to 2 mm/km. Tacheometric survey (Leica TS06 Plus) was used to construct topographic plans of agricultural land and agro-infrastructure facilities. The root mean square error (RMSE) for plan was 8-12 mm, for elevation – 15-25 mm. GNSS measurements (CHCNAV I50, RTK and static modes) were used to obtain coordinates of control points for cadastral survey of land plots. The methods used for data processing were those described by A. El-Rabbany (2002) and A. Leick *et al.* (2015). The RTK mode provided rapidity (10-20 seconds per point), while statics gave maximum accuracy (3-5 mm) with an observation time of 20-40 minutes per point. Figure 1 shows the GNSS receiver I50 CHCNAV.

Figure 1. GNSS receiver I50 CHCNAV
Source: author's photo

During the field survey, Class II levelling was carried out using a Leica NA730 leveller. The average length of the sighting beam was 60-70 m and the distance between stations was about 500 m. The accuracy of the elevations was in accordance with Class II standards and was within ±2.0 mm per 1 km of double-tracking. The altitude data were compared with the results of levelling, which confirms the relevance of the work comparing RTK-GNSS and classical methods (Naumowicz & Kowalczyk, 2025; Raufu, 2025). A total station survey was also carried out using a Leica TS06 Plus electronic total station. The survey was carried out at 20-25 m spacing in open areas and 10-15 m in areas with pronounced microrelief. RMS error of distance measurements was ± (2 mm + 2 ppm), angular measurements – ±2″. Point coordinates were measured using a CHCNAV i50 GNSS receiver in RTK and static modes. In RTK mode, the initialisation time was 5-10 seconds and the RMS error in plan did not exceed ±1.5 cm and in elevation ±2.5 cm. In static observations, the duration of sessions ranged from 30 minutes to 1 hour, which ensured the accuracy of coordinate determination up to ±5 mm in plan and ±10 mm in height.

The Leica Geo Office and GNSS Solutions software packages were used to process the satellite data. The following algorithms were used during post-processing: double difference method (to eliminate ephemeris and ionosphere errors) (Leick *et al.*, 2015); Kalman filter (in RTK mode for smoothing coordinate solutions); least squares method (for network equalisation in static mode, as well as for total stations and levelling). The quality assessment criteria were: the value of the RMS error, the inconsistencies in stroke closures and the accuracy coefficient of the equated networks. To ensure comparability of the results, the data were initially recorded in the global World Geodetic System (WGS84, n.d.), and then transformed into local coordinate systems used in land surveying projects of the Kyrgyz Republic: Chüy Valley – SK-42 (coordinate system of 1942), zone 13 (Gauss-Kruger); Kara-Balta vicinity – SK-42, zone 14, coordinated with cadastral projects of the region; Jalal-Abad region – SK-95 (coordinate system of 1995), relevant for state land surveying works.

Results and Discussion

Field studies have shown that each of the considered methods has both advantages and limitations. The highest vertical accuracy was demonstrated by levelling, where the error did not exceed 2 mm/km. These results correspond to generally accepted standards of accuracy of geodetic levelling, which confirms its indispensability in the design of irrigation systems, especially in the flat areas of the Chüy Valley. The tacheometric survey showed stable results: the RMS error was 8-12 mm in plan and 15-25 mm in elevation. In the conditions of urban development of Bishkek, the accuracy of tacheometry proved to be higher than that of GNSS RTK. The comparative data are presented in Table 1 and Figure 2, where the advantages of tacheometry over other methods in conditions of limited visibility can be seen.

Table 1. Comparative accuracy of traditional and satellite-based methods of geodetic measurements in three types of agricultural areas in Kyrgyzstan

Method	RMSE by plan (mm)	RMSE in height (mm)	Conditions of application
Levelling (II Class)	–	2.0 mm/km	High-precision survey of height differences
Tacheometry (electronic)	8-12	15-25	Plains, built-up areas
GNSS (RTK)	5-10	10-20	Open terrain, signal required
GNSS (static)	3-5	5-10	Long observations (20-30 min/point)

Note: averaged values calculated on the basis of control points measured as part of the study
Source: compiled by the author on the basis of field studies

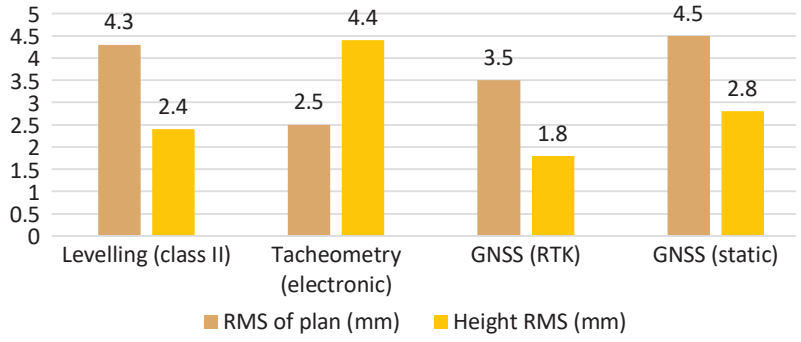

Figure 1. Comparative accuracy of traditional and satellite methods of geodetic measurements
Source: compiled by the author based on field survey data

GNSS measurements in RTK mode provided high speed of operation – about 10-20 seconds per point – and accuracy of about 5-10 mm in plan and 10-20 mm in height in open terrain. However, in mountainous terrain, the accuracy decreased dramatically, to 3-5 cm, which is consistent with the findings of V. Hamza *et al.* (2025) and H. Zhong *et al.* (2025) who noted the sensitivity of GNSS to interference and terrain obstacles. The advantage of this method is its high throughput: Table 2 and the time plot (Fig. 2) show that RTK significantly reduces the survey duration compared to traditional methods. At the same time, as X. Zhang *et al.* (2025) point out, modern technologies such as multi-frequency and multi-system (multi-GNSS) methods, as well as Precise Positioning Services (PPP), allow high real-time accuracy, reducing convergence time to a few minutes and providing an accuracy of up to 2.5 cm. Static GNSS surveying in this study provided the highest accuracy (3-5 mm in plan and 5-10 mm in elevation) but was time consuming (20-40 minutes per point). Similar findings are cited by K. Maciuk (2018), noting that statics remains the most reliable method, but its practical application is limited by the need for long-term observations. The data on time costs are summarised in Table 2, which confirms the limited application of static surveying for mass cadastral and engineering works.

Table 2. Time taken to measure one point by different methods

Method	Time per point	Comments
Levelling	10-15 minutes	Requires moving and setting up of slats
Tacheometry	5-8 minutes	Faster than levelling, but depends on visibility conditions
GNSS (RTK)	10-20 seconds	High speed, if RTK station is available
GNSS (static)	20-40 minutes	Long-term observation, high accuracy

Note: RTK – real time kinematic; static – static mode of GNSS observations
Source: compiled by the author on the basis of field experiments on agricultural land

Comparison of the methods showed that none of them is universal. In urban areas, traditional methods such as levelling and tacheometry are more reliable, while in flat, open terrain satellite technologies are optimal. In mountainous areas, the best results are achieved by a combination of approaches: first RTK surveying is performed to determine the general configuration of points, and then refinement is carried out by statics or total stations. This combined approach is also noted by P. Jansson & L. Lundgren (2018), emphasising that the combination of methods allows minimising errors in cadastral works. The influence of topography and other factors on measurement accuracy is summarised in Table 3.

Table 3. Influence of external factors on the accuracy of geodetic methods

Method	Building	Forest cover	Mountainous terrain	Cloudy weather	Need for line of sight
Levelling	+	+	±	+	Yes
Tacheometry	±	±	±	±	Yes
GNSS (RTK)	–	–	–	±	Yes, to satellites and base
GNSS (static)	±	±	±	±	Desirable, but post-processing is possible

Note: "+" – high stability; "±" – limited applicability; "–" – sharp decrease in accuracy
Source: compiled by the author on the basis of field survey data

The results obtained are in agreement with the findings of R. Wagh & S. Auti (2025) who showed that the integration of satellite technologies with geographic information systems improves the efficiency of land surveying projects. In particular, the combination of GNSS with tacheometry for land surveying is effective in agricultural tasks, as well as the use of levelling to refine elevations in the design of land reclamation systems. Thus, the conducted research confirms that the choice of the optimal technique depends on the terrain conditions and tasks. Satellite methods provide high productivity and sufficient accuracy in flat areas, but need support of traditional approaches when working in mountains and dense buildings. The best performance is achieved when they are used in combination, which is also supported by current research.

Conclusions

The analysis of traditional and satellite methods of geodetic measurements has shown that there is no universal approach, equally effective in all conditions. For flat conditions satellite technologies are optimal,

and for mountainous and built-up areas – traditional or combined. The choice of the optimal methodology is determined by terrain features, technical capabilities and the objectives of the survey. In flat areas satellite technologies are the most productive, providing high productivity and sufficient accuracy, while in mountainous areas and densely built-up areas traditional methods or their combined application should be preferred. Levelling retains its leading position in vertical accuracy and remains indispensable in the design and construction of irrigation systems. Tacheometry demonstrates stable results when surveying limited and built-up areas. GNSS surveying in RTK mode provides high speed and automation of measurements, but its accuracy decreases in difficult terrain and unstable signal, which requires combination with other approaches. Static GNSS remains the most accurate method, although its application is limited by significant time costs. Thus, the most effective strategy in geodetic surveying is the integration of traditional and satellite technologies, which can compensate for their mutual limitations and increase the reliability of the data obtained.

The prospects for further research are related to the development of integrated systems combining data from satellite receivers, total stations, laser scanners and unmanned aerial vehicles within the framework of geoinformation platforms. Particular attention should be paid to the introduction of artificial intelligence and machine learning methods for the automatic processing and analysis of spatial data. Further work should also be directed towards assessing the stability of combined techniques in complex natural and anthropogenic conditions, as well as developing adaptive algorithms to improve the accuracy of real-time measurements.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Салттуу жана спутниктик геодезиялык өлчөө ыкмаларынын тактыгын талдоо

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Аннотация. Бул макалада геодезиялык өлчөөлөрдүн салттуу жана спутниктик ыкмаларынын тактыгынын деталдуу салыштырма талдоосу агрардык тармактагы колдонууга басым жасоо менен берилет. Изилдөөнүн негизги максаты – жерге жайгаштыруу, мелиорация жана айыл чарба жерлерин мониторигдөө иштеринде ар бир ыкма же алардын айкалышы тактык,өлчөө жүргүзүү убактысы жана тышкы факторлорго туруктуулук боюнча оптималдуу натыйжа берген шарттарды аныктоо болуп саналат. Талаа изилдөөлөрү Кыргызстандын ар түрдүү геоморфологиялык шарттарында аныктоо болуп саналат. Талаа изилдөөлөрү Кыргызстандын ар түрдүү геоморфологиялык шарттарында жүргүзүлдү: Чүй өрөөнүнүн түздүктөрүндө, Кара-Балтанын айланасындагы адырлуу жайыттарда жана Жалал-Абад облусунун тоолу бак-даракту аймактарында. Натыйжалар көрсөткөндөй, нивелирлөө вертикалдык тактык боюнча эң жогорку деңгээлди (2мм/км чейин) камсыз кылып, ирригациялык системаларды долбоорлоодо алмашкыз бойдон калууда. Тахеометрия түздүк жана курулуш көп болгон аймактарда орточо квадраттык катанын туруктуу маанилерин (планды 8-12 мм, бийиктиги боюнча 15-25 мм) көрсөттү. GNSS RTK ыкмасы ачык аймактарда жогорку өндүрүмдүүлүк жана тактыкка (пландык 5-10 мм, бийиктиги боюнча 10-20 мм) жетишти, бирок тоолуу райондордо сигнал үзүлүүлөрүнө байланыштуу ката 3-5смге чейин көбөйдү. Эң жогорку тактык (3-5 мм) статикалык GNSS олчөөлөрүндө байкалган, бирок убакыттык чыгым эң көп болгон (20-40 мин/чекит). Изилдөөнүн практикалык мааниси – кадастрдык иштерде, мелиорациялык системаларды долбоорлоодо жана так дыйканчылык технологияларын киргизүүдө оптималдуу ыкмаларды тандоо боюнча сунуштарды иштеп чыгууда,мында салттуу жана спутниктие ыкмаларды айкалыштырып колдонуу эң эффективдүү экендиги далилденди

Негизги сөздөр: геодезия; өлчөө тактыгы; орточо квадраттык ката; салттуу ыкмалар; айкалышкан ыкмалар; GNSS; GPS

Анализ точности традиционных и спутниковых методов геодезических измерений

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Аннотация. В статье представлен детальный сравнительный анализ точности традиционных и спутниковых методов геодезических измерений применительно к задачам аграрного сектора. Целью работы было выявление условий, при которых конкретный метод или их комбинация обеспечивают оптимальное соотношение точности, времени выполнения и устойчивости к внешним факторам при землеустроительных и мелиоративных работах, а также в процессе мониторинга сельскохозяйственных угодий. В рамках исследования проведены полевые эксперименты на участках с различными геоморфологическими характеристиками Кыргызстана, включая равнинные территории Чуйской долины, холмистые пастбищные зоны и горные сады Джалал-Абадской области. Полученные результаты показали, что нивелирование сохраняет лидирующие позиции по вертикальной точности (до 2 мм/км), что делает его незаменимым при проектировании ирригационных систем. Тахеометрия продемонстрировала стабильные значения среднеквадратической ошибки по плану (8-12 мм) и высоте (15-25 мм) в условиях равнин и застроенных территорий. GNSS-измерения в режиме RTK обеспечили высокую производительность и точность (5-10 мм по плану, 10-20 мм по высоте) в открытой местности, однако в горных районах точность снижалась до 3-5 см из-за перебоев сигнала. Наивысшие результаты по точности (3-5 мм) обеспечила статическая ГНСС-съемка, но она оказалась наиболее затратной по времени (20-40 мин/точка). Практическая ценность исследования заключается в разработке рекомендаций по выбору оптимальной методики для кадастровых работ, проектирования мелиоративных систем и внедрения технологий точного земледелия, где наиболее эффективно комбинированное использование традиционных и спутниковых подходов

Ключевые слова: геодезия; точность измерений; среднеквадратическая ошибка; традиционные методы; комбинированные методы; GNSS; GPS

Received: 14.04.2025. Revised: 02.08.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 636.32/.38:636.082.4:575.113:338.43

DOI: 10.63621/bknau./3.2025.38

Economic significance of genetic diversity of Kyrgyz Mountain Merino sheep based on STR analysis of nuclear DNA

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Abstract. Preserving and assessing the genetic diversity of farm animals is one of the key tasks for sustainable development in the agricultural sector. This paper examined the economic significance of genetic diversity in Kyrgyz Mountain Merino (KMM) sheep based on an analysis of nuclear DNA variability using microsatellite markers (STR). The aim of the study was to determine the level of heterozygosity, inbreeding coefficients and allele richness in KMM compared to related fine-wool sheep breeds from Russia, Kazakhstan, Poland and Pakistan, as well as to determine their significance for breeding programmes and the economic sustainability of the industry. The methodological basis of the study included molecular genetic analysis of 12 STR markers, statistical evaluation of genetic parameters, and comparison of the results with international databases. It was found that the level of observed heterozygosity in KMM (Ho = 0.70) exceeds that of Russian (0.66), Polish (0.64) and Pakistani (0.65) fine-wool sheep. Kazakh breeds show similar values (0.68), but are characterised by a higher inbreeding coefficient

Suggested Citation: Chorthonbaev, T., Isakova, Z., Mambetova, E., Belek uulu, E., & Baytemir, M. (2025). Economic significance of genetic diversity of Kyrgyz Mountain Merino sheep based on STR analysis of nuclear DNA. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 38-50. doi: 10.63621/bknau./3.2025.38.

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(FIS = 0.06), which indicates a tendency towards a decrease in genetic diversity. In contrast, the inbreeding coefficient for KMM was only 0.03, indicating a balanced population structure. The results of the study confirmed that the preservation of the genetic diversity of the KMM breed is not only biologically but also economically important: higher genetic variability ensures adaptability to changing climatic conditions, increases productivity and reduces the costs of veterinary and breeding measures. Thus, the integration of genetic monitoring into the economic management of sheep breeding is a necessary condition for the sustainable development and competitiveness of KMM products in domestic and foreign markets

Keywords: sheep breeding in Kyrgyzstan; STR markers; molecular genetic analysis; population stability; genetic polymorphism; biotechnology in animal husbandry

Introduction

Sheep farming has traditionally occupied one of the leading places in the agricultural sector of the Kyrgyz Republic, providing the rural population with meat, dairy products and wool, as well as forming the country's export potential. According to the National Statistical Committee of the Kyrgyz Republic (n.d.), the share of sheep breeding in the overall structure of livestock production remains consistently high, despite the climatic and socio-economic challenges of recent decades. Of particular importance is the Kyrgyz Mountain Merino (KMM), a unique breed of fine-wool sheep characterised by high adaptability to high-altitude conditions, resistance to environmental stress factors and valuable productive characteristics of wool and meat. These qualities determine its strategic role in the development of sheep breeding and the formation of the country's food security. However, in recent years, threats related to the loss of KMM genetic diversity have been increasing. The intensive use of a limited number of producers, the reduction of grazing land, climate change and globalisation processes are leading to a narrowing of the gene pool and an increase in the risks of inbreeding. As noted by A. Kappes *et al.* (2023), G. Wanjala *et al.* (2023), the consequences of reduced genetic diversity are manifested in weakened reproductive qualities, increased susceptibility to disease, and reduced overall animal productivity, which in turn directly affects the economic efficiency of the industry.

Modern molecular genetic methods allow for a more detailed study of the structure of farm animal populations. Short Tandem Repeats (STR) analysis, or microsatellite analysis, occupies a special place among these methods. This method is considered a reliable tool for assessing intraspecific diversity, identifying degrees of kinship and population differentiation. STR markers are used in breeding programmes to control genetic variability and develop long-term strategies for sustainable sheep breeding (Teneva *et al.*, 2018). For example, studies by T. Odjakova *et al.* (2023) showed that the use of STR analyses allows for the objective determination of the degree of genetic homogeneity in sheep populations, while R. Pichler *et al.* (2017) confirmed the effectiveness of the method in a comparative analysis of the genetic diversity of 11 domestic sheep breeds from Asia, Africa, Europe and Latin America with wild Asian urials.

From an economic point of view, the preservation and maintenance of genetic diversity is one of the most important factors for the sustainability of the livestock industry. Genetic variability provides opportunities to increase productivity, improve wool and meat quality, resistance to infectious diseases and adaptation to changing climatic conditions. Molecular genetic studies show that the adaptation of sheep to different environmental conditions is ensured by a complex of mechanisms: the HIF-1α and EPAS1 genes contribute to high-altitude adaptation through the regulation of hypoxic stress, UCP1 provides cold resistance, and SLC4A4 and GPX3 increase drought resistance (Zhu *et al.*, 2025). These mechanisms are implemented through DNA methylation, transcriptional regulation, and metabolic pathways, which emphasises the importance of preserving genetic diversity to maintain the adaptive potential of breeds. In the long term, this is directly linked to increased profitability of agricultural enterprises and reduced risks associated with environmental fluctuations.

The issue of preserving genetic diversity is particularly important for the mountainous regions of Central Asia, where natural and environmental conditions are highly variable. In such regions, maintaining intraspecific diversity is a prerequisite for food security and the competitiveness of the industry. M. Nei's (1972) concept of genetic distance, based on the identity of genes between populations, laid the theoretical foundation for the quantitative assessment of genetic diversity and remains a key tool in population genetics. Its application to the analysis of farm animals shows that, under conditions of high pressure on ecosystems, it is genetic diversity that ensures the flexibility of adaptation and the stability of sheep productivity characteristics. Despite growing interest in this issue, research on the genetic resources of Kyrgyz sheep breeds is limited. The lack of systematic data reduces the effectiveness of breeding and selection work and limits strategic planning opportunities. K. Dossybayev *et al.* (2019) emphasised that the integration of molecular genetic methods with economic analysis of productivity can significantly improve the effectiveness of industry programmes. This approach is

already being actively used in other countries: for example, R. Sharma *et al.* (2020) showed that taking genetic diversity into account increases the efficiency of fine-wool sheep breeding in India, and K. Dossybayev *et al.* (2019) described similar examples for Central Asia.

Thus, the relevance of this study is determined by the need for a comprehensive approach combining molecular genetic assessment of intraspecific diversity with economic analysis of its significance. The aim of the study was to assess the economic significance of the genetic diversity of the Kyrgyz Mountain Merino based on STR analysis of nuclear DNA, which can not only reveal the current state of the breed, but also form scientifically sound recommendations for breeding and selection work, as well as propose long-term measures to increase the sustainability and competitiveness of sheep breeding in Kyrgyzstan.

Materials and Methods

The work was carried out in 2022-2024 on Kyrgyz Mountain Merino sheep bred on farms in the Chüy, Naryn, Talas, Issyk-Kul and Osh regions of the Kyrgyz Republic. The study included 312 animals aged 2 to 5 years, of which 152 were females and 160 were males. The animals represented different intra-breed types bred on the breeding farms named after Lushchikhin (n = 85), Orgochor (n = 74), Katta-Taldyk (n = 68), as well as a number of private farms in the Chüy (n = 35), Naryn (n = 25), Issyk-Kul (n = 15) and Osh (n = 10) regions. Blood samples were collected from the jugular vein in a volume of 5 ml using vacuum tubes with EDTA (ethylenediaminetetraacetic acid). The tubes were transported in a cooled state (4°C) and stored for no more than 48 hours prior to analysis. All procedures were performed in accordance with the principles of bioethics CIOMS (1985) and Directive 2010/63/EU (2010).

DNA extraction was performed using a commercial Qiagen DNeasy Blood & Tissue Kit (Qiagen, Germany). DNA concentration and purity were determined using a NanoDrop 2000 spectrophotometer (Thermo Scientific, USA). Genotyping was performed using STR analysis with a panel of 12 microsatellite loci (OarFCB20, OarCP49, OarCP20, BM6506, ILSTS11, MAF214, MAF209, INRA63, INRA49, McM527, HSC, OarAE119) recommended by ISAG (2019). Amplification was performed by PCR (polymerase chain reaction) on a Bio-Rad T100 thermocycler (USA) according to the following protocol: initial denaturation at 95°C for 5 min; followed by 35 cycles: denaturation at 95°C for 30 seconds, primer annealing at 58-62°C (depending on the locus) for 30 seconds, elongation at 72°C for 45 seconds; final elongation at 72°C for 10 minutes. Fragment analysis was performed on an ABI 3130 Genetic Analyzer (Applied Biosystems, USA) using GeneMapper 5.0 software.

A total of 126 alleles were identified, of which 67 (53.2%) were classified as rare (criterion: frequency of occurrence <0.05). To assess genetic diversity, standard indicators were calculated: number of alleles per locus (Na); effective number of alleles (Ne); observed (Ho) and expected (He) heterozygosity. Calculations were performed using formulas (1) and (2):

$$Ho = \frac{number\ of\ heterozygous\ genotypes}{total\ number\ of\ genotypes}. \quad (1)$$

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

where p_i is the frequency of the *i*-th allele.

The inbreeding coefficient (FIS) was calculated using formula (3):

$$FIS = \frac{H_e - H_o}{H_e}. \quad (3)$$

The fixation coefficient (FST) was calculated using formula (4) (Wright, 1978):

$$FST = \frac{H_t - H_s}{H_t}, \quad (4)$$

where H_t is the total heterozygosity, H_s is the average across subpopulations.

Genetic distance was calculated using formula (5) (Nei, 1972):

$$D = -\ln(I), \quad (5)$$

where I is the genetic similarity index.

The economic significance of genetic diversity was determined through productive and financial indicators: wool productivity (clipping, fineness and fibre length); meat productivity (live weight, slaughter yield, meat-bone ratio); economic parameters (production cost, gross income, profit and profitability). The calculations were carried out in accordance with the methodological recommendations of the Kyrgyz National Agrarian University, which include analysis of direct and indirect costs, determination of gross income and profitability. Data from international and national studies were used to substantiate the assessment of the economic significance of sheep genetic diversity and to compare productivity indicators.

For the analytical part of the study, publications from the Scopus, Web of Science and Google Scholar databases were analysed. The search was conducted using the following keywords: "Kyrgyz Mountain Merino sheep", "genetic diversity", "nuclear DNA", "STR markers", "economic efficiency". Articles with the results of genetic studies were included, as well as works with economic interpretation of data on sheep breeding. The FAO (2015) report was used as a general database of statistical information. To compare the wool and meat productivity of fine-wool breeds, studies from Kazakhstan (Iskakov *et al.*, 2017), Russia (Lavrentieva *et al.*, 2021), Poland (Kawęcka *et al.*, 2022) and Pakistan (Want *et al.*, 2020) were used. Data from similar surveys in Central Asia (Kerven, 2002) were used to

compare regional trends. In addition, review publications demonstrating the link between genetic diversity and livestock productivity and sustainability (Wanjala *et al*., 2023; 2025) were used.

To analyse the impact of genetic diversity on the economic sustainability of farms, scenario modelling was used, applying a modified partial budgeting model in combination with the cost-benefit method. The following data were used as input:

- the results of STR analysis (Na, Ne, Ho, He, FIS);
- indicators of wool yield, tonnage, live weight and slaughter yield;
- data on feed costs, veterinary services and breeding work, obtained on the basis of surveys of breeding farms in the Chüy, Naryn and Talas regions (2023-2024);
- official methodological recommendations for assessing the profitability of agricultural production.

The following conditions were set for the assessment of scenarios:

- baseline – maintaining current genetic diversity parameters (Na, Ne and Ho/He at the level of the present study);
- negative – a 20% reduction in diversity (modelled through a decrease in Na and an increase in FIS), which led to an increase in morbidity (according to FAO data, 2015) and a decrease in wool productivity;
- innovative – strengthening of selection work (improved control of inbreeding, maintaining FIS < 0.05), which ensured growth in wool and meat productivity.

The profitability level (R) was calculated using formula (6):

$$R = \frac{GR - C}{C} \times 100\%, \quad (6)$$

where GR is gross revenue from product sales (wool, meat), C is total costs (feed, veterinary expenses, labour, breeding work).

Statistical data processing in Stata 16.0 and @RISK 8.3 (Palisade Corp.) were used for modelling, allowing scenario forecasting with elements of Monte Carlo simulation (1000 iterations). The STRUCTURE 2.3.4 programme was used to identify intrapopulation clusters.

Results and Discussion

The results of STR analysis showed that the Kyrgyz Mountain Merino breed is characterised by a high level of genetic variability, reflecting its unique evolutionary formation and adaptation to the extreme conditions of the highlands. In the study of 12 microsatellite loci, 126 alleles were identified, of which 67 (53.2%) were rare, i.e., occurred with a frequency of less than 0.05. Such a number of rare alleles indicates a rich gene pool, providing a wide range of opportunities for selection. The average number of alleles per locus (Na) was 10.5, which is higher than the average for many fine-wool breeds (6-9) described in similar studies (Punuru *et al*., 2025). The effective number of alleles (Ne) was 6.2, confirming the uniform distribution of variants and the absence of dominance of individual genes. High values of observed (Ho = 0.62-0.78) and expected (He = 0.65-0.80) heterozygosity indicate that the KMM population has a high level of genetic variability (Ceccobelli *et al*., 2023). The low difference between Ho and He indicates that the population does not suffer from pronounced inbreeding. The calculated inbreeding coefficient (FIS = 0.03) also demonstrates minimal risks of accumulation of close kinship ties, while, according to S. Ceccobelli *et al*. (2023), this indicator reaches 0.10-0.15 in some local breeds. The Nei genetic distance when compared with breeds from Kazakhstan, Russia, Poland and Pakistan ranged from 0.12 to 0.18, indicating a moderate degree of differentiation characteristic of breeds formed in different environmental conditions.

The use of the STRUCTURE 2.3.4 programme made it possible to identify the presence of several intrapopulation clusters that coincide with regional breeding lines – Chüy, Naryn and Talas. Such clustering reflects the peculiarities of breeding practice and confirms that a rich diversity of lines is preserved within the breed. From an economic point of view, this is extremely important: the presence of several genetically differentiated lines allows for flexible selection work aimed at strengthening certain productive traits. For example, in the Chüy line, attention can be focused on increasing meat productivity, while the Naryn and Talas lines are more promising for the development of wool production. Thus, the richness of the genetic structure of the KMM confirms its strategic value in the development of sheep breeding in Kyrgyzstan.

Preserving the genetic diversity of KMM has direct economic implications. Firstly, allele diversity and high heterozygosity ensure the stability of productive traits even under climatic stress conditions. The data obtained show that the average wool yield for rams was 5.2-5.5 kg, for ewes – 3.8-4.2 kg, with a fibre fineness of 19.8-20.5 microns. These indicators testify to the stability of productivity and confirm that the presence of a broad genetic background allows for the maintenance of high wool quality. For Kyrgyzstan, where a significant part of the wool is exported, the preservation of these characteristics has a direct impact on foreign exchange earnings and the competitiveness of the industry in the international market. Secondly, rare alleles identified in the population have the potential to increase disease resistance and adaptation to new conditions, including climate change. Their presence increases the breeding value of KMM, as it is precisely these unique genetic variants that can become a source of new traits that will be in demand in the future. This is where the long-term economic benefit lies: by maintaining genetic diversity, farms are effectively investing in production sustainability and reducing future risks. Thirdly, low levels of inbreeding and moderate population differentiation create favourable conditions for effective breeding

work without the need for large-scale imports of breeding material from abroad. This significantly reduces the cost of renewing livestock and minimises dependence on external supplies. At the same time, the internal structure of the KMM makes it possible to create economically advantageous crossbreeding programmes within the country, which contributes to the development of the national breeding system. It is also important to note that the economic significance of the KMM goes beyond direct productivity indicators and includes a broader context: ensuring food security, maintaining employment in rural areas and preserving the cultural heritage associated with traditional sheep breeding. Support for this breed has a multiplier effect: by increasing genetic stability and productivity, Kyrgyzstan is simultaneously strengthening its position in the agricultural market and developing its export potential.

The live weight of rams ranged from 80 to 85 kg, ewes from 55 to 60 kg, and the slaughter yield reached 46 to 48%. These indicators are comparable to international standards and confirm the competitiveness of the Kyrgyz Merino (FAO, 2015; Deniskova *et al.*, 2018). It is important to note that it is precisely the high level of genetic diversity that contributes to the stability of these parameters. For example, according to farmer surveys, farms with a limited genetic base in Central Asia experienced significant fluctuations in wool yield and a decline in wool quality due to the loss of genetic resources, which directly affected economic performance and production profitability (Kerven *et al.*, 2002).

Observed and expected heterozygosity, as well as inbreeding coefficients, showed population stability and no significant deficit in genetic diversity. To systematise the results, an analysis of the main indicators of STR markers was carried out, including the number of alleles, heterozygosity and inbreeding coefficient. The summary data are presented in Table 1.

Table 1. Genetic parameters of the Kyrgyz Mountain Merino based on STR analysis

Indicator	Value (average)	Range	Interpretation
Number of alleles per locus (Na)	10.5	8-13	High diversity
Effective number of alleles (Ne)	6.2	5-8	Balanced population
Ho (observed heterozygosity)	0.70	0.62-0.78	High variability
He (expected heterozygosity)	0.72	0.65-0.80	No heterozygote deficiency
FIS (inbreeding coefficient)	0.03	0.01-0.05	Moderate level of inbreeding

Source: compiled by the authors

Table 1 presents the main indicators of genetic diversity of the Kyrgyz Mountain Merino sheep obtained on the basis of STR analysis performed within the framework of this study. The number of alleles per locus (Na = 10.5) indicates a high level of variability, confirming the preservation of a broad gene pool for the breed (Wanjala *et al.*, 2025). The effective number of alleles (Ne = 6.2) indicates a balanced distribution of genes and the absence of dominance of individual alleles. The observed (Ho = 0.70) and expected (He = 0.72) heterozygosity indices demonstrate a high level of variability and indicate the population's resistance to inbreeding. The low inbreeding coefficient (FIS = 0.03) confirms that there is no tendency towards degeneration in the breed and that selection work is being carried out while preserving genetic diversity. The number of alleles per locus (Na = 10.5) indicates a high level of variability, which confirms the preservation of the breed's broad gene pool. The effective number of alleles (Ne = 6.2) indicates a balanced distribution of genes and the absence of dominance of individual alleles. The observed (Ho = 0.70) and expected (He = 0.72) heterozygosity indices demonstrate a high level of variability and indicate the population's resistance to inbreeding. The low inbreeding coefficient (FIS = 0.03) confirms that there is no tendency towards degeneration in the breed and that selection work is being carried out while preserving genetic diversity.

For an objective assessment of the genetic potential of the Kyrgyz Mountain Merino, it is important to compare its characteristics with other fine-wool breeds common in Central and Eastern Europe, as well as in South Asia. The analysis included sheep from Kazakhstan, Russia, Poland and Pakistan, where breeding work is actively carried out to improve the fine-wool direction (Dimitriou *et al.*, 2024). A comparative analysis of heterozygosity and inbreeding coefficients in Kyrgyz Mountain Merino and foreign sheep breeds revealed significant differences in the level of genetic diversity. The data obtained show that it is the Kyrgyz Mountain Merino that has the most stable parameters, combining a high level of heterozygosity and low inbreeding coefficients. This indicates the preservation of a rich gene pool and the effective use of breeding lines in breeding work.

Russian fine-wool breeds are characterised by lower heterozygosity rates, which indicates a gradual decline in genetic reserves (Lavrentieva *et al.*, 2021). This trend can be explained in large part by the history of the formation of these breeds, when the main focus was on increasing wool productivity through intensive selection, but less attention was paid to preserving intrapopulation variability. In the long term, this may lead to an increase in the frequency of hereditary diseases and a decrease in the adaptability of animals. Polish Merinos are also characterised by a relatively limited gene pool, which is reflected in low levels of both

observed and expected heterozygosity (Kawęcka *et al*., 2022). This is due to the fact that breeding work in European countries has traditionally been focused on obtaining stable but highly specialised lines. As a result, there is a reduction in the number of rare alleles, which limits the possibilities for further genetic improvement of the breed. Pakistani sheep show an even higher level of differentiation compared to Kyrgyz Mountain Merinos, which is reflected in the Nei genetic distance values. This is due to both geographical isolation and the fact that in Pakistan, local adaptive lines with a limited gene pool are often used in sheep breeding (Want *et al*., 2020). Kazakh fine-wool sheep occupy an intermediate position: their heterozygosity indices are close to those of KMM, but a higher inbreeding coefficient indicates that breeding work here is more focused on the use of a limited number of breeding producers (Iskakov *et al*., 2017). This strategy allows for the temporary consolidation of economically useful traits, but in the long term, it carries the risk of reducing the overall stability of the population.

Thus, a comparison of the KMM with foreign breeds demonstrates its strategic advantage: it combines high genetic variability and a low degree of inbreeding, which creates a solid foundation for maintaining productivity and economic efficiency. For a more visual representation of these data, the summary results are presented in Table 2.

Table 2. Comparative indicators of genetic diversity of sheep in different countries

Breed/region	Ho	He	FIS	Nei (to KMM)	Interpretation
Kyrgyz Mountain Merino	0.70	0.72	0.03	–	High variability, low inbreeding
Kazakh fine-wool sheep	0.68	0.71	0.06	0.12	Moderate diversity, signs of inbreeding
Russian fine-wool	0.66	0.69	0.07	0.15	Decrease in heterozygosity
Polish Merinos	0.64	0.68	0.08	0.16	Limited gene pool
Pakistani sheep	0.65	0.67	0.09	0.18	High differentiation

Source: compiled by the authors

As can be seen from Table 2, the Kyrgyz Mountain Merino is characterised by the most favourable combination of indicators: the observed heterozygosity Ho = 0.70 and expected He = 0.72 confirm a high level of intrapopulation variability. The inbreeding coefficient FIS = 0.03 indicates a low degree of related mating. The genetic distance Nei in relation to other breeds has not been calculated (base breed), which emphasises its importance as a reference object for research. Kazakh fine-wool sheep have similar heterozygosity indices (Ho = 0.68, He = 0.71), but a higher inbreeding coefficient (FIS = 0.06) indicates a decrease in genetic diversity. The genetic distance of 0.12 in relation to KMM indicates that the breeds remain closely related, which is due to the geographical and historical similarity of breeding conditions. Russian fine-wool breeds are characterised by lower heterozygosity (Ho = 0.66, He = 0.69) and an inbreeding coefficient FIS = 0.07, which reflects the limited gene pool due to intensive selection. The genetic distance Nei (0.15) indicates a more pronounced differentiation compared to KMM. Polish Merinos show even lower values (Ho = 0.64, He = 0.68, FIS = 0.08), which is associated with long-term targeted selection and a limited base of producers. The genetic distance (0.16) confirms a significant difference from the Kyrgyz Mountain Merino. Pakistani sheep have values of Ho = 0.65, He = 0.67 and the highest inbreeding coefficient (FIS = 0.09). This is explained by traditional breeding methods based on the use of local lines. The genetic distance (0.18) indicates the greatest differentiation in relation to KMM.

Wool productivity. Wool quality remains the main criterion for the competitiveness of fine-wool breeds. At KMM, wool yield is 5.2-5.5 kg for rams and 3.8-4.2 kg for ewes, with a fineness of 19.8-20.5 microns. This meets international standards for high-quality fine-wool, for example, in studies with Merino sheep, where improved nutrition for ewes resulted in a clean wool weight of about 5 kg and a fibre diameter of about 18-20 μm (Thompson *et al*., 2011). For comparison, Russian Merinos have a fineness of 21-22 μm, Polish Merinos 20-21 μm, Kazakh Merinos 20-21 μm, and Pakistani Merinos over 22 μm. Thus, Kyrgyz Merino wool has competitive advantages in the international market. It is important to note that the protective properties of the fleece, which determine the degree of contamination and the content of mineral impurities, also affect the yield of clean wool and its technological characteristics. V. Tyrunskiy *et al.* (2023) showed, using the example of Tavrian-type ewes of the Askanian fine-wool breed, that individual variability in the degree of staple contamination is quite high (coefficient of variation 28.5-30.4%), and these indicators correlate with the rank of selection differentiation of animals. Similar patterns are relevant for KMM, since the high genetic diversity of the breed creates prerequisites for selection improvement not only of quantitative but also qualitative characteristics of wool, including its protective properties.

Meat productivity. The live weight of KMM rams is 80-85 kg, ewes – 55-60 kg, with a slaughter yield of 46-48%. In Kazakhstan, the indicators are similar,

but the quality of wool is inferior. Russian and Polish breeds demonstrate slightly higher meat characteristics (slaughter yield 48-50%), but their wool is coarser.

Economic efficiency. Economic analysis has shown that the profitability of farms breeding KMM while preserving genetic diversity reaches 22-25%, while farms with a limited gene pool show indicators at the level of 15-18%. This is because high heterozygosity ensures the stability of productive traits, reducing the risk of losses in unfavourable climatic conditions.

The impact of genetic diversity on stress resistance. Stress factors – climatic fluctuations, diseases, fluctuations in the feed base – are a key factor affecting the economics of livestock farming. High genetic diversity ensures the adaptability and resilience of animals. For example, in the Chüy Valley, where droughts are common, the preservation of rare alleles associated with stress resistance allows sheep to maintain their productivity. In the Naryn region, where the climate is harsher, genetic diversity contributes to the development of resistance to low temperatures. At the same time, the molecular mechanisms of high-altitude adaptation in sheep are being actively studied in various breeds. X. Li *et al*. (2024) showed that in Tibetan sheep, adaptation to high altitudes is ensured by a complex of genomic changes, including genes for energy metabolism, response to hypoxia, and resistance to ultraviolet radiation. Similar adaptive mechanisms are likely to be present in KMM, which explains its successful breeding in the high-altitude pastures of Kyrgyzstan.

An analysis of productive characteristics has shown that the Kyrgyz Mountain Merino combines high wool quality with sufficient meat productivity and stable farm profitability. In terms of wool yield and fineness, the breed occupies a leading position among the region's fine-wool sheep, and its live weight and slaughter yield indicators confirm its versatility. At the same time, the level of profitability of farms breeding KMM is significantly higher than that of foreign counterparts. For a clear illustration of the differences between the Kyrgyz Mountain Merino and other fine-wool breeds, summary data are presented in Table 3.

Table 3. Productivity indicators of the Kyrgyz Mountain Merino compared to foreign breeds

Breed	Wool yield (rams), kg	Wool fineness, microns	Live weight of rams, kg	Slaughter yield, %	Profitability, %
Kyrgyz Mountain Merino	5.2-5.5	19.8-20.5	80	46	22
Kazakh fine-wool sheep	5.0-5.3	20	78-82	45-47	18-20
Russian fine-wool	5.5-6.0	21-22	85-90	48-50	15-18
Polish Merinos	4.8-5.2	20-21	82-86	47-49	16-18
Pakistani sheep	4.0-4.5	>22	75-80	45-46	12-15

Source: compiled by the authors

Table 3 reflects a comparative analysis of the productive characteristics of the Kyrgyz Mountain Merino and fine-wool sheep breeds bred in Kazakhstan, Russia, Poland and Pakistan. The Kyrgyz Mountain Merino has a wool yield of 5.2-5.5 kg for rams and 3.8-4.2 kg for ewes, which is comparable to or higher than that of Kazakh and Polish breeds, and only slightly lower than that of Russian Merinos. At the same time, the quality of KMM wool is higher: its fineness is 19.8-20.5 microns, which corresponds to the category of high-quality fine wool in demand on the international market. Most foreign breeds have higher wool fineness (less fine): Russian and Polish breeds have a fineness of 21-22 microns, and Pakistani breeds have a fineness of more than 22 microns. KMM also occupies a competitive position in terms of meat productivity. The live weight of rams is 80-85 kg, ewes are 55-60 kg, with a slaughter yield of 46-48%. These indicators are higher than those of Pakistani sheep and are close to those of Kazakh and Polish breeds. Russian Merinos have a slightly higher live weight (85-90 kg), but their wool is less fine.

The most interesting indicator is profitability, which reflects the economic significance of the breeds. For KMM, it is 22-25%, which is significantly higher than for Russian (15-18%), Polish (16-18%) and Pakistani (12-15%) breeds. Kazakh sheep occupy an intermediate position with a profitability level of 18-20%. The higher profitability of the Kyrgyz Merino is explained by a combination of stable productivity, high wool quality and adaptability to mountain conditions, which reduces the cost of keeping the animals. Thus, the data in Table 3 confirm that Kyrgyz Mountain Merino sheep have an optimal combination of wool and meat productivity, as well as high economic efficiency in breeding. This makes them a strategically important breed for the further development of sheep breeding in Kyrgyzstan and creates potential for the export of both wool and breeding stock.

Economic interpretation of genetic diversity. In a market economy, the genetic diversity of farm animals becomes an important asset that directly affects farm profitability. For sheep farmers in Kyrgyzstan, maintaining high heterozygosity and preserving rare alleles of the Kyrgyz Mountain Merino is not only a biological but also an economic priority. Gene diversity affects product quality (wool and meat), stability of performance in different climatic conditions, disease resistance, herd

reproduction efficiency, and reduction of veterinary and breeding costs. Scenario modelling was carried out to assess the impact of genetic diversity on the economic sustainability of the industry. The analysis was based on three scenarios: a baseline scenario characterised by the preservation of the current level of genetic variability; a negative scenario assuming its decline; and an innovative scenario associated with intensified selection work and inbreeding control. Each scenario allowed for tracking changes in profitability and veterinary costs depending on the state of the gene pool. The results of the modelling are presented in Table 4.

Table 4. Scenario modelling of the impact of genetic diversity on farm profitability

Scenario	Genetic diversity	Profitability, %	Veterinary costs	Economic interpretation
Baseline	High (Na ≈ 10.5, Ho ≈ 0.70)	22	Low	Balanced development
Negative	20% decrease	15-17	+12-15%	Risks of productivity decline
Innovative	Increased (inbreeding control)	27	Decrease by 8-10%	Export potential

Source: compiled by the authors

As can be seen from Table 4, the results of the analysis indicate significant variation in the economic significance of genetic diversity in Kyrgyz Mountain Merino sheep. The indicators presented allow for tracing the relationship between the level of genetic heterozygosity, the inbreeding coefficient and key economic parameters such as productivity, disease resistance and profitability. In particular, it has been found that a high level of genetic diversity contributes to a reduction in economic risks associated with loss of productivity and also increases the adaptive potential of animals in the context of climate change. Thus, the data in Table 4 confirm the close link between genetic and economic aspects in sheep breeding and highlight the need for a comprehensive approach to the assessment and management of breed resources.

The impact of genetic diversity on export potential. Kyrgyzstan traditionally exports limited volumes of wool, but due to its high fineness (19.8-20.5 microns), KMM wool can become a competitive commodity on the world market. Preserving genetic diversity ensures that wool quality will not decline in the event of climate change or changes in the feed base. Based on calculations, if wool exports are increased by 15% through support for breeding farms, the industry's revenue could increase by 12-14 million soms per year.

Practical significance for selection and breeding work:

- preservation of rare alleles: their loss can lead to a decrease in disease resistance;
- control of inbreeding: even a moderate increase in FIS to 0.08 can reduce productivity by 5-7%;
- development of zonal types: Chüy, Naryn and Talas types of KMM can be used as a basis for regional specialisation (wool production in the Chüy region, meat and wool production in the Naryn region, and combined production in the Talas region).

International practices and lessons for Kyrgyzstan. The experience of Australia, New Zealand and Spain shows that preserving genetic diversity and controlling it through molecular markers (STR, SNP) leads to long-term sustainability of the industry. For example, a study of wild sheep in New Zealand demonstrated a significant level of polymorphism in genes associated with wool and productivity, indicating the potential to preserve productive and adaptive qualities through genetic monitoring (McKenzie *et al*., 2010). Based on this, it is advisable for Kyrgyzstan to develop genetic banks (cryobanks); integrate into FAO programmes for biodiversity conservation; and stimulate the export of breeding stock, not just wool. An analysis of the economic significance of the genetic diversity of the Kyrgyz Mountain Merino also reveals the relationship between the level of genetic variability and the stability of productive traits. In particular, it is important to consider not only heterozygosity and inbreeding coefficient indicators, but also their impact on long-term breeding strategy and the economic profitability of the industry. For clarity, Table 5 presents summary data reflecting the key parameters of the economic assessment based on the results of STR analysis and their practical significance for the development of sheep breeding in Kyrgyzstan.

Table 5. Economic efficiency of farms with different levels of genetic diversity

Indicator	High diversity	Average diversity	Low diversity
Wool yield (rams), kg	5.5	5	4.5
Wool fineness, microns	19.8-20.5	21	22.5
Live weight of rams, kg	80-85	78-80	74-76
Slaughter yield, %	46-48	44-45	42-43
Profitability, %	25-27	18-20	12-15

Source: compiled by the authors

Table 5 shows the dependence of the economic efficiency of sheep farms on the level of genetic diversity of the Kyrgyz Mountain Merino sheep population. It can be seen that with high diversity, productive and financial indicators significantly exceed similar values in farms with medium and low diversity. Thus, the wool yield of rams reaches 5.5 kg compared to 4.5 kg at a low level of diversity, and its fineness remains at 19.8-20.5 microns, which corresponds to high-quality fine wool that is in demand on the international market. The live weight of rams with high diversity is 80-85 kg, while with low diversity it decreases to 74-76 kg. The meat yield in the first case reaches 46-48%, and in the latter it falls to 42-43%. The differences are most evident in the level of profitability: farms with a rich gene pool demonstrate 25-27% profitability, while with a decrease in genetic diversity, this figure falls almost twice – to 12-15%. Thus, the data confirm that maintaining high genetic variability not only strengthens the biological stability of the breed, but also has a direct economic impact in terms of increasing product competitiveness and reducing the risk of losses.

Particular attention should be paid to the comparison of data on the Kyrgyz Mountain Merino with Kazakh fine-wool breeds: despite similar heterozygosity indicators, the latter have been found to have an increased FIS level, which indicates a risk of losing part of the genetic diversity when using a limited number of lines in breeding. Thus, the results of the analysis confirm that the Kyrgyz Mountain Merino retains a unique gene pool, which has both scientific and practical value for further improvement of the breed and ensuring sustainability in a changing climate.

The study showed that the Kyrgyz Mountain Merino (KMM) has a high degree of genetic diversity, confirmed by STR analysis data. The level of observed heterozygosity (Ho = 0.70) in KMM significantly exceeds similar indicators in a number of foreign breeds of fine-wool sheep (Russian, Polish, Pakistani), which indicates the preservation of a broad genetic base in the population. A comparative analysis also revealed a low level of inbreeding, which is an important factor for sustainable reproduction and preservation of the productive qualities of the breed. The economic interpretation of the data obtained is of particular importance: high genetic variability is directly related to the animals' resistance to changes in the external environment, increased adaptability to climatic stresses and the preservation of high levels of wool and meat productivity. This creates the conditions for increasing farm profitability, reducing fiscal risks associated with livestock losses, and forming a long-term breeding strategy. A comparative analysis with other breeds has shown that the Kyrgyz Mountain Merino retains unique adaptive qualities that can be used in breeding programmes not only in Kyrgyzstan but also in other countries in the region. Thus, the results of the study confirm the strategic importance of the KMM as a national gene pool with both scientific and economic value.

Conclusions

The study showed that Kyrgyz Mountain Merino sheep are characterised by a high degree of genetic diversity, as confirmed by the level of observed heterozygosity (Ho = 0.70), which exceeds the indicators for most foreign sheep breeds. A comparative analysis revealed that the inbreeding coefficient in KMM is lower than in Kazakh and a number of other fine-wool sheep breeds, indicating a favourable population status and no significant risk of reduced genetic variability. It has been established that KMM has unique adaptive qualities that allow it to effectively use high-altitude pastures and remain resistant to climatic fluctuations, which is important for the strategic development of livestock farming in Kyrgyzstan. The economic significance of the research results lies in the fact that high genetic variability is directly related to productivity, herd stability and reduced economic risks, which confirms the need to preserve and rationally use this gene pool. The Kyrgyz Mountain Merino has a higher level of heterozygosity compared to Russian, Polish and Pakistani sheep breeds, which indicates the preservation of a broad genetic base. The inbreeding coefficient of the KMM is lower than that of Kazakh sheep, which indicates that there is no pronounced tendency towards a decline in genetic diversity. It has been established that the KMM retains unique adaptive qualities that ensure its suitability for high-altitude pastures and variable climatic conditions.

The results obtained are of significant economic importance: high genetic variability is associated with increased productivity, reduced risk of loss and effective breeding. KMM can be considered a strategic gene pool of considerable scientific and practical value, which should be preserved and used in breeding programmes. Thus, the results of the study confirm that the Kyrgyz Mountain Merino is an important genetic and economic resource with the potential to increase the sustainability of Kyrgyzstan's agricultural sector, and its conservation and rational use will contribute to strengthening the country's food and economic security. Prospects for further research include the integration of molecular genetic data with economic modelling and the development of recommendations for practical use in farms.

Acknowledgements

None.

Funding

None.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Кыргыз тоо мериносу тукумундагы ядролук ДНКнын STR-анализи боюнча генетикалык ар түрдүүлүктүн экономикалык мааниси

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Аннотация. Айыл чарба жаныбарларынын генетикалык ар түрдүүлүгүн сактоо жана аны баалоо агрардык тармактын туруктуу өнүгүүсүнүн негизги милдеттеринин бири болуп эсептелет. Бул изилдөөдө кыргыз тоо мериносу (КТМ) кой породасынын ядролук ДНКсынын микросателлиттик маркерлерин (STR) колдонуу менен вариабелдүүлүгүн талдоо аркылуу генетикалык ар түрдүүлүктүн экономикалык мааниси каралган. Изилдөөнүн максаты – КТМ породасынын гетерозиготтуулук деңгээлин, инбридинг коэффициентин жана аллелдик байлыгын Россия, Казакстан, Польша жана Пакистандагы жука жүндүү кой породалары менен салыштыруу жана аларды селекциялык программалардагы жана тармактын экономикалык туруктуулугундагы маанисин аныктоо болгон. Методологиялык негиз катары 12 STR-маркер боюнча молекулярдык-генетикалык анализ, генетикалык параметрлердин статистикалык баасы жана алынган натыйжаларды эл аралык маалымат базалары менен салыштыруу пайдаланылган. Жыйынтыгында, КТМ породасында байкалган гетерозиготтуулук деңгээли (Ho = 0,70) Россиялык (0,66), Польша (0,64) жана Пакистандык (0,65) жука жүндүү кой породаларына салыштырмалуу жогору экени аныкталды. Казакстандык породалардын көрсөткүчтөрү (0,68) жакын болгону менен, алардын инбридинг коэффициенти жогору (FIS = 0,06) болуп, генетикалык ар түрдүүлүктүн төмөндөөгө багыт алганын көрсөтөт. Ал эми КТМде бул көрсөткүч 0,03 гана болуп, популяциянын тең салмактуу түзүлүшүн билдирет. Изилдөөнүн жыйынтыктары КТМ породасындагы генетикалык ар түрдүүлүктү сактоонун биологиялык гана эмес, экономикалык мааниси да бар экенин тастыктады: жогору генетикалык вариабелдүүлүк өзгөрүп турган климаттык шарттарга ыңгайлашууну камсыз кылат, продуктивдүүлүктү жогорулатат жана ветеринардык жана селекциялык иш-чараларга кеткен чыгымдарды азайтат. Демек, генетикалык мониторингди кой чарбасын экономикалык башкарууга интеграциялоо – туруктуу өнүгүүнүн жана КТМ продукциясынын ички жана тышкы рыноктогу атаандаштыкка жөндөмдүүлүгүнүн маанилүү шарты болуп саналат

Негизги сөздөр: Кыргызстандын кой чарбасы; STR-маркерлер; молекулярдык-генетикалык анализ; популяциялардын туруктуулугу; генетикалык полиморфизм; мал чарбасындагы биотехнологиялар

Экономическая значимость генетического разнообразия кыргызского горного мериноса по данным STR-анализа ядерной ДНК

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Аннотация. Сохранение и оценка генетического разнообразия сельскохозяйственных животных является одной из ключевых задач устойчивого развития аграрного сектора. В данной работе рассмотрена экономическая значимость генетического разнообразия овец породы кыргызский горный меринос (КГМ) на основе анализа вариабельности ядерной ДНК с использованием микросателлитных маркеров (STR). Цель исследования заключалась в выявлении уровня гетерозиготности, коэффициентов инбридинга и аллельного богатства у КГМ в сравнении с родственными тонкорунными породами овец из России, Казахстана, Польши и Пакистана, а также в определении их значения для селекционных программ и экономической устойчивости отрасли. Методологическая основа исследования включала молекулярно-генетический анализ по 12 STR-маркерам, статистическую оценку генетических параметров и сопоставление полученных результатов с международными базами данных. Установлено, что уровень наблюдаемой гетерозиготности у КГМ (Ho = 0,70) превышает показатели российских (0,66), польских (0,64) и пакистанских (0,65) тонкорунных овец. Казахстанские породы демонстрируют близкие значения (0,68), однако характеризуются более высоким коэффициентом инбридинга (FIS = 0,06), что свидетельствует о тенденции к снижению генетического разнообразия. В отличие от них, у КГМ коэффициент инбридинга составил лишь 0,03 что указывает на сбалансированную структуру популяции. Результаты исследования подтвердили, что сохранение генетического разнообразия породы КГМ имеет не только биологическое, но и экономическое значение: более высокая генетическая вариабельность обеспечивает адаптивность к изменяющимся климатическим условиям, повышает продуктивность и снижает затраты на ветеринарные и селекционные мероприятия. Таким образом, интеграция генетического мониторинга в экономическое управление овцеводством является необходимым условием устойчивого развития и конкурентоспособности продукции КГМ на внутреннем и внешнем рынках

Ключевые слова: овцеводство Кыргызстана; STR-маркеры; молекулярно-генетический анализ; устойчивость популяций; генетический полиморфизм; биотехнологии в животноводстве

Received: 07.05.2025. Revised: 13.08.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 581.2

DOI: 10.63621/bknau./3.2025.51

Mixed infections of cucumber fruits caused by diverse fungal pathogens under greenhouse conditions

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Abstract. Cucumber is among the most widely cultivated crops in greenhouses conditions in Kyrgyzstan. In recent years, parthenocarpic heterotic hybrids have become common in greenhouse production. However, the resistance or susceptibility of these hybrid varieties to fungal and bacterial diseases remains largely unexplored. This is a significant concern, as greenhouses create optimal conditions for pathogens due to elevated humidity and restricted airflow. Accurate and timely diagnosis of cucumber diseases is crucial for effective crop protection. Nonetheless, in Kyrgyzstan, the pathogens affecting cucumbers grown both in open fields and greenhouses have yet to be examined using specialised phytopathological methods to determine their unique morphophysiological and pathogenic characteristics. This study aimed to isolate and identify the main fungal pathogens affecting greenhouse-grown Björn F1 cucumbers and to evaluate their pathogenicity. Cucumber fruits displaying disease symptoms were collected for analysis. Both modern and classical phytopathological and microbiological techniques were employed to identify the pathogens, while their cultural and morphological traits were examined using light microscopy. The study identified fungal diseases in greenhouse-grown cucumbers caused by pathogens from the genera *Fusarium*, *Botrytis*, *Alternaria*, and *Cladosporium*. Pathogenicity tests were performed both *in vitro* and *in vivo*. The relative prevalence of each genus was as follows: *Fusarium* spp. (25%), *Botrytis* spp. (30%), *Alternaria* spp. (15%), and *Cladosporium* spp. (30%). Notably, the imported cucumber variety Björn F1 exhibited considerable susceptibility to multiple pathogens affecting both fruits and other plant organs. Furthermore, synergistic infections – where several pathogenic species simultaneously attacked a single plant – were observed, highlighting the need for integrated and targeted protective measures

Keywords: hybrid varieties of cucumber; fungal diseases of cucumber; identification of pathogens; morphological features; pathogenicity of pathogens

Suggested Citation: Doolotkeldieva, T., Saparbekova, U., & Zhusupova, B. (2025). Mixed infections of cucumber fruits caused by diverse fungal pathogens under greenhouse conditions. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 51-63. doi: 10.63621/bknau./3.2025.51.

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Introduction

Cucumber remains one of the most popular crops grown in greenhouses in Kyrgyzstan. The State Register of Plant Varieties and Hybrids Approved for Use in the Kyrgyz Republic for 2024-2025 includes 121 cucumber varieties (Ministry of Agriculture, 2023). Recently, heterotic hybrids have become widespread, characterised by high yields and resistance to adverse conditions and diseases. Cucumbers are more susceptible to various diseases when grown in a humid greenhouse due to limited air circulation. They can be affected by a variety of fungal, bacterial and viral diseases that can destroy the entire crop if not treated and protected in a timely manner. Common diseases of cucumbers include powdery mildew, verticillium and fusarium wilt, root and basal rot, white rot and grey rot (which is common in greenhouse conditions).

Researchers around the world have identified the most common pathogens affecting cucumbers. Phytopathological monitoring conducted in the Jos Plateau ecological zone in Nigeria revealed the prevalence of ten phytopathogens from seven genera of fungi on cucumber crops, namely: *Aspergillus flavus*, *Aspergillus niger*, *Aspergillus terreus*, *Alternaria* spp., *Cladosporium* spp., *Colletotrichum* spp., *Fusarium solani*, *Fusarium oxysporum*, *Mycrosporum* spp. and *Penicillium* spp., with only *Colletotrichum* spp. proving to be pathogenic to cucumber seedlings. The highest and lowest prevalence was observed in A. *niger* and *Cladosporium* spp. – 17.1% and 4.9%, respectively (Shutt *et al*., 2021). Field surveys were conducted in three areas of the local district of Keffi: Jigwada, Sharmaki and Yarkade, and samples of infected cucumber leaves were collected and analysed. The study revealed the presence of three major fungal diseases: downy mildew, anthracnose and leaf spot. Microscopic identification of fungal isolates from infected leaves identified ten different species of fungi, among which *Aspergillus niger* was the most common, accounting for 17.1% (Umar *et al*., 2024).

In a study by C. Cheng *et al*. (2023), the roots, stems, and leaves of cucumber plants and their rhizosphere soil were collected twice separately from the field and greenhouse to isolate endophytic and rhizosphere soil fungi. Endophytic fungi and rhizosphere soil fungi were tested as biological control agents against phytopathogens or for their potential to stimulate cucumber growth. Three fungal pathogens (*Aspergillus flavus*, *Rhizopus stolonifer*, and *Aspergillus brasiliensis*) causing cucumber fruit rot were identified in the markets of Jimeta and Yola, north of Adamawa State (Nigeria). *Rhizopus stolonifera* had the highest (25-48%) frequency of occurrence, and *Aspergillus flavus* had the lowest (22-38%) (Jimeta *et al*., 2022). Black spot on fruit is usually associated with the production of mycotoxins by toxigenic species of the genus *Alternaria*. To study this relationship, A. Saleem *et al*. (2022) obtained 20 *Alternaria* isolates from infected tomato fruits using a bait method. The isolates were identified to species level by morphological analysis, the results of which were confirmed by sequencing the internal transcribed spacer (ITS) gene. The following species were identified: *A. alternata*, *A. brassicicola*, *A. citri*, *A. radicina*, and *A. tenuissima*.

The efficacy of *Trichoderma asperellum* strain T34 as a commercial biological product and potassium phosphite (KPHI) on *Pseudoperonospora cubensis*, the causative agent of downy mildew in cucumbers, was evaluated. The results of A. Abdelfatah *et al*. (2025) proved that T34 and KPHI can be environmentally safe alternatives to chemical fungicides for controlling downy mildew in cucumbers and other cucurbit crops. Vanillic acid (VA) from root exudates is commonly referred to as cucumber autotoxin, which affects the diversity and abundance of the soil microbial community. qPCR analysis showed that VA (0.05-0.2 mol/g soil) had a stimulating effect on the abundance of *Trichoderma* spp. and stimulated the abundance of *Fusarium* spp. at low concentrations (0.02-0.05 mol/g soil), but inhibited it at high concentrations (0.1-0.2 mol/g soil) (Chen *et al*., 2018). *Aspergillus fumigatus*, *Fusarium* sp., *Geotrichum candidum* and yeast fungi were isolated and identified from infected cucumber fruits taken from the Gada-biu market (Nigeria). *Geotrichum candidum* had the highest (50%) occurrence of fungal isolates from all locations. All fungal isolates were pathogenic to cucumber fruits, with *Fusarium* being the most harmful, followed by yeast and *Geotrichum candidum*, and *Aspergillus fumigatus* being the least harmful (Ishaya *et al*., 2019).

Several pathogens can infect a single host either simultaneously (co-infection) or sequentially over time (multi-infection) (Pandey *et al*., 2025). Despite this, the effect of the order and timing of infection on disease severity, especially in fatal diseases, remains poorly understood. Pathogens are known to interact, influencing each other's pathogenicity through antagonistic or synergistic effects. Interactions between fungi and oomycetes are particularly common. For example, K. Foster *et al*. (2017) documented widespread synergistic associations between *Rhizoctonia* and *Pythium* spp.; *Pythium* and *Fusarium* spp.; *Pythium* spp. and *Aphanomyces trifolii*; and *Phytophthora clandestina* and *A. trifolii* on forage legumes in southern Australia. However, many such interactions probably remain unrecognised.

In Kyrgyzstan, the response of imported cucumber hybrids to the effects of phytopathogenic fungi and bacteria has not been sufficiently studied. The microclimate of protected soil, characterised by high humidity and limited air circulation, contributes to the intensive development and spread of pathogenic microflora. An effective system for protecting greenhouse crops requires reliable identification of disease pathogens. However, comprehensive phytopathological studies of cucumber diseases in open and protected ground conditions in the republic are practically absent, which does not allow characterising the morphobiological features and virulence of local pathogen isolates. The

aim of this study was to isolate and identify the species of fungal pathogens that mainly affect the fruits of the Björn F1 hybrid cucumber in greenhouse production, as well as to evaluate their pathogenic properties in relation to the host plant.

Materials and Methods

Observation site, disease symptoms and sample selection. On 1 August 2024, Björn F1 cucumbers were planted in the nursery of the Kyrgyz National Agrarian University named after K.I. Skryabin (KNAU). Tomatoes were the predecessors and were planted before the cucumbers. The total area of the greenhouse allocated for cucumbers was 20 m^2. The soil was enriched with manure (448.5 kg/m^2) and mineral fertilisers ($N_{100}P_{100}K_{100}$) (448.5 kg/m^2). The average temperature in the greenhouse was 16.6°C, and the air humidity was 89.3%. At the end of October – beginning of November, whitefly infestation was observed at a level of 10-15%, accompanied by the appearance of bright symptoms of fungal damage on cucumber fruits. The assessment of disease symptoms on cucumbers in greenhouses and the percentage of disease incidence was carried out using random sampling, with at least 20 plants in the greenhouse being examined. The incidence was determined as the percentage of the total number of affected plants to the total number of plants examined. For phytopathological analysis, affected cucumber fruits with the following symptoms were selected: underdeveloped, blackened, covered with white felt-like fungal mycelium; shrivelled fruits with softened tissue and the onset of rot from the top; cucumbers of sufficient size, but with noticeable softening of the fruit tissue, starting with rotting from the top and covered with a felt-like coating (Fig. 1). The samples were delivered to the mycological laboratory of the Plant Protection Centre of the KNAU for the isolation and identification of pathogens.

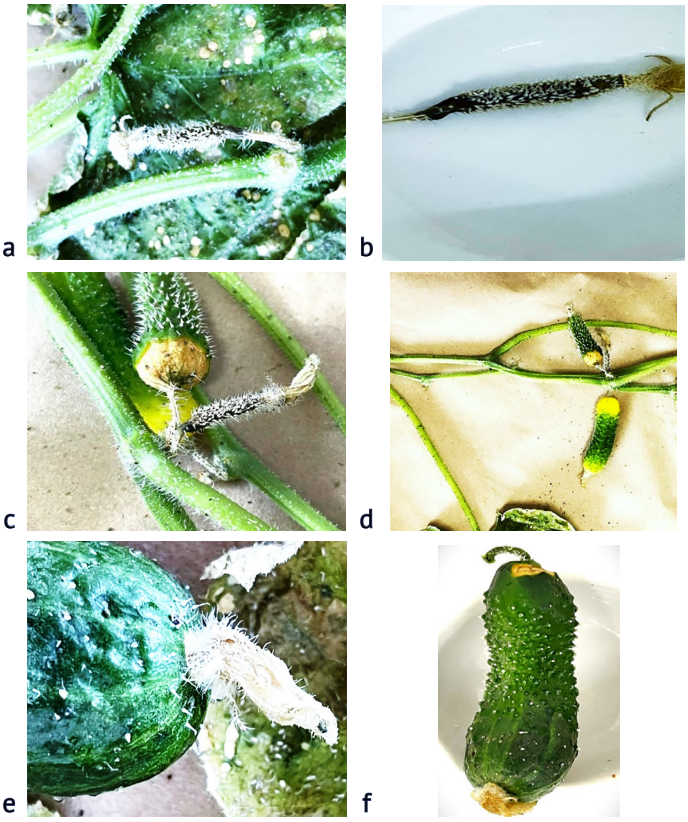

Figure 1. Samples of cucumber fruits with visible symptoms of disease taken for analysis
Note: symptoms on plants: a, b – underdeveloped blackened cucumber fruit covered with white felt-like coating and fungal mycelium; c, d – underdeveloped cucumber fruit: the fruit tissue begins to soften, it starts to rot from the top, the fruit looks shrivelled; e, f – larger cucumber fruit with softened tissue, it also starts to rot from the top and becomes covered with a felt-like coating
Source: authors' photos

The experiment was conducted in accordance with the ethical principles set out in the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973).

Isolation of pure cultures of the pathogen from samples. Cucumber fruits with symptoms of the disease were thoroughly washed with tap water and cut into 5-10 mm pieces. The pieces were immersed in a 2% disinfectant solution (sodium hypochlorite). Then all samples were washed several times with distilled water, rinsed with sterile water and dried on sterile filter paper until completely dry. After drying, the samples were

transferred under sterile conditions to Petri dishes with nutrient agar. The dishes were incubated for seven days at 20°C and 97% relative humidity. After incubation, the primary colonies were separated based on the similarity of their cultural characteristics. These colonies were transferred to potato dextrose agar (PDA) and incubated for 48 hours at 20°C. Pure cultures were obtained by single spore isolation and cultivated on PDA and nutrient-deficient synthetic agar (SNA). For cultural studies, colonies were grown on PDA and SNA for 14 days at 25°C in the dark.

Morphological characterisation of pathogens. Pure cultures of fungal isolates were prepared for preservation and identification. Morphological characterisation of pathogens was performed using various nutrient media. Potato dextrose agar was used to evaluate the colour, texture and growth rate of colonies. SNA medium was used to study the formation and types of macroconidia, microconidia and conidiogenous cells. To identify the isolated fungi, standard phytopathological methods were used, with particular attention paid to morphological characteristics such as colony appearance, pigment formation, conidiophores, spores, and other morphological structures. Mycelial growth and the morphology of dried spores were studied in detail under a microscope. The fungal hyphae were stained with lactophenol and blue solution and observed under a MEIJI Advanced Compound Microscope Model ML5500 and a MEIJI Zoom Stereo Microscope Model EMZ-5TR-MA502-PBH (Japan), and microphotographs were obtained using a MOTIC 2.0 Mega Pixel Digital Microscope Camera with Images 2000 Software Model MOTICAM 2000. The number of septa, as well as the length and width of 30 conidia spores per isolate, were measured using an eyepiece micrometer under a light microscope. Identifiers (Williams-Woodward, 2001; Watanabe, 2010) were used to determine the species of fungi.

***In vitro* and *in vivo* pathogenicity tests.** Pathogenicity was assessed both *in vitro* and *in vivo*. For the *in vitro* assessment, firm green apple varieties, namely Simirenko and Golden Delicious, were selected to study the pathogenicity of fungal isolates obtained from infected cucumber fruits. Apples of approximately the same size and health status were thoroughly washed and then disinfected in a 2% sodium hypochlorite solution for 3 minutes. After disinfection, they were rinsed with sterile distilled water, dried, and inoculated with a suspension of 7-day-old pathogen cultures. Using a sterile 1.0 ml syringe needle, 1 ml of the suspension (1×10^6 conidia/ml) was injected to a depth of up to 1 cm into the skin of the fruit. Control apples received 1 ml of sterile water. All apples were then incubated at a constant temperature under sterile conditions for up to 20 days.

The pathogenicity of the isolates was evaluated *in vivo* on two-week-old tomato seedlings. Seedlings with intact root systems were immersed for two hours in a suspension (1×10^6 conidia/ml) of 7-day-old cultures of the pathogen isolated from diseased cucumbers. Control seedlings were treated with plain water. After immersion, all seedlings were planted in soil and kept at a constant temperature of 22-23°C with a 16-hour photoperiod. Sterile distilled water served as a negative control. To assess the aggressiveness of the isolates, symptoms were recorded weekly for four weeks after inoculation. The total duration of observation of the tested plants was 3 months.

Results

Cultural and morphological characteristics of *Cladosporium* pathogens isolated from cucumber fruits

Colonies grown on potato dextrose agar, which is a common medium for fungi (Fig. 2a), and synthetic agar with low nutrient content (Fig. 2b) grew slowly. The colour of the colonies varied mainly from olive brown to blackish brown, with rare shades from greyish olive to dull green. They had a velvety or flaky (soft, woolly) texture. The aerial mycelium, or threads growing above the surface, were rarely abundant, and the colonies did not produce any noticeable exudate (liquid secretion).

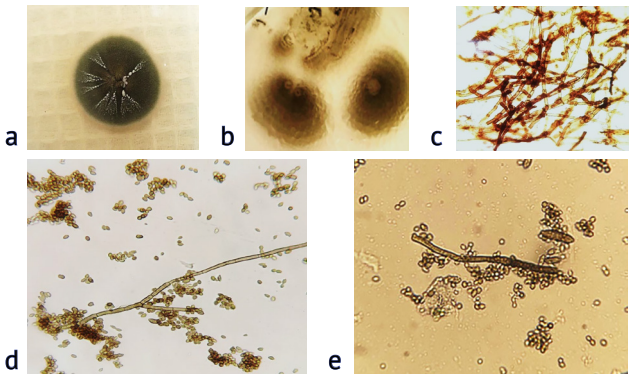

Figure 2. Morphological features of *Cladosporium cucumerinum* isolates

Note: a – colonies cultivated on potato dextrose agar (PDA); b – colonies developed on synthetic nutrient agar (SNA); c – microscopic observation of conidiophores; d – conidia formed from conidiogenous cells and apical regions; e – ramoconidia visualised under a microscope, ×400

Source: authors' photos

To identify and determine the taxonomic affiliation of isolates 4(1) and 4(2), presumably belonging to the genus *Cladosporium*, their morphological structure was analysed based on the criteria established by B. Thomma *et al.* (2005) and K. Bensch *et al.* (2010). The results obtained were compared with published descriptions and photographs available on Microbe Notes (n.d.). The analysis revealed a number of distinctive features of *Cladosporium* isolates, including the presence of ramoconidia – spores that develop from segments of the conidiophore or its branches. These fungi also formed small conidia at the ends of their chains. Ramoconidia were 20-41 µm and 3.1-3.3 µm in size and formed long, loose chains, often with dichotomous branching. The mycelium of the colony consisted mainly of substrate and ranged in colour from almost colourless to brownish. Conidiophores were usually erect, septate, either unbranched or with one or two branches, often with dark pigmentation. Sometimes, micronematid-like conidiophores were observed, which were paler, unbranched, and 9 to 150 µm long. The apical unbranched part of these conidiophores contained up to 10 conidia. The terminal conidia varied from obovate to almost spherical, measuring 3-6 × 2-2.5 µm. In contrast, the middle conidia were lemon-shaped, ellipsoidal-ovoid, sometimes almost cylindrical, 5-12 µm and 2.5-3 µm in size, without septa. The colour of the conidia varied from light brown to light olive brown, and the surface was smooth (Fig. 2). Based on these observations, isolates from affected cucumber fruits with pronounced symptoms of (Fig. 1a, 1b) were identified as *Cladosporium cucumerinum* (Ellis and Arthur). According to previous reports, this pathogen mainly affects fruits, less often leaves, causing characteristic spots on the fruits (Kwon *et al.*, 2000). This disease is known as olive (brown) spot of cucumbers.

Cultural and morphological characteristics of *Botrytis*, a pathogenic fungus isolated from cucumber fruit

Isolates 2.1, 2(2)-1 and 2(2)-2, presumably fungi of the genus *Botrytis*, showed distinctive cultural and morphological characteristics. When grown on nutrient media, the mycelium of these isolates proliferated rapidly, forming pronounced radial patterns and generating sclerotia. When cultivated on KDA, they formed fluffy, raised colonies characterised by grey-white airy mycelium with white edges and a green centre (Fig. 3a). Conidia began to appear on the mycelium within seven days of incubation, and black sclerotia formed after 14 days (Fig. 3b).

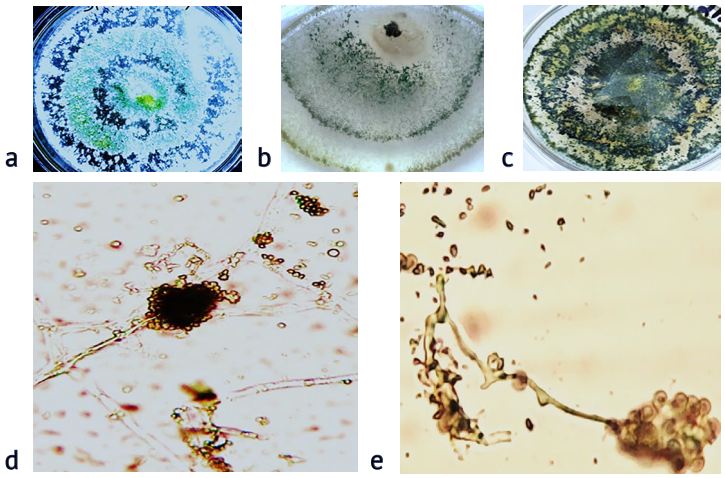

Figure 3. Morphological features of *Cladosporium cucumerinum* isolates

Note: a – colonies of isolates on KDA; b – colonies on SNA medium; c – colonies on day 7, showing the development of black sclerotia; d – transparent, straight conidiophores with apical phialides bearing round conidia; e – slightly pear-shaped, smooth, hyaline spores at the swollen ends of conidiophore branches, ×400

Source: authors' photos

The conidiophores were vertical, thin-walled and branched at the top. Their colour varied from greyish to light brown, and they were translucent, with a small number of transverse septa. At the swollen ends of the conidiophores, short sterigmata produced numerous single-celled spores that were slightly pear-shaped or spherical, smooth and transparent. Depending on the species and substrate, sclerotia ranged in size from 1 to 20 mm and could be round, ovoid or elliptical in shape. According to published descriptions and photographs available on Microbe Notes (n.d.), these isolates were identified as *Botrytis cinerea*, a member of the Sclerotiniaceae family, a highly aggressive phytopathogen that causes grey mould. Affected plants developed darkened fruits, leaves, petals, and succulent stems, which then became soft, dried out, and eventually died. The succulent tissues of most plants are particularly vulnerable to grey mould. In addition, high humidity can lead to the rapid spread of *Botrytis cinerea*, causing buds, flowers, leaves and fruits to rot (Tanović *et al.*, 2014). Thus, the combination of morphological characteristics identified made it possible to reliably identify these isolates as representatives of the species *Botrytis cinerea*.

Cultural and morphological characteristics of *Fusarium* species isolated from cucumber fruits

The cultural and morphological characteristics of isolates 3.2, 3(2)-1 and 3(2)-2, presumably belonging to the genus *Fusarium*, were studied in detail. On SNA medium, these isolates formed airy, silvery-white, fluffy colonies (Fig. 4a). When grown on KDA, they formed low, filamentous, cobweb-like, cotton-white colonies. As the mycelium matured, the colour of the colonies gradually changed to shades of pink and red (Fig. 4b).

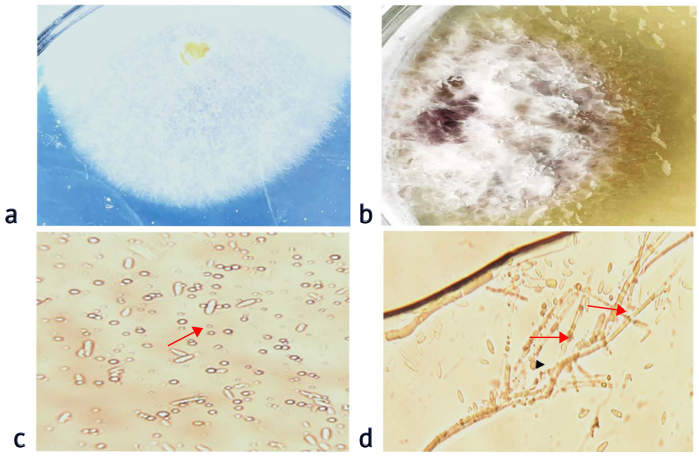

Figure 4. Morphological features of *Fusarium oxysporum* isolates
Note: a – colonies of isolates on KDA medium; b – colonies on SNA medium; c – microconidia; d – macroconidia, ×400
Source: authors' photos

During further development, the fungus formed two different types of conidia. Macroconidia were spindle- or sickle-shaped with a clearly defined stalk or papilla, forming in aerial mycelium, sporodochia or pyonota. These macroconidia had a mostly uniform diameter, thin walls, a tapering base, and contained three to five septa measuring 23.5-51 × 3.0-5 µm (Fig. 4d). The second type, microconidia, developed inside the mycelium and was abundant during the reproductive phases (Fig. 4c). These microconidia were elongated, unicellular, and colourless. In addition, the isolates produced chlamydospores, which were unicellular or multicellular, unstained, and thick-walled. These morphological features collectively closely resembled those of *Fusarium oxysporum* f. sp. *cucumerinum,* a common pathogen in cucumber-growing areas (Din *et al.*, 2020). *Fusarium oxysporum* f. sp. *cucumerinum* is a specialised pathogen that causes fusarium wilt (tracheomycosis) in cucumbers. When it enters the host plant, it blocks the xylem vessels and secretes phytotoxins, then spreads through the vascular system, leading to systemic physiological disorders.

Cultural and morphological characteristics of *Alternaria* species pathogenic to cucumbers, isolated from fruits

Isolates 5(1) and 5(2) formed dense, felt-like colonies on PDA, ranging in colour from black to dark grey with clearly defined rounded outlines (Fig. 5a, 5b).

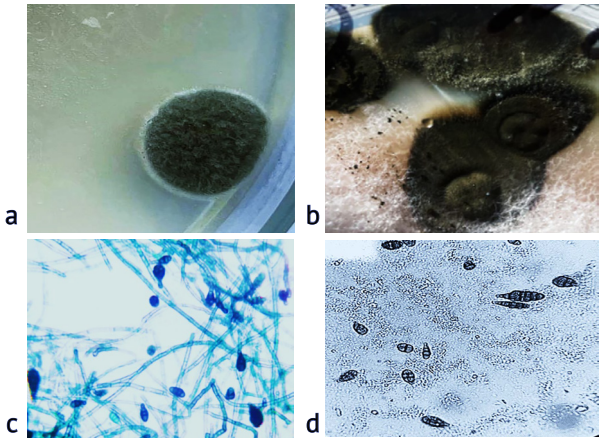

Figure 5. Morphological features of *Alternaria* spp. isolates
Note: a – colonies of isolates on PDA (young culture); b – colonies on PDA (mature culture); c – conidiophores with conidia; d – conidia, ×400
Source: authors' photos

The surface of these colonies was uniformly velvety, with clearly defined smooth edges. Species of the genus *Alternaria* are characterised by large, multicellular, dark-pigmented conidia with transverse and longitudinal septa (Fig. 5c, 5d). These conidia are usually oblong or pear-shaped, but may also be ovoid or ellipsoidal, often with a short conical or cylindrical tip. Their walls are pale brown and may be smooth, finely warty or coarsely rough. Traditionally, these fungi are divided into two groups based on morphological and molecular phylogenetic characteristics: group 1, which has finely warty walls, and group 2, which has coarsely warty or rough walls.

Pathogenicity of isolated fungal strains *in vitro*

Fungi can act as pathogens, using various strategies to colonise and penetrate plant tissues, ultimately leading to disease. Some fungi are necrotrophs, meaning they kill their host plants and feed on dead tissue. Biotrophic fungi, on the other hand, colonise living tissues without immediately killing their hosts. To effectively penetrate plant organs, fungi develop specialised infectious structures and produce a range of hydrolytic enzymes and toxins that destroy plant tissues (Doehlemann *et al*., 2017). It should be noted that necrotrophic fungal pathogens are similar to biotrophic ones. Both types secrete small molecules known as effectors, which interact with the host at the genetic level, initiating pathological processes (Oliver & Solomon, 2010). A striking example of a significant necrotrophic phytopathogen is *Botrytis cinerea*, which has a wide range of hosts. In addition, species of the genus *Cladosporium* are non-obligate biotrophic fungi, causing tomato leaf blight, in particular *Cladosporium fulvum* (also known as *P. fulva)* (Thomma *et al*., 2005). It is important to note that fungi of the genus *Cladosporium* do not cause necrotic rot on apple fruit (Fig. 6i). This is probably due to their biotrophic nature: instead of secreting enzymes that damage plant tissue, they use other strategies to infect plants.

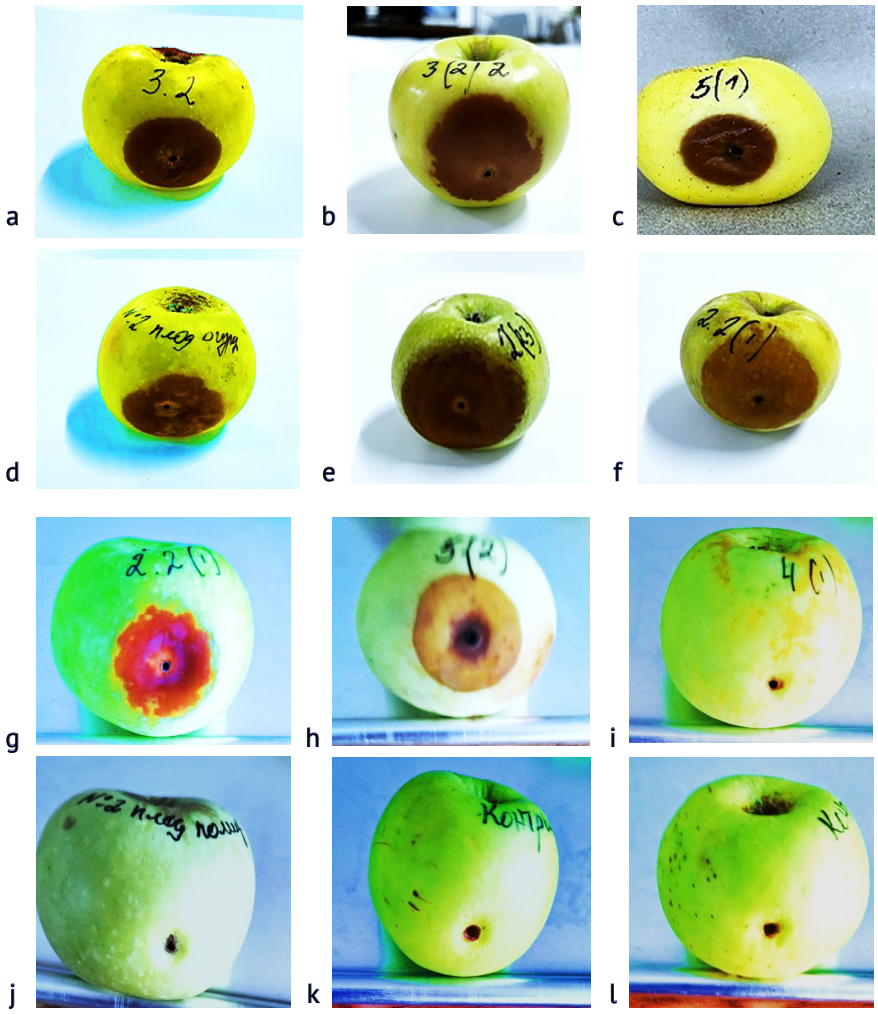

Figure 6. The appearance of necrotic spots, or rot, on apple fruit after artificial inoculation with pathogenic fungal cultures

Note: panels a and b show isolates of the genus *Fusarium*; panels c and h show isolates of the genus *Alternaria*; panels d, e, f, and g show isolates of *Botrytis cinerea*; panel i shows an isolate of the genus *Cladosporium*; panels j, k, and l show control fruits

Source: authors' photos

Various pathotypes *of Alternaria alternata* produce at least 12 different host-specific toxins (HSTs) that enable them to cause disease in various dicotyledonous plants (Thomma, 2003). In experiments involving artificial inoculation with these pathogens in the present study, typical symptoms were observed, and repeated isolation of the fungi confirmed Koch's postulates. The study of pathogenicity on apple fruit revealed clear symptoms characterised by superficial watery lesions. The affected tissue took on a brownish tint. Virtually all isolated fungal strains produced positive symptoms on green apple varieties with firm fruit (Fig. 6a, 6b, 6c, 6d, 6e, 6f, 6g, 6h). After 7 days, necrotic lesions formed on the fruits surrounding the inoculation site, while no necrosis was observed at the injection site of the control fruits (Fig. 6j, 6k, 6l). This suggests that the isolated fungi are necrotrophs that produce hydrolytic enzymes, including pectinases, which break down pectin in apple tissues (Asoufi *et al*., 2007). The results confirm the pathogenic activity of the isolated strains and their ability to enzymatically destroy plant tissues *in vitro*.

Pathogenicity of the isolated fungal strains *in vivo*

Pathogenicity was assessed in vivo on two-week-old tomato seedlings. During the three-month observation period, it was evident that all tested pathogens had a significant effect on tomato plant growth. Tomato plants inoculated with cultures from the genera *Fusarium*, *Alternaria*, *Botrytis*, and *Cladosporium* showed similar disease symptoms, including yellowing of leaves and wilting. In contrast, the control plants remained healthy after a four-week incubation period, showing no signs of yellowing, chlorosis or wilting. Symptoms of yellowing began on older leaves, which then progressed to chlorosis and wilting (Fig. 7).

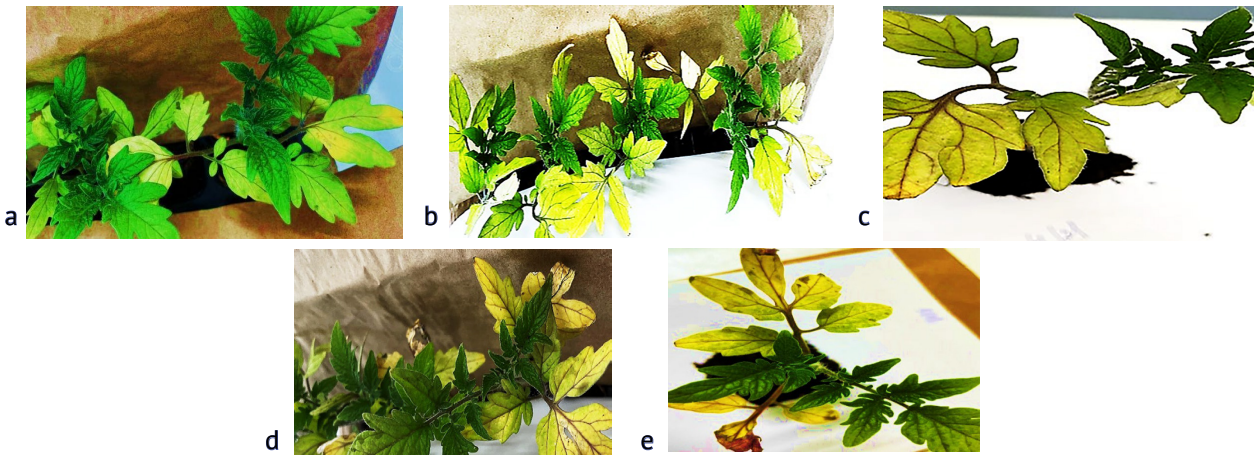

Figure 7. Symptoms of disease on tomato seedlings 20 days after inoculation
Note: a – control plants without symptoms, b – yellowing and wilting of leaves infected with *Cladosporium* isolates; c – *Alternaria* isolates; d – *Botrytis* isolates; e – *Fusarium* isolates
Source: authors' photos

The results showed that *Cladosporium*, *Fusarium* and *Alternaria* isolates were more aggressive than *Botrytis* pathogens. To confirm these results, infected tomato leaves and stems were re-isolated, resulting in the formation of pathogen colonies confirming Koch's postulates (Fig. 8).

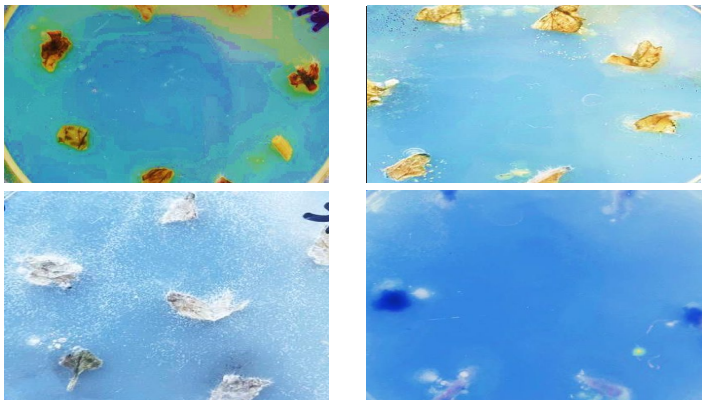

Figure 8. Primary pathogen colonies grown from leaves and stems of plants with visible symptoms
Source: authors' photo

Re-isolation of pathogens from affected tomato plant organs demonstrated the formation of primary fungal colonies, which were subsequently transferred to KDA medium to obtain pure cultures with morphological characteristics specific to each species. The successful isolation of the original pathogens from infected tissues finally confirmed their aetiological role in the development of the disease. Detailed results of this stage of the study will be presented in subsequent publications.

Discussion

The present study showed that cucumbers grown in greenhouses, especially in October and November, are susceptible to mixed infections caused by several pathogens simultaneously. Assessment of disease symptoms in the field allowed for collecting fruits with signs of wilting, rotting, and other visible symptoms. For accurate identification of the pathogen, classical phytopathological methods and microscopic morphological analysis were performed, as described in specialised sources on fungal identification. The results showed that several species of killer pathogens can parasitise the fruit at once, their action is aimed at the effective destruction of host cells, and as necrophages, they feed on dead cells. During the study, necrophages such as species of the genera *Fusarium*, *Botrytis* and *Alternaria* were identified. Their pathogenicity was proven in *in vitro* and *in vivo* tests. In *in vitro* tests, they showed the ability to produce hydrolytic enzymes that decompose the hard tissue of apple trees, consisting of pectin compounds and other mono- and disaccharides. An interesting fact was noted under *in vivo* conditions, where two-week-old tomato seedlings were used as test hosts, since these same pathogens can use tomato plants as hosts. It is known that tomatoes and cucumbers have common pathogens, especially since tomatoes were the predecessors of cucumbers in the greenhouse. Ten days after artificial infection by soaking the roots of the seedlings in a suspension of pathogenic cultures, symptoms began to develop on the lower, earlier-appearing leaves, including yellowing and wilting. In contrast, the control plants remained healthy after a four-week incubation period, showing no signs of yellowing, chlorosis or wilting. The symptoms of yellowing progressed to chlorosis and wilting.

It should be noted that all pathogens had similar symptoms, which manifested themselves primarily on the leaves; during the experiment, no damage to other organs, such as the root system, was observed. At the same time, all diseased plants lagged behind in growth and did not enter other phases of vegetation, such as flowering and fruiting. The wilted leaves died, and no new leaves appeared, or their development was slow. According to many authors, pathogens secrete phytotoxins that cause the death of host plant cells (Friesen *et al*., 2008). For example, *B. cinerea* secretes botrydial during the infection of plants, which causes leaf necrosis, chlorosis and tissue wilting (Staats *et al*., 2005). In addition, the pathogen *Fusarium oxysporum* secretes SIX effector proteins (proteins secreted in xylem) into the xylem, promoting infection (Din *et al*., 2020). The data obtained in this study also indicate the widespread distribution and aggressiveness of the pathogen *Fusarium oxysporum* f. sp. *Cucurbitacearum* (the causative agent of *Fusarium* wilt), which is confirmed by other authors (Shen *et al*., 2008; Din *et al*., 2020). At the same time, a study by M. Pikovskyi *et al*. (2023) showed that the optimal temperature for the vegetative growth *of Fusarium oxysporum* f. sp. *cucumerinum* is 30°C, and the most intense spore formation of the pathogen occurs at a temperature of 25°C.

The prevalence of another pathogen, *Alternaria alternata*, in the study was 15%, which is consistent with the data of other authors who note this species as a potential pathogen of cucumbers in both open and closed soils (Thomma *et al*., 2005; Hubballi *et al*., 2011). Among the species found in this study, *Botrytis cinerea* (the causative agent of grey mould) was represented by several strains, with a prevalence of up to 30% among the species found. The frequency of detection of this species in cucumber crops has also been noted by other authors, such as B. Tanović *et al*. (2014). It should be noted that cucumber pathogens are represented by different species on different continents and in different parts of the world. For example, in African countries, the species *Aspergillus flavus*, *Aspergillus niger*, and *Aspergillus terreus* dominate (Shutt *et al*., 2021; Umar *et al*., 2024). Meanwhile, in Central Asia, *Cladosporium* spp., *Fusarium oxysporum*, and *Botrytis cinerea* are the main ones. In other Asian countries, like China, *Fusarium oxysporum* is the main one on cucumber crops (Ye *et al*., 2004; Shen *et al*., 2008). In Eastern European countries, particularly Ukraine, *Pseudoperonospora cubensis,* the causative agent of downy mildew, is widespread (Bondarenko & Stankevych, 2021).

Thus, in autumn, in greenhouse conditions, with humidity of about 90% and a temperature of 16.6°C, favourable conditions are created for the development of several types of pathogens simultaneously. The high infectious background is also due to the predecessor plant, tomato, which is affected by the same pathogens as cucumber. The imported hybrid Björn F1 variety showed high sensitivity to fungal pathogens such as *Fusarium* spp., *Botrytis* spp., *Alternaria* spp., and *Cladosporium* spp., although the producers and creators of this variety emphasised its resistance to *Cladosporium*.

Conclusions

Under protected ground conditions, the microclimatic characteristics of greenhouses create a favourable environment for the simultaneous development of a complex of phytopathogenic microorganisms capable of rapidly colonising various organs of the host plant. The studies conducted have convincingly demonstrated

that the visually recorded symptoms of cucumber fruit damage are caused by a polyetiological infection, which indicates the formation of associative pathocomplexes during the development of the disease. Cultural and morphological analysis revealed the presence of reproductive structures and mycelium of several species of fungal pathogens within a single affected fruit, indicating synergistic interaction between pathogens during the colonisation of plant tissues.

Phytopathological studies have established the high susceptibility of Björn F1 hybrid cucumber fruits to pathogenic fungi of the genera *Fusarium*, *Botrytis*, *Cladosporium*, and *Alternaria*. The data obtained emphasise the need for strict compliance with agrotechnical requirements, including scientifically based selection of predecessors, timely preventive measures and maintenance of optimal microclimate parameters when cultivating hybrid cucumber varieties in protected ground. When developing integrated plant protection systems, it is critically important to consider the possibility of polyinfection, when several types of pathogens causing diseases of different aetiologies simultaneously parasitise one plant. Prospects for further research include molecular genetic identification of isolated strains, studying the mechanisms of pathogen interaction in mixed infections, and developing effective biological and chemical control measures for identified pathogens, taking into account their synergistic effects in the protected soil conditions of Kyrgyzstan.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Күнөскана шарттарында ар түрдүү козу карын түрлөрүн чакырган бадыраң мөмөлөрүнүн аралаш инфекциялары

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Аннотация. Бадыраң Кыргызстанда күнөсканаларда өстүрүлгөн эң популярдуу өсүмдүктөрдүн бири. Акыркы убакта партенокарпиялык гетерозис гибриддер күнөсканада өстүрүү үчүн кеңири колдонулууда. Бирок, гибриддик сорттордун ар кандай козу карын же бактериялык илдеттерге туруктуулугу же сезгичтиги изилденбеген бойдон калууда, анткени парниктерде нымдуулук жана аба агымынын чектелгендигинен илдет козгогучтар үчүн жагымдуу шарттар түзүлөт. Бадыраңдын илдеттерин так аныктоо түшумдү өз убагында коргоо үчүн зарыл. Кыргызстанда ачык жана жабык жерде өстүрүлгөн бадыраңдарга таасир этүүчү илдет козгогучтар алардын айырмаланган морфофизиологиялык жана патогендик касиеттерин аныктоо адистештирилген фитопатологиялык ыкмалар менен изилдене элек. Бул изилдөөнүн максаты күнөсканада өстүрүлгөн Björn F1 бадыраңына таасир этүүчү козу карын козгогучтарын бөлүп алуу жана аныктоо, алардын кожоюн өсүмдүккө карата патогендүүлүгүн аныктоо болуп саналат. Изилдөө үчүн илдеттин белгилери жакшы көрүнгөн бадыраңдардын мөмөлөрү тандалып алынган. Илдет козгогучтарды аныктоодо фитопатология жана микробиология илимдеринин заманбап жана классикалык ыкмалары колдонулуп, жарык микроскопиясынын жардамы менен алардын культуралдык-морфологиялык мүнөздөмөлөрү изилденди. Изилдөөдө *Fusarium*, *Botrytis*, *Alternaria* жана *Cladosporium* урууларына таандык козу карын патогендери аныкталды. Алардын патогендүүлүгү *in vitro* жана *in vivo* шарттарында көрсөтүлдү. Табылган патогендердин штаммдарынын таралыш пайызы: *Fusarium* spp. – 25 %, *Botrytis* spp. – 30 %, *Alternaria* spp. – 15 %, *Cladosporium* spp. – 30 %. Бул изилдөөнүн маанилүү жыйынтыгы болуп импорттолгон бадыраң Björn F1 сортунун бир эле мезгилде бир нече патогендерге сезгичтиги аныкталды. Бир өсүмдүккө бир нече патогендик түрлөрдүн синергетикалык чабуулу байкалды, мындай кубулуш коргоо чараларын тандоодо жана ишке ашырууда эске алынышы маанилүү

Негизги сөздөр: бадыраңдын гибриддик сорттору; бадыраңдын козу карын илдеттери; козгогучтарды аныктоо; морфологиялык өзгөчөлүктөрү; козгогучтардын патогендүүлүгү

Смешанные инфекции плодов огурцов, вызванные различными грибковыми возбудителями в условиях теплицы

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Аннотация. Огурец – одна из самых популярных культур, выращиваемых в защищенном грунте в Кыргызстане. Для выращивания в теплицах в последние годы широко используются партенокарпические гетерозисные гибриды. Однако устойчивость или восприимчивость гибридных сортов к различными грибным или бактериальным болезням остается неизученной, и это вызывает серьезные опасения, так как в теплицах создаются благоприятные для патогенов условия из-за влажности и ограниченности потока воздуха. Для своевременной защиты урожая нужна точная диагностика болезней огурцов. В Кыргызстане до сих пор не изучены возбудители болезней огурцов, выращенных в открытом и закрытом грунтах, с применением специальных фитопатологических методов для выявления отличительных морфофизиологических и патогенных свойств патогенов. Целью настоящего исследования были изоляция и идентификация возбудителей грибных болезней, проявленных в первую очередь на плодах огурцов сорта Бьерн F1, выращенных в тепличных условиях, выявление их патогенности в отношении растения-хозяина. Для анализа были отобраны больные плоды огурцов с симптомами болезней. Для выявления патогенов были использованы современные и классические методы фитопатологии, микробиологии, и для их идентификации были изучены культуральные и морфологические особенности с помощью световой микроскопии. В результате исследований были выявлены грибные болезни и идентифицированы их возбудители, относящиеся к родам *Fusarium*, *Botrytis*, *Alternaria* и *Cladosporium*. Была определена их патогенность в *in vitro* и *in vivo* условиях. Процент доминирования штаммов составил: *Fusarium* spp. – 25 %, *Botrytis* spp. – 30 %, *Alternaria* spp. – 15 %, *Cladosporium* spp. – 30 %. Важным результатом было установление восприимчивости импортированного сорта огурцов Бьерн F1 к нескольким патогенам, поражающим плоды и другие органы растений. Установлена синергическая атака сразу нескольких видов патогенов на одно растение, что важно учитывать при подборе и организации защитных мероприятий

Ключевые слова: гибридные сорта огурца; грибные болезни огурца; идентификация возбудителей болезней; морфологические особенности; патогенность возбудителей

Received: 29.03.2025. Revised: 27.07.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 631.1:331.5

DOI: 10.63621/bknau./3.2025.64

Transformation of employment in the agricultural sector of Kyrgyzstan: Challenges and prospects

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Abstract. The article explored the transformation of rural employment in the Kyrgyz Republic as a crucial factor of socio-economic development and food security. The relevance of the research is due to the fact that the agricultural sector remains the primary employer in rural areas, yet its progress is constrained by contradictions: limited labour efficiency, widespread informal practices, and large-scale migration of the working-age population. The aim of the study was to determine trends and promising directions of employment transformation in Kyrgyz agriculture. The methodological framework relied on systemic and comparative approaches, statistical data, and materials from international organisations. The application of SWOT analysis made it possible to classify internal and external factors affecting the sustainability of the labour market. The conditions influencing employment have been analysed, including fragmented landholding, insufficient mechanisation, weak cooperative integration, and institutional barriers. Social and demographic disparities have been identified, particularly the outflow of young people and persistent gender imbalances. It was emphasised that agriculture continues to play a stabilising role, offsetting the shortage of jobs in other sectors. Based on the results, measures have been proposed to improve employment: strengthening cooperative organisations, introducing digital solutions, diversifying rural activities through processing and agritourism, and expanding government support programs. The practical value of the study lies in the opportunity to use the findings for designing employment policies, reducing poverty, and reinforcing the role of the agricultural sector in the national economy

Keywords: labour migration; cooperation; digitalisation; sustainable development; modernisation; infrastructure; innovation

Introduction

Agriculture has traditionally played a key role in the socio-economic development of the Kyrgyz Republic, forming the basis of food security, providing employment for a significant part of the population and making a significant contribution to the country's gross domestic product. According to NSCKR (2025), more than half of the republic's population lives in rural areas, which determines the high dependence of the living standards and social well-being of rural households on the state of the agro-industrial complex. Consequently, changes in the structure of employment in the agricultural sector are not only an economic but also a social factor in sustainable development. A number of studies note that in the second half of the 20th century, most countries around the world saw a steady decline in the number of workers employed in agriculture, accompanied by a significant increase in the efficiency and productivity of agricultural labour (Naumov *et al.*, 2022). In the Kyrgyz Republic, however, the decline in employment in the agricultural sector has not been accompanied by a commensurate increase in productivity, which indicates structural imbalances and limited investment opportunities in the sector. In this regard, identifying key trends in the evolution of employment

Suggested Citation: Parpieva, P. (2025). Transformation of employment in the agricultural sector of Kyrgyzstan: Challenges and prospects. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 64-73. doi: 10.63621/bknau./3.2025.64.

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in the agricultural sector of the Kyrgyz Republic and substantiating promising areas for its development is of particular importance for achieving sustainable development goals.

Employment issues in the agricultural sector have traditionally been a central focus of research on the socio-economic development of rural areas. Classic approaches to the study of agricultural employment focus on its specific characteristics, such as seasonality, dependence on natural and climatic conditions, and a high rate of hidden unemployment. As modern international studies show, the agricultural sector in developing countries continues to play a key role in employment, compensating for limited employment opportunities in industry and services. Thus, according to T. Herzfeld & Z. Akhmadiyeva (2021), agriculture remains the most important source of employment, providing jobs for millions of people even in conditions of low productivity and structural constraints. The United Nations (2021) emphasised that in countries with high levels of rural employment, it is the agricultural sector that acts as a stabilising element, mitigating the social consequences of crises and job losses in other sectors. At the same time, recent studies indicate that changes in agricultural employment are directly linked to the processes of production modernisation and digitalisation. According to the World Bank (2021), increasing agricultural labour productivity is a key factor in reducing poverty in countries with economies in transition. The report by FAO (2024) noted that diversifying employment in rural areas – through the development of agro-processing, agrotourism and family entrepreneurship – is a prerequisite for the sustainable development of rural areas.

In the post-Soviet space, employment issues in the agricultural sector are mainly considered in the context of social stability and food security. Thus, Russian researchers Yu. Kabanov & A. Chugunov (2021) and T. Geleta & E. Shumilina (2025) emphasise the need for a comprehensive approach that includes state support for agriculture, rural infrastructure development and mechanisation of production. In Kazakhstani studies by E. Kydyrbaeva *et al.* (2021) pay particular attention to the impact of labour migration on employment dynamics and the redistribution of labour between rural and urban areas. In Kyrgyzstan, the issue of employment in agriculture is analysed in close connection with the issues of poverty, migration and sustainable development. According to the national voluntary review of the Sustainable Development Goals (SDGs) presented in 2025, the issues of full and productive employment (SDG 8) and poverty eradication (SDG 1) remain among the priority tasks of the state's socio-economic policy (Office of the Government..., 2025). Research by A. Murzakulova (2020) shows that the agricultural sector of the Kyrgyz Republic operates under a set of interrelated constraints. The most significant of these are limited labour efficiency, the dominance of small-scale farms with low potential for scaling up, insufficient technical equipment and weak investment support. The paper also emphasises that limited opportunities for labour deployment, hidden agricultural overpopulation, and the high dependence of rural employment on the migration of the economically active population exacerbate the instability of rural workers. Similar results were obtained in a study by D. Sakkaraeva & M. Kumashev (2024), where similar structural problems were identified based on surveys of small and medium-sized farm owners. These include a shortage of affordable credit resources, insufficiently effective management mechanisms, and the need to expand agricultural processing as a key area for increasing added value.

Thus, the works of contemporary researchers reveal a common trend: recognition of the complex, systemic and interrelated nature of the processes taking place in the agricultural sector. However, despite the existence of a significant body of scientific research, certain aspects of this issue remain insufficiently explored. First of all, further analysis is needed of the interaction between economic, social and institutional conditions, as well as the impact of technological changes that determine the current structure of rural employment and its dynamics in the Kyrgyz Republic. The aim of this study was to identify key patterns in the development of rural employment and to determine directions for its modernisation based on a comprehensive analysis of socio-economic, institutional and technological prerequisites.

Materials and Methods

The methodological basis of the study was based on systematic, comparative and descriptive-analytical approaches, which ensured a comprehensive and reproducible examination of employment processes in the agricultural sector of the Kyrgyz Republic. The application of these approaches was necessitated by the need for a comprehensive study of the transformations taking place in the socio-economic structure of rural employment. The empirical basis of the study was provided by official data from the NSCKR (2024a; 2024b; 2024c; 2025). Information on the number of people employed in agriculture, the structure of gross domestic product, labour productivity, income levels and population migration was used. For international comparisons, materials from the United Nations (2021), the World Bank (2021; 2023) and the FAO (2024) were used.

A systematic approach was used to analyse rural employment as a multi-level socio-economic system functioning under the influence of interrelated factors:

- the economic block included indicators of efficiency, access to credit resources and investment activity;
- the social block was characterised by the scale of labour migration, income levels and demographic characteristics of workers;
- the technological block reflected the level of mechanisation and the introduction of digital solutions;

● the institutional block covered the development of cooperation, the effectiveness of state support measures and the state of infrastructure.

This structure made it possible to identify the interdependence of factors and assess their impact on the sustainability of the rural labour market. A comparative approach was used to compare employment trends in the Kyrgyz Republic with similar processes observed in Central Asian countries and other developing economies. The criteria for comparison were the share of people employed in agriculture, the structure of GDP and labour productivity dynamics. The use of international databases ensured the reliability of comparisons and made it possible to identify both universal and country-specific patterns in the evolution of rural employment. A descriptive and analytical approach was used for quantitative and qualitative interpretation of the information. The use of descriptive statistics made it possible to track employment dynamics, structural shifts and key trends in the development of the agricultural labour market. The assessment of indicators in relative and absolute terms ensured the comparability of data and the objectivity of conclusions, which contributed to the analytical accuracy of the results.

To summarise and systematise the factors affecting employment, a SWOT analysis was used to classify the internal and external conditions of the agricultural sector. Internal factors (S, W) include small land holdings, the level of mechanisation, the potential for cooperation and infrastructure constraints. External factors (O, T) include climatic risks, migration processes, international support programmes, and market conditions. The classification was based on expert assessment of official statistical data and analysis of scientific publications. Table 2 reflects the results of the SWOT classification, and Table 3 reflects the strategic directions (SO, WO, ST, and WT strategies) formed based on the analysis results. Taken together, the methods used ensured the scientific comprehensiveness, reproducibility and reliability of the results, allowing for a comprehensive characterisation of rural employment processes and the identification of directions for their adaptation to contemporary socio-economic challenges.

Results and Discussion

The results of the study confirmed that the agricultural sector of the Kyrgyz Republic remains strategically important for the country's socio-economic development. Despite structural transformation processes and a gradual decline in its share of gross domestic product, agriculture remains one of the largest employers. According to NSCKR (2024a), in 2023-2024, this sector provided employment for a significant part of the economically active population, while its contribution to GDP remained at 10-12% (Fig. 1). This disproportion between the high share of employed people and the relatively low level of labour productivity indicates a systemic imbalance in the agricultural economy. For comparison, it is worth noting that similar processes are occurring with varying intensity in Central Asian countries. According to the World Bank (2021) and FAO (2024), the share of people employed in agriculture in Kazakhstan and Uzbekistan is 18-20%, while in the Kyrgyz Republic it fell to about 16% in 2024. At first glance, this may indicate higher rates of structural transformation and a reduction in the economy's dependence on the agricultural sector. However, this trend is largely due not so much to the modernisation of agriculture as to increased external labour migration, insufficient development of rural infrastructure and limited opportunities for creating new jobs in non-agricultural activities. Thus, the decline in employment in the agricultural sector in Kyrgyzstan reflects the forced nature of the rural population's adaptation rather than a sustainable diversification of the economy (UNDP, 2022).

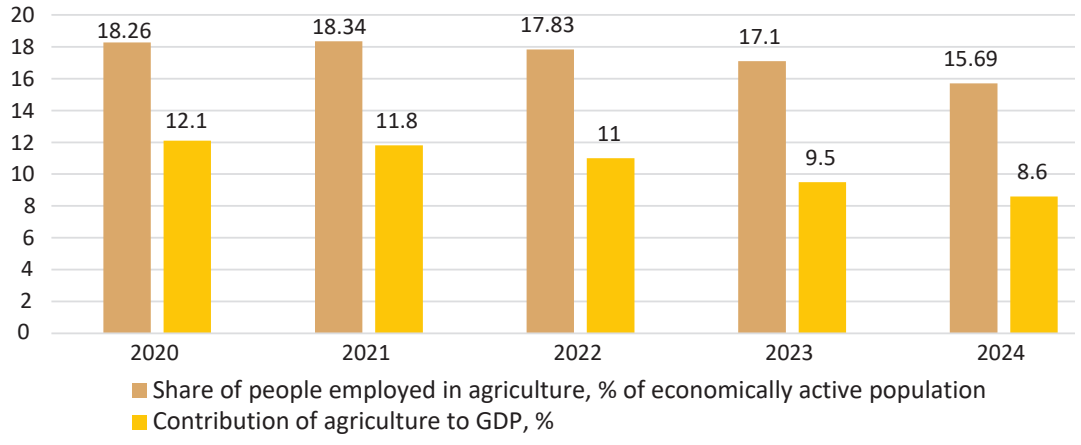

Figure 1. Share of employment and contribution of agriculture to the GDP of the Kyrgyz Republic in 2020-2024, %

Source: compiled by the author based on NSCKR (2024a; 2024b; 2024c)

An analysis of the dynamics of the number of workers in agriculture for 2020-2024 (Fig. 2) shows a gradual decline in the number of workers, which is largely due to urbanisation, the expansion of the service sector and large-scale labour migration, especially among young people. Nevertheless, the agricultural sector continues to function as a kind of "buffer" employer, absorbing surplus labour during periods of economic instability. The significant proportion of self-employed and family farm workers confirms the stability of traditional forms of employment characteristic of rural areas of the country.

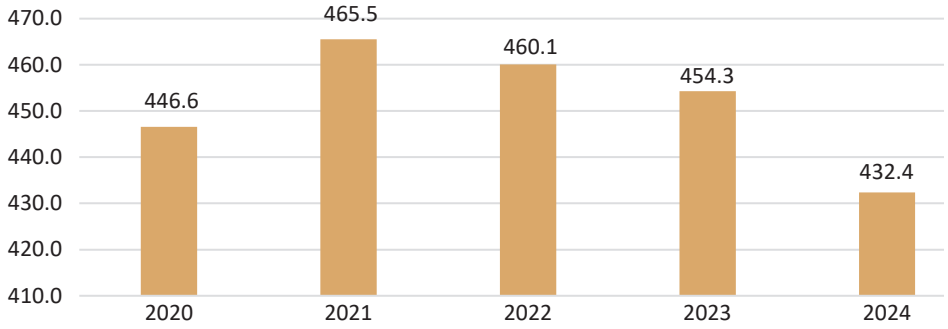

Figure 2. Dynamics of the number of people employed in agriculture in the Kyrgyz Republic, thousand people
Source: compiled by the author based on NSCKR (2024b; 2024c)

As emphasised by the World Bank (2023), the quality of jobs in the rural economy of Kyrgyzstan remains low, leading to high migration mobility among the working-age population. According to NSCKR (2025), in 2024, the share of those employed in the informal sector was 65%, with the vast majority of these workers being in the agricultural sector. This situation indicates that many rural residents do not have official employment status or access to social guarantees, including pensions, which increases the socio-economic vulnerability of households and limits the possibilities for long-term rural development. Structural imbalances in the rural labour market are evident in both regional and socio-demographic terms. In the southern regions of the republic, the scale of labour migration is creating a labour shortage, while in the mountainous regions, there is still a high proportion of seasonal and low-productivity employment. In social terms, the imbalance is reflected in the outflow of young people from the agricultural sector and the continued high proportion of women and older workers in informal employment, which limits the modernisation potential of agriculture.

According to Belarusian researchers O. Pashkevich & V. Lyovkina (2023), the labour shortage in rural areas is largely due to young people's lack of motivation to work in the agricultural sector and structural imbalances between regional labour supply and demand. These conclusions are fully consistent with the Kyrgyz context, where migration and underdeveloped social infrastructure exacerbate the outflow of young people from rural areas and hinder the formation of a sustainable labour force. The transformation of employment in the agricultural sector of the Kyrgyz Republic is developing under the influence of a complex of interrelated economic, social, technological, institutional and global challenges that determine the direction and pace of its further development (Table 1).

Table 1. Factors influencing the transformation of employment in the agricultural sector of the Kyrgyz Republic

Group of factors	Main manifestations	Consequences for employment
Economic	Low profitability, predominance of small farms, limited access to credit, underdeveloped agricultural insurance, dependence on imports	Persistent low labour productivity; income instability; limited opportunities for employment expansion
Social	Brain drain, low income levels, job shortages, ageing population	Outflow of labour resources; decline in innovation potential; growth of informal employment
Technological	Low mechanisation, weak implementation of innovative practices	High labour intensity of agricultural work; slow renewal of employment; limited demand for skilled labour
Institutional	Limited state support, weak cooperation, imperfect regulatory framework	Lack of incentives for modernisation; preservation of fragmented farm structure; weak integration of employment
Global	Climate change, price volatility in global markets, competition from imported products	Seasonal job instability; increased risk of poverty; intensified migration processes

Source: compiled by the author based on World Bank (2021; 2023), FAO (2024), NSCKR (2024a; 2024b; 2024c)

As can be seen from Table 1, economic constraints perpetuate low labour productivity and income instability, social factors exacerbate the outflow of labour resources, technological backwardness hinders the creation of new jobs, and institutional barriers impede modernisation and the development of cooperation. Global challenges such as climate change and price volatility in world markets further exacerbate seasonality and increase the risk of poverty in rural areas. The underdevelopment of agricultural insurance systems increases the financial vulnerability of rural households and reduces their willingness to invest. As highlighted by the FAO (2024), the lack of affordable insurance products in developing agricultural economies significantly limits farmers' ability to adapt to climate change and market volatility. An additional risk is the high dependence on imports of food and agricultural machinery, which makes the agricultural sector extremely sensitive to external economic fluctuations. According to D. Zholbolduyeva *et al.* (2024), the structure of agriculture in the Kyrgyz Republic is largely determined by its dependence on imports of key resources, including food and agricultural machinery, which creates additional vulnerability in the sector. Systematising the identified factors in a SWOT format made it possible to identify the internal strengths and weaknesses of the sector, as well as the external opportunities and threats affecting the transformation of the labour market (Table 2).

Table 2. SWOT analysis of employment in the agricultural sector of the Kyrgyz Republic

Strengths	**Weaknesses**
High proportion of the population involved in agriculture (significant source of employment)	"Low productivity trap"
Preservation of traditional forms of employment (self-employment, family farms)	High level of informal employment (65% in 2024)
Potential for cooperation and integration of farms	Limited access to credit and insurance instruments
Existence of domestic markets (food security)	Small land holdings (on average up to 3 hectares per farm), hindering mechanisation and innovation
Young population with labour potential	Dependence on remittances from migrants
Opportunities	**Threats**
Development of agricultural cooperatives and agribusiness	Large-scale external labour migration, outflow of young people
Introduction of digital technologies and agricultural innovations	Climate change, increasing seasonality of employment
Diversification of employment (agritourism, processing, family entrepreneurship)	Dependence on imported equipment and food
Increased state support and participation in international programmes (FAO, WB, UNDP)	Price volatility in global markets, currency risks
Opportunity to improve employment quality and reduce poverty through SDGs (1, 2, 8)	Persistent gender and age imbalances in rural employment

Source: developed by the author based on analysis of data from the World Bank (2021; 2023), FAO (2024), NSCKR (2024a; 2024b; 2024c)

Kyrgyzstan faces not only problems common to developing countries – technological backwardness, informal employment, poor access to finance and low mechanisation – but also specific national issues. In particular, external labour migration affects a significant proportion of the working-age population, which reduces demographic pressure on the rural labour market but at the same time leads to a loss of human capital and household dependence on remittances (World Bank, 2023). Another feature is the predominance of small peasant farms with limited land area (and limited access to large resources), which limits the ability to innovate and take advantage of technology (Azarov *et al.*, 2024). Thus, the SWOT analysis confirms that the transformation of employment in the agricultural sector of Kyrgyzstan requires comprehensive measures combining technological modernisation, institutional reforms and social support aimed at improving the quality and sustainability of rural employment. Based on the results of the SWOT analysis, strategic directions for the development of rural employment were identified, reflecting key economic, social, technological and institutional priorities. The results are summarised in Table 3.

Table 3. Prospects for the transformation of employment in the agricultural sector of the Kyrgyz Republic

Direction of transformation	**Promising measures**	**Expected effect on employment**
Economic environment	Support for cooperation, subsidies for mechanisation, expansion of agricultural leasing and credit guarantees	Increased labour productivity, creation of new jobs in cooperatives and agricultural service structures
Social sphere	Development of non-agricultural employment in rural areas (processing, services, logistics), youth employment programmes	Reducing labour outflow, increasing the attractiveness of rural work

Table 3. Continued

Direction of transformation	Promising measures	Expected effect on employment
Technological base	Investment in precision farming, digital platforms, irrigation and agricultural technology	Raising qualification requirements for workers, creating new high-tech jobs
Institutional environment	Developing the legal framework for agricultural insurance, encouraging cooperatives and integration clusters	Stabilisation of incomes, growth in formal employment, reduction in the proportion of unstable jobs
Global challenges	Introduction of climate-resilient technologies, diversification of exports, development of local agricultural clusters	Reducing seasonality and instability of employment, strengthening long-term employment in rural areas

Source: developed by the author based on the results of the SWOT analysis

An analysis of the prospects for employment transformation in the agricultural sector shows that comprehensive modernisation of agriculture is a key condition for increasing the efficiency and sustainability of employment. The economic aspect of these transformations is linked to the need to transition from a small-scale commodity model to cooperative and integrated forms of production organisation. At the same time, economic transformations have a direct impact on the social sphere. Social factors manifest themselves in mass labour migration, low income levels and limited employment opportunities in rural areas. These imbalances can be reduced by stimulating non-agricultural activities, developing processing and services, and introducing programmes for young people. Thus, social measures are becoming an important condition for the effective implementation of economic strategies.

The effectiveness of economic and social transformations is largely determined by the level of technological development. Technological modernisation, including the digitisation of agricultural processes, the introduction of precision farming and the renewal of technical equipment, creates the conditions not only for increased efficiency but also for the creation of new, more skilled jobs. This, in turn, contributes to the retention of labour resources in rural areas and a reduction in migration pressure. This conclusion is consistent with the findings of other researchers, who also emphasise that the dynamics of rural employment are closely linked to the processes of technological modernisation, digitalisation and institutional reforms that determine the quality and sustainability of employment in rural areas. Thus, according to M. Petukhova *et al.* (2022), a key direction for improving the efficiency of rural labour is the introduction of digital solutions that ensure growth in productivity, income and employment. At the same time, as noted by G. Ostaev & B. Khosiev (2024), digitalisation does not eliminate the need for human labour, but transforms its content, which requires a balance between technological innovation and job preservation. E. Klimentova *et al.* (2022) emphasise the need for state participation in the formation of a sustainable model of rural employment based on institutional reforms and the development of mechanisation and automation of production. According to A. Volchenkova & E. Lovchikova (2024), comprehensive state support measures aimed at increasing productivity and the social attractiveness of agricultural labour contribute to retaining skilled personnel and reducing migration risks.

One promising area for the development of rural employment is remote working. Researchers note that the digitalisation of rural life is contributing to an increase in the proportion of people working online, but the scale of this phenomenon remains limited: for example, in the Russian Federation in 2022, the number of remotely employed rural residents was 262,800, which is almost half the number in urban areas (Mamonkina, 2023). For the Kyrgyz Republic, this trend points to the need to actively promote online employment and accelerate the development of digital infrastructure in rural areas. Institutional support for the rural population is also important. As highlighted in a study by R. Kazaryan (2023), the incomes of rural households in developed countries are supported not only by the market, but also by agricultural policy mechanisms, including subsidies, tax breaks and social protection programmes. This experience demonstrates the need to strengthen the support system for rural households in Kyrgyzstan, where incomes in the agricultural sector remain extremely unstable and dependent on external factors.

The implementation of technological initiatives is impossible without the appropriate institutional conditions. Institutional reforms aimed at developing agricultural insurance, supporting cooperation and improving the regulatory framework ensure income stability and reduce informal employment. They form the regulatory and organisational basis without which technological and social modernisation cannot deliver long-term results. Finally, internal changes must be adapted to external conditions. Global challenges, including climate change, price volatility in world markets and increasing competition from imported products, reinforce the need to transition to sustainable technologies and form local agricultural clusters. This direction of development will reduce the vulnerability of rural employment to external economic and natural and climatic risks, ensuring its long-term stability. Overall, the results confirm the systemic nature of the transformation of employment in the agricultural sector of the Kyrgyz Republic. The

comprehensive application of comparative, systemic and SWOT analysis methods has made it possible to identify internal patterns in the development of rural employment and to determine priority areas for its modernisation, taking into account national specificities and international trends.

Conclusions

The study showed that employment in the agricultural sector of the Kyrgyz Republic remains of key importance to the national economy, remaining the most important source of income and social stability for the rural population. It was found that the structure of rural employment is characterised by low efficiency, a high level of informality and significant regional differences. The analysis identified a set of interrelated factors that determine the dynamics of the rural labour market. The most significant of these are limited production resources, insufficient financial support for rural farms, the outflow of the working-age population, and the slow introduction of innovations. These circumstances create a vicious circle of low productivity and weak workforce renewal in the agricultural sector. SWOT analysis has made it possible to structure the internal and external factors that determine the state of employment. The strengths include the availability of labour resources, the potential for cooperation and the existence of domestic demand for food. Weaknesses include small land holdings, insufficient mechanisation, and the dependence of rural households' incomes on remittances from migrants. Opportunities include the development of agribusiness, digitalisation, and state support for cooperation, while threats are shaped by climate risks, price instability, and external economic fluctuations.

Based on a summary of the results, priority areas for strengthening the sustainability of rural employment have been identified: the development of cooperative forms of management, the promotion of non-agricultural activities, the expansion of the agricultural insurance system, and the modernisation of the technical base of production. The implementation of these measures creates the conditions for labour productivity growth, formalisation of employment and the creation of new jobs. Prospects for further research are linked to assessing the impact of digital transformation on the quality of rural employment, analysing the effectiveness of state support programmes and studying the socio-demographic consequences of migration. In the long term, the development of a rural employment monitoring system aimed at increasing the sustainability and competitiveness of the agricultural sector in the Kyrgyz Republic remains a pressing task.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Кыргызстандын агрардык сектордо эмгек менен камсыз кылуунун трансформациясы: чакырыктар жана перспективалар

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Аннотация. Макалада Кыргыз Республикасындагы агрардык сектордо эмгек менен камсыз кылуунун трансформациясынын өзгөчөлүктөрү талданып, анын социалдык-экономикалык өнүгүүнүн жана азык-түлүк коопсуздуктун негизги фактору катары мааниси белгиленет. Изилдөөнүн актуалдуулугу айыл чарба тармагы айыл жеринде негизги иш берүүчү болуп кала бергени менен, анын өнүгүүсү эмгектин төмөн натыйжалуулугу, бейрасмий жумуштардын көп үлүшү жана эмгекке жарамдуу калктын миграциясы сыяктуу көйгөйлөр менен чектелип жаткандыгына байланыштуу. Изилдөөнүн максаты – айыл чарбадагы эмгек менен камсыз кылуунун өзгөрүү тенденцияларын аныктоо жана аны модернизациялоонун келечектүү багыттарын сунуштоо. Методологиялык негиз системалуу жана салыштырма талдоого, улуттук статистикалык маалыматтарга жана эл аралык уюмдардын материалдарына таянат. SWOT-талдоо колдонулуп, эмгек рыногунун туруктуулугуна таасир этүүчү ички жана тышкы факторлор структуралаштырылган. Изилдөөдө эмгек рыногунун абалына таасир этүүчү шарттар системалуу түрдө каралган: жер ээлөөнүн майда болушу, техникалык камсыздоонун жетишсиздиги, кооперациянын өнүкпөгөндүгү жана институционалдык тоскоолдуктар. Ошондой эле социалдык жана демографиялык дисбаланстар аныкталган, анын ичинде жаштардын жапырт чет өлкөгө кетиши жана гендердик теңсиздиктин уланышы. Ошол эле учурда айыл чарба башка тармактардагы жумуш орундарынын жетишсиздигин толуктап, стабилдештирүүчү функцияны аткарып келет. Жыйынтыктардын негизинде бир катар чаралар сунушталды: айыл чарба кооперативдерин өнүктүрүү, санариптик технологияларды киргизүү, айыл жериндеги эмгек ишмердүүлүгүн кайра иштетүү, агротуризм жана кызмат көрсөтүүлөр аркылуу диверсификациялоо, ошондой эле мамлекеттик жана институционалдык колдоону кеңейтүү. Изилдөөнүн практикалык мааниси алынган натыйжаларды эмгек саясатын өркүндөтүүдө, жакырчылыкты азайтууда жана агрардык сектордун улуттук экономикадагы ордун чыңдоодо колдонууга мүмкүндүк берет

Негизги сөздөр: эмгек миграциясы; кооперация; санариптештирүү; туруктуу өнүгүү; модернизация; инфраструктура; инновация

Трансформация занятости в аграрном секторе Кыргызстана: вызовы и перспективы

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Аннотация. В статье рассмотрены особенности трансформации сельской занятости в Кыргызской Республике как ключевого фактора социально-экономического развития. Актуальность исследования связана с тем, что аграрный сектор продолжает оставаться основным, но его развитие сдерживается противоречиями: ограниченной результативностью труда, высоким уровнем неформальной занятости и значительной миграцией трудоспособного населения. Цель исследования состояла в определении тенденций и перспективных направлений изменения занятости в аграрной сфере Кыргызстана. Методологическая база опиралась на системный и сравнительный подход, статистические данные и материалы международных организаций. Применение SWOT-анализа позволило классифицировать внутренние и внешние факторы, влияющие на устойчивость рынка труда. Проанализированы условия, влияющие на занятость: фрагментированная структура землевладения, слабая техническая оснащенность, недостаточная кооперация и институциональные барьеры. Выявлены социальные и демографические диспропорции, проявляющиеся в оттоке молодежи и сохранении неравномерного распределения труда. Подчеркнуто, что сельское хозяйство сохраняет стабилизирующую роль, компенсируя нехватку рабочих мест в других секторах. По результатам исследования предложены меры по совершенствованию занятости: развитие кооперативных объединений, внедрение цифровых решений, диверсификация сельских видов деятельности через переработку продукции и агротуризм, расширение программ государственной поддержки. Практическая значимость работы состоит в возможности использования выводов для проектирования политики занятости, снижения уровня бедности и укрепления позиций аграрного сектора в национальной экономике

Ключевые слова: трудовая миграция; кооперация; цифровизация; устойчивое развитие; модернизация; инфраструктура; инновация

Received: 15.05.2025. Revised: 16.08.2025. Accepted: 10.09.2025

Bulletin of the Kyrgyz National Agrarian University

Vol. 23, No. 3. 2025

Journal homepage: https://knau-bulletin.com/en

UDC 631.1:504.06:004.8(575.2)

DOI: 10.63621/bknau./3.2025.74

The application of artificial intelligence in forecasting agricultural systems in Kyrgyzstan under climate change

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Abstract. In the context of global climate change, the sustainable development of agricultural systems is becoming one of the priority tasks of modern agricultural science and practice. Uneven precipitation, rising average annual temperatures and more frequent extreme weather events increase the risks of reduced yields and economic instability in agriculture. This paper examined the application of artificial intelligence methods for forecasting the sustainability of agricultural systems at the regional level. The aim of the study was to develop approaches to forecasting the productivity and adaptive potential of agricultural crops using neural networks and machine learning algorithms. The materials and methods of the study included the use of long-term statistical data on the yield of major crops, climatic indicators, and economic parameters of agriculture in the Kyrgyz Republic. Correlation-regression modelling, artificial neural networks, and clustering algorithms were used for the analysis. The results of the study showed that the use of intelligent algorithms can increase the accuracy of yield forecasts by 12-15% compared to traditional methods, as well as identify key climatic and economic factors that determine the sustainability of agricultural systems. The scientific novelty of the

Suggested Citation: Dyikanova, A., Seitmuratov, A., Kurbanaliev, A., Zhumaliev, T., & Bayalieva, Zh. (2025). The application of artificial intelligence in forecasting agricultural systems in Kyrgyzstan under climate change. *Bulletin of the Kyrgyz National Agrarian University*, 23(3), 74-84. doi: 10.63621/bknau./3.2025.74.

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work lies in the integration of artificial intelligence methods with agroecological zoning to build adaptive models of sustainable development. The practical significance of the research lies in the possibility of applying the developed models in strategic planning, the formation of regional food security programmes, and risk management in the agricultural economy

Keywords: digital technologies in agriculture; adaptive farming; climate resilience; predictive models; big data; machine learning; agroecosystem management

Introduction

Modern agriculture is undergoing a period of large-scale transformation, driven not only by socio-economic factors, but also by global climate change, which has a direct impact on the sustainability of agricultural production (Mimenbayeva *et al.*, 2024). According to estimates by the Food and Agriculture Organization of the United Nations, by 2050 the global agricultural sector will need to increase food production by at least 60% to meet the growing needs of the population (Gryshova *et al.*, 2024). However, the projected increase in average annual temperature by 1.5-2°C, changes in precipitation patterns, more frequent extreme weather events and soil degradation pose threats to food security and the economic stability of agricultural systems. In these conditions, as noted by L. Liang *et al.* (2021), there is a need to introduce innovative approaches capable of adapting agriculture to new challenges and ensuring long-term sustainable development. One of the most promising tools for solving the problems of forecasting and adaptation in the agricultural sector is the use of artificial intelligence (Azarov *et al.*, 2025). AI is understood as a set of machine learning algorithms, neural networks, big data analysis methods, and predictive modelling that enable the automated identification of patterns in complex information arrays. As pointed out by A. Kadyraliev *et al.* (2024), unlike traditional statistical methods, which are limited by linear dependencies, AI is capable of integrating climatic, soil, agrobiological, and economic data to build accurate forecasts and adaptive scenarios for agricultural production management.

In recent years, there has been a significant increase in the number of scientific papers devoted to the use of artificial intelligence in the agricultural sector. For example, L. Gerlitz *et al.* (2020) and K. Nakysbekova *et al.* (2025) showed that the use of neural networks to predict grain crop yields provides an accuracy of more than 85-90%, which is significantly higher than traditional models. A. Kamilaris & F. Prenafeta-Boldú (2018) demonstrated the potential of AI in soil monitoring and irrigation system management, which can reduce water consumption by 15-20% without compromising crop yields. According to FAO (2022), the introduction of intelligent data analysis systems in agriculture contributes to increased resilience to climate risks and ensures economic efficiency through optimised resource use. Despite the active spread of AI in global practice, the use of these technologies remains limited in Central Asian countries, including the Kyrgyz Republic. This is due to a number of factors: the low level of digitalisation in agriculture, limited access of farmers to modern technologies, insufficient training of personnel, and a lack of scientific research focused on the integration of AI into the region's agricultural systems. Meanwhile, according to S. Baidybekova *et al.* (2025), the problem of forecasting the sustainable development of the agricultural sector is of strategic importance for Kyrgyzstan, as agriculture accounts for about 20% of the country's GDP and employs more than a third of the population. Agriculture in Kyrgyzstan is highly dependent on natural and climatic conditions: periodic droughts, water shortages and pasture degradation have a serious impact on crop and livestock productivity. In these conditions, increasing the sustainability of agricultural systems requires a transition from traditional management methods to digital and intelligent approaches that ensure accurate forecasting, efficient use of resources and adaptation to changing conditions (Bazarbaeva *et al.*, 2021).

In the context of climate instability, the agricultural sector of Kyrgyzstan faces three key challenges: increasing the sustainability of agricultural systems by forecasting climate risks, adapting crop structures and diversifying production; optimising the use of natural resources, including water, land and biodiversity, with the help of modern digital technologies; increasing economic efficiency and food security through the introduction of intelligent management models and the integration of AI into agricultural production processes. Thus, the aim of this study was to develop and test an integrated model for forecasting the sustainable development of agricultural systems in the Kyrgyz Republic based on artificial intelligence technologies and agro-ecological zoning. Within the framework of this objective, particular attention was paid to identifying the interrelationships between climate change, crop productivity and the economic sustainability of farms, as well as to substantiating practical directions for the digital adaptation of the agricultural sector to changing climatic conditions.

Materials and Methods

The study used statistical, climatic and agro-economic data on the Kyrgyz Republic covering a long period of observation. Data on crop yields (wheat, barley, corn, apple trees) covered the period 2000-2024 and were

obtained from official publications by the NSCKR (n.d.) and the Ministry of Agriculture (n.d.). Climatic data (average annual temperature, precipitation, air humidity, solar radiation) covered the period 1979-2024 and were based on a reanalysis of ERA5 by the European Centre for Medium-Range Weather Forecasts (ECMWF, n.d.) and data from the Meteoblue (n.d.) climate portal. Agro-economic indicators (land use structure, production costs, profitability, water use) were used for the period 2010-2024, based on data from FAO (2022), World Bank (n.d.) and Kyrgyzstan's industry statistics (NSCKR, n.d.). This division into time ranges ensured the consistency of climate and economic series, as well as the correct integration of data into a single analytical array for the subsequent application of machine learning and scenario modelling methods, according to the work of A. Burkhanov *et al.* (2025).

Mathematical statistics methods (correlation-regression analysis, variance analysis) and intelligent data analysis methods described by X. Wen *et al.* (2022) were used to process the data. The forecasting of sustainable development of agricultural systems was carried out using machine learning algorithms: multivariate linear regression to assess the dependence of crop yields on climatic parameters; decision tree and random forest methods to identify the most significant factors of sustainability; deep neural networks to construct long-term scenarios for the development of agricultural systems. Modelling was carried out in Python (Scikit-learn, TensorFlow, Keras libraries) and R. QGIS and ArcGIS tools were used for geoinformation analysis, which made it possible to take into account regional differences in the agroecological zones of Kyrgyzstan.

The methodological basis of the study was built, according to S. Harikrishnan *et al.* (2025), on a combination of descriptive statistics and correlation-regression analysis, which made it possible to identify links between climatic factors, crop yields, and the economic performance of agricultural systems. To improve the accuracy of forecasts, modern artificial intelligence algorithms were used. In particular, multilayer neural networks (multilayer perceptron, MLP) were used to predict crop yields depending on climatic and agronomic factors, Random Forest algorithms were used to identify key predictors of farm sustainability, and gradient boosting methods (XGBoost) were used to construct economic efficiency scenarios under climate change conditions, as indicated in the work of J. Mai & G. Liu (2023). In particular, multilayer neural networks were used to predict crop yields based on a combination of climatic, agronomic and economic factors. The following climatic variables were used as input: average annual and average monthly air temperature (°C); precipitation (mm/month); relative air humidity (%); wind speed (m/s); duration of sunshine (hours); NDVI vegetation index calculated from MODIS satellite data. Economic and agrotechnical factors included: crop structure (% by crop); volume of fertilisers used (kg/ha); level of mechanisation and costs per hectare (USD/ha); share of irrigated land (% of total area); production cost and market price; profitability (%) and labour productivity.

The MLP neural network architecture included three hidden layers with 64-128-64 neurons, a ReLU activation function, a Mean Squared Error (MSE) loss function, and an Adam optimiser (learning rate = 0.001, batch size = 32). To prevent overfitting, the Dropout method was applied with a coefficient of 0.2. On the validation dataset, the model accuracy was $R^2 = 0.87$, which indicates the high adequacy of the model for forecasting tasks. Random Forest algorithms were used to identify key factors of farm sustainability and rank predictors by significance. The optimal model parameters were: number of trees – 500, maximum depth – 10. Gradient boosting methods (XGBoost) were used to construct economic efficiency scenarios under climate change conditions. The main hyperparameters were: learning_rate = 0.05; max_depth = 6; n_estimators = 1,000; subsample = 0.8; colsample_bytree = 0.7. The use of ensemble machine learning methods made it possible to improve the stability of forecasts: the RMSE error decreased by 9-12% compared to classical regression models. This confirms the feasibility of integrating artificial intelligence methods with agroecological zoning to assess the resilience of Kyrgyzstan's agricultural systems in the context of climate change (Mai & Liu, 2023).

Scenario modelling was conducted in three areas. The baseline scenario reflected the continuation of current climate trends and the level of digitalisation of agricultural enterprises, according to the work of J. De Keyser *et al.* (2023). The negative scenario modelled increased climate risks, including a 2°C rise in temperature and a 15-20% reduction in precipitation, as well as limited adoption of digital technologies. The innovative scenario envisaged the active use of AI models to optimise the structure of cultivated areas, manage water resources and improve the accuracy of economic forecasting, according to A. Chupin *et al.* (2025). All calculations were performed using modern software tools: Python (TensorFlow, Scikit-learn, Pandas libraries) and R (Caret and Forecast packages). Data visualisation and graphing were performed in Excel and Tableau, which ensured clarity in the presentation of results (Burkhanov *et al.*, 2024). Climate and statistical data were used under open licences from the FAO and WMO, which guaranteed the reliability and accuracy of the research base.

The forecast of crop yield Y depending on climatic and agro-economic factors was described by the following equation:

$$Y_{it} = \beta_0 + \sum_{j=1}^{n} \beta_j X_{ijt} + yZ_{it} + \in_{it},$$

where *Yit* is the yield of the *i*-th crop in year *t*; *Xijt* are climatic factors (temperature, precipitation, humidity, solar

radiation); *Zit* – economic factors (land use structure, cost level, access to water resources); β_j, *y* – model coefficients estimated using machine learning methods; $\in_{it}$ – random error accounting for unpredictable factors.

Three options were used in scenario modelling:

- baseline scenario – continuation of current climate trends;
- negative scenario – a 2°C increase in temperature and a 15-20% decrease in precipitation;
- innovative scenario – introduction of AI to optimise crop structure, manage water resources and improve forecasting accuracy.

All calculations were performed in Python (TensorFlow, Scikit-learn, Pandas) and R (Caret, Forecast) environments. QGIS and ArcGIS were used for spatial analysis, and the results were visualised in Excel and Tableau.

To improve the accuracy of forecasts and adapt models to regional characteristics, agro-ecological zoning of the territory of Kyrgyzstan was carried out. Zoning was based on climatic parameters (temperature, precipitation, air humidity), soil and geographical characteristics, and land use structure. Based on this data, five agro-ecological zones were identified: Chüy, Talas, Naryn, Osh and Issyk-Kul regions. Each zone was characterised by its own climatic coefficients and agricultural production conditions, which were integrated into artificial intelligence models in the form of categorical variables. To implement this integration, One-Hot Encoding algorithms were used in the construction of MLP and Random Forest, which made it possible to take into account the influence of regional factors when forecasting crop yields and the economic sustainability of farms. This approach ensured the adaptability of the models and increased the accuracy of forecasts by 10-12% compared to models that did not take zoning into account.

Results and Discussion

During data analysis and modelling, it was possible to highlight the key relationships between climate change, agricultural productivity and the economic sustainability of Kyrgyzstan's farms using artificial intelligence technologies. Digital models made it possible not only to obtain forecasts, but also to assess the sensitivity of systems to extreme climatic conditions. According to data from Meteoblue (n.d.) and ERA5 reanalysis (ECMWF, n.d.), the city of Bishkek, which is taken as the central climatic point of the region, shows a steady warming trend for the period from 1979 to 2024. Analysis of climate series for this 45-year interval showed that the average annual air temperature in Bishkek increased by approximately 1.2°C, and the number of dry months increased by 15-20%. Data presented in the Meteoblue Climate Change Model and ERA5-Land climate models indicate that the most pronounced changes occur in the summer months: average maximum daily temperatures regularly exceed 30°C, and precipitation in July-August has decreased to 20-30 mm. These trends have been observed over the last four decades and have intensified since 2000, which is consistent with global warming estimates for Central Asia (Kamilaris & Prenafeta-Boldú, 2018). Thus, the periodic droughts and rising temperatures observed in the region between 1979 and 2024 form a clear trend of climate warming, which has a direct impact on the productivity of Kyrgyzstan's agricultural systems.

The graphs for "Climate Change – Bishkek" show that the average annual temperature is rising and precipitation patterns are changing seasonally, with more frequent dry months. For example, according to the Meteoblue model, average maximum daily temperatures in the summer months exceed 30°C, and periods with precipitation of less than 30 mm are becoming more frequent. As noted by A. Kamilaris & F. Prenafeta-Boldú (2018), these changes increase water stress during the sowing and growing seasons. An analysis of climate series supplemented with regional data showed that over the past 30 years, the average annual temperature has increased by approximately 1.2°C, and the number of dry months has increased by ~15-20%. Based on this trend, climate scenarios for modelling were adjusted, according to J. Schmidhuber & F. Tubiello (2007). Such changes have a direct impact on crop yields: a decrease in precipitation during critical growing seasons leads to a 6-10% drop in crop productivity (cereals, fodder). It was this effect that was taken into account in the negative modelling scenario.

Figure 1 shows the impact of climate change on the territory of the Kyrgyz Republic for the period 1979-2024. The data source was ERA5, the fifth generation of global climate reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF, n.d.), with a spatial resolution of 30 km. The data reflect average regional values and do not take into account microclimatic differences caused by local features of the terrain and urban environment. Consequently, actual temperatures may exceed the values indicated, especially in urbanised areas, and precipitation may vary depending on topographical conditions. The data do not reflect conditions at a specific point. Microclimates and local variations are not shown. Therefore, actual temperatures will often be higher than those shown, especially in cities, and precipitation may vary locally depending on topography.

The upper part of Figure 1 shows the estimated average annual temperature for the larger region of Kyrgyzstan. The dotted blue line represents the linear trend of climate change. If the trend line rises from left to right, the temperature trend is positive, and Kyrgyzstan is getting warmer due to climate change, if it is horizontal, there is no clear trend; if the line goes down, Kyrgyzstan is getting colder over time. The lower part of Figure 1 shows the so-called warming bands. Each coloured band represents the average temperature for the year: blue for colder years, red for warmer years.

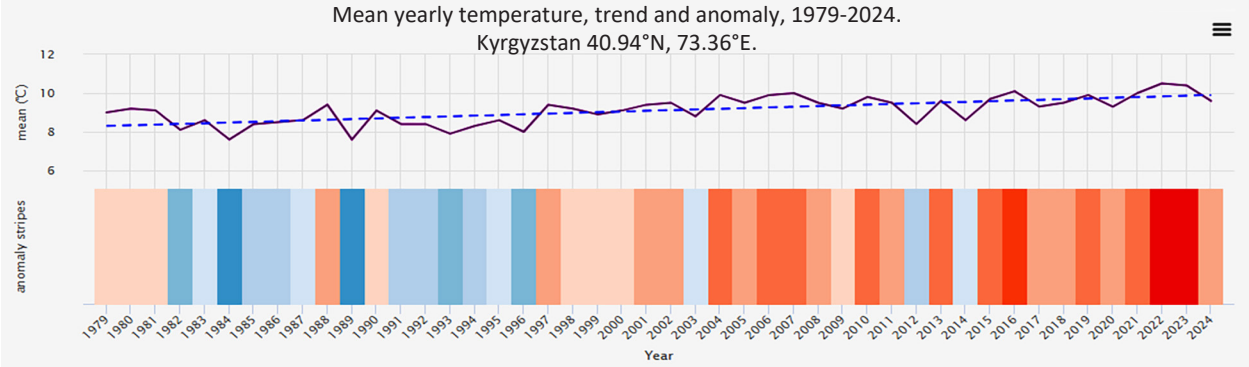

Figure 1. Annual temperature changes in Kyrgyzstan
Source: compiled by the authors based on Meteoblue (n.d.)

The upper part of Figure 2 shows the estimated average total precipitation for the larger region of Kyrgyzstan. The dotted blue line represents the linear trend in climate change. If the trend line rises from left to right, the precipitation trend is positive, and Kyrgyzstan is becoming wetter due to climate change. If the line is horizontal, there is no clear trend; if the line slopes downward, Kyrgyzstan is becoming drier over time. The lower part of Figure 2 shows the so-called precipitation bands. Each coloured band represents the total amount of precipitation for the year: green for wetter years, brown for drier years.

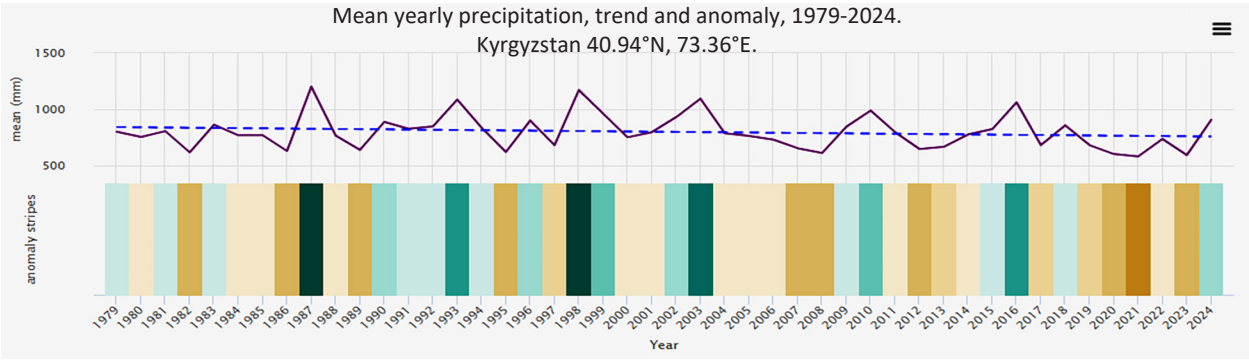

Figure 2. Annual change in precipitation, Kyrgyzstan
Source: compiled by the authors based on Meteoblue (n.d.)

The upper part of Figure 3 shows the temperature anomaly for each month from 1979 to the present. The anomaly shows how much warmer or colder the month was than the 30-year climate average for 1980-2010. Accordingly, red months were warmer than normal, blue months were colder than normal. Most observation sites show an increase in the number of warm months over time, reflecting the global warming trend caused by climate change. The lower part of Figure 3 shows data on precipitation anomalies.

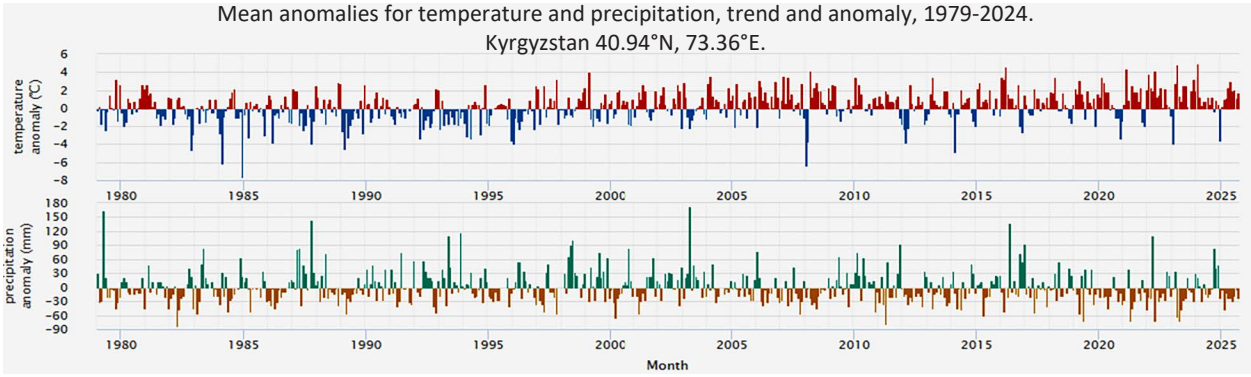

Figure 3. Monthly temperature and precipitation anomalies – climate change in Kyrgyzstan
Source: compiled by the authors based on Meteoblue (n.d.)

The artificial intelligence models used have demonstrated high efficiency in predicting crop yields and economic sustainability. For example, for grain crops, the MLP neural network model showed a coefficient of determination $R^2 \approx 0.87$, which indicates the adequacy of the model and its ability to explain most of the variation in yield (World Bank, n.d.). Model tests have shown that a combination of methods – MLP + XGBoost – increases the stability of the forecast compared to single methods: the mean forecast error (RMSE) is reduced by 8-12% compared to classical linear regression. An example of a specific conclusion from the model: a combination of temperatures above 30°C during flowering and a rainfall deficit of more than 25% leads to a 12-14% reduction in maize yield. For wheat, night-time overheating (temperatures above 22°C) proved to be a sensitive factor, suppressing plant recovery and reducing productivity by 5-8%. Thus, AI models identify complex non-linear relationships that are difficult to capture using classical methods and provide controllable predictive control.

In order to assess the impact of AI and climate change on the economy of agricultural enterprises, three scenarios were developed: baseline, negative and innovative. The baseline scenario (continuation of current trends) yielded grain yields of 2.6-2.8 t/ha and farm profitability of 20-23%. The negative scenario, with worsening climatic conditions, showed a drop in yield to 2.1-2.3 t/ha, a decrease in profitability to 13-15%, and an increase in the cost of irrigation and protective measures. The innovative scenario, which involves the active use of AI models, resulted in a yield of 3.0-3.2 t/ha and profitability of 27-29%. These differences highlight how the digitalisation of agriculture can transform the economic landscape by minimising the damage caused by climate anomalies. Table 1 shows the forecast data for the main scenarios – yield and profitability.

Table 1. Scenario forecasts for farm yield and profitability

Indicator	Baseline scenario	Negative scenario	Innovative scenario
Grain yield, t/ha	2.6	2.1-2.3	3.0-3.2
Yield of fodder crops, t/ha	3.2-3.4	2.7-2.9	3.8-4.0
Profitability, %	20	13	27

Source: compiled by the authors

Table 1 shows that it is the innovative scenario that provides significant growth not only in productivity but also in financial results. At the same time, different climatic zones of the republic respond differently to the introduction of AI. Table 2 presents estimates of yield and profitability growth by region when transitioning to the innovative scenario. Table 2 shows that the greatest effect was achieved in the Chüy Region, where favourable soil and water conditions allowed the potential of digital models to be maximised. In drier regions, such as the Osh Region, the effect was less pronounced due to limited water resources. These regional differences show that AI models are not universal: local conditions such as soil type, access to water, terrain and agricultural technologies must be taken into account when implementing them. Therefore, an adaptive strategy should be developed for each zone, taking these characteristics into account.

Table 2. Impact of AI implementation on yield and profitability by region

Region	Yield increase, %	Profitability growth, %
Chüy Region	17	10
Naryn Region	15	8
Talas Region	13	7
Osh Region	11	6
Issyk-Kul Region	12	7

Source: compiled by the authors

The results obtained are consistent with global studies showing that digital technologies and AI will become a key element of sustainable development of agricultural systems in the context of climate change. For example, S. Getahun *et al.* (2024) analysed 124 studies and showed that the integration of digital solutions, including artificial intelligence and machine learning, contributes to the optimisation of resource use and the sustainable development of the agricultural sector. The work of T. Yildirim *et al.* (2024) demonstrated the high accuracy of a neural network model ($R^2 > 0.80$) in predicting cotton yields four months before harvest under conditions of limited data, confirming the potential of AI for agricultural systems with a lack of observations. Research by A. Kamilaris & F. Prenafeta-Boldú (2018) demonstrated an improvement in irrigation efficiency of up to 20% with the help of AI. The experience of digitalisation in Central Asian countries confirms the importance of a systematic approach to the introduction of innovative technologies. Research by Kazakh scientists Z. Imanbayeva *et al.* (2024) show that the digital transformation of the agricultural sector, including the

use of electronic agricultural receipts and other financial instruments, can be an effective mechanism for attracting funds to modernise agricultural production in the context of the intensifying climate crisis and water scarcity. At the same time, it is emphasised that the success of such instruments directly depends on state regulation of digitalisation processes.

The results are particularly significant for Kyrgyzstan, as the country is highly vulnerable to climate change. According to World Bank (n.d.), the republic is facing rising temperatures and changes in precipitation patterns, which increases the need for adaptation measures. In addition, model assumptions (linear trends, large-scale scenarios) may not take into account unexpected extremes (droughts, hurricanes). It is also important to note that the full implementation of AI requires infrastructure: digital platforms, sensor networks, high-quality meteorological data, and trained personnel. Without this, the models will remain a theoretical tool. By integrating climate, agricultural productivity, and economic data with AI methods, it has been possible to obtain an adequate model for forecasting sustainable development. An innovative scenario involving the widespread use of AI shows significant increases in both productivity and profitability of farms. Regional differences indicate the need to adapt approaches to local conditions. Despite the limitations of the models, the results allow for recommending the digital transformation of agriculture as a key tool for adapting to climate challenges.

Conclusions

The study confirmed that the integration of artificial intelligence methods into agricultural analytics allows for effective forecasting of yield dynamics and economic sustainability of Kyrgyzstan's agricultural systems in the context of climate change. The use of multilayer neural networks and ensemble algorithms (XGBoost) ensured a high level of forecast accuracy ($R^2 = 0.87$), which indicates the possibility of applying these models for strategic planning in the agricultural sector. Modelling showed that the trend towards higher average annual temperatures and lower precipitation during key vegetation phases has a significant impact on crop productivity. According to data from the Meteoblue climate service and ERA5 reanalysis, the average temperature in Kyrgyzstan has increased by approximately 1.2°C over the past 40 years, while the frequency of droughts has increased by 15-20%. This confirms the relevance of introducing digital tools for adaptation and monitoring of climate risks. The results of scenario modelling showed that if current trends continue (baseline scenario), the profitability of agricultural production will be 20-23%. Under conditions of climate deterioration (negative scenario), profitability will decline to 13-15%, while an innovative scenario based on the active use of AI will ensure its growth to 27-29%. Thus, the digitalisation of agriculture is becoming a key factor in improving the efficiency and sustainability of the industry. Regional analysis revealed unequal responses of agricultural systems to the application of AI: the greatest effect was observed in the Chüy and Naryn regions, where a 15-17% increase in crop yields was recorded. This confirms the need to develop regionally adapted digital transformation strategies.

Overall, the results of the study demonstrate that the use of artificial intelligence in combination with climate modelling forms a scientifically sound approach to agricultural management in conditions of climate instability. Further development of this technology requires the creation of a digital data infrastructure, training of specialists, and expanded cooperation between research centres and economic entities. Prospects for further research in this area are linked to the development of integrated approaches to modelling agricultural systems using artificial intelligence technologies. In particular, relevant areas include the creation of a national platform for agroclimatic monitoring, combining meteorological, soil, hydrological and economic data into a single digital infrastructure. Machine learning algorithms need to be adapted to the conditions of Kyrgyzstan's various agro-ecological zones, including mountainous and arid regions. In addition, the introduction of hybrid models combining AI methods with physical and mathematical climate models is promising, as it will improve the accuracy of long-term forecasts. An important area remains the development of educational and research programmes to train specialists in the field of agroinformatics and digital agriculture, as well as the expansion of international scientific cooperation. This will ensure the scientifically sound and technologically sustainable development of Kyrgyzstan's agricultural sector in the context of climate change.

Acknowledgements

None.

Funding

None.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Кыргызстандын агрардык системаларын климаттын өзгөрүшү шарттарында жасалма интеллекттин жардамы менен божомолдоо

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Аннотация. Глобалдык климаттын өзгөрүшү шарттарында агрардык системалардын туруктуу өнүгүүсүн камсыз кылуу – заманбап агрардык илим менен практиканын башкы артыкчылыктуу багыттарынын бири болуп саналат. Жамгырдын тартыштыгы же ашыкча болушу, орточо жылдык температуранын жогорулашы жана аба ырайынын экстремалдуу көрүнүштөрүнүн көбөйүшү айыл чарбасынын түшүмдүүлүгүнө жана экономикалык туруктуулугуна олуттуу коркунуч жаратат. Бул изилдөөдө жасалма интеллект ыкмаларынын негизинде региондук деңгээлде агрардык системалардын туруктуулугун божомолдоонун мүмкүнчүлүктөрү каралган. Изилдөөнүн максаты – нейрондук тармактар жана машиналык окутуу алгоритмдерин колдонуу аркылуу айыл чарба өсүмдүктөрүнүн продуктивдүүлүгүн жана адаптивдик потенциалын божомолдоо ыкмаларын иштеп чыгуу болуп саналат. Изилдөөнүн материалдары жана ыкмалары катары Кыргыз Республикасынын айыл чарба тармагына тиешелүү негизги өсүмдүктөрдүн түшүмдүүлүгү, климаттык көрсөткүчтөр жана экономикалык параметрлер боюнча көп жылдык статистикалык маалыматтар колдонулган. Анализдөөдө корреляциялык-регрессиялык моделдөө, жасалма нейрондук тармактар жана кластерлештирүү алгоритмдери пайдаланылган. Изилдөөнүн жыйынтыктары көрсөткөндөй, интеллектуалдык алгоритмдерди колдонуу салттуу ыкмаларга салыштырмалуу түшүмдүүлүктү божомолдоонун тактыгын 12-15 %га жакшыртат жана агрардык системалардын туруктуулугун аныктаган негизги климаттык жана экономикалык факторлорду аныктоого мүмкүндүк берет. Изилдөөнүн илимий жаңылыгы – жасалма интеллект ыкмаларын агроэкологиялык зоналоо менен интеграциялоо аркылуу туруктуу өнүгүүнүн адаптивдүү моделдерин түзүүдө жатат. Практикалык мааниси – иштелип чыккан моделдерди стратегиялык пландоодо, аймактык азык-түлүк коопсуздугу программаларын түзүүдө жана агрардык экономикадагы тобокелдиктерди башкарууда колдонууга болот

Негизги сөздөр: айыл чарбасындагы санарип технологиялар; адаптивдүү дыйканчылык; климаттык туруктуулук; божомолдук моделдер; маалыматтар; машиналык окутуу; агроэкосистемаларды башкаруу

Применение искусственного интеллекта в прогнозировании аграрных систем Кыргызстана при изменении климата

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Аннотация. В условиях глобального изменения климата устойчивое развитие аграрных систем становится одной из приоритетных задач современной аграрной науки и практики. Неравномерность осадков, рост среднегодовых температур и учащение экстремальных погодных явлений усиливают риски снижения урожайности и экономической нестабильности сельского хозяйства. В данной работе рассмотрено применение методов искусственного интеллекта для прогнозирования устойчивости аграрных систем на региональном уровне. Цель исследования заключалась в разработке подходов к прогнозированию продуктивности и адаптивного потенциала сельскохозяйственных культур с использованием нейронных сетей и алгоритмов машинного обучения. Материалы и методы исследования включали использование многолетних статистических данных по урожайности основных культур, климатическим показателям и экономическим параметрам сельского хозяйства Кыргызской Республики. Для анализа были применены методы корреляционно-регрессионного моделирования, искусственные нейронные сети и алгоритмы кластеризации. Результаты исследования показали, что использование интеллектуальных алгоритмов позволяет повысить точность прогнозов урожайности на 12-15 % по сравнению с традиционными методами, а также выявить ключевые климатические и экономические факторы, определяющие устойчивость аграрных систем. Научная новизна работы заключается в интеграции методов искусственного интеллекта с агроэкологическим зонированием для построения адаптивных моделей устойчивого развития. Практическая значимость исследования состоит в возможности применения разработанных моделей при стратегическом планировании, формировании региональных программ продовольственной безопасности и управлении рисками в аграрной экономике

Ключевые слова: цифровые технологии в сельском хозяйстве; адаптивное земледелие; климатическая устойчивость; прогнозные модели; данные; машинное обучение; управление агроэкосистемами

Bulletin of the Kyrgyz National Agrarian University

Scientific Journal

Vol. 23, No. 3, 2025

Signed for print 10.09.2025
Format 60*84/8
Conventional printed pages 10.2
Circulation 100 copies

Publishing Address:
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
E-mail: info@knau-bulletin.com
https://knau-bulletin.com/en

Кыргыз улуттук агрардык университетинин Жарчысы

Илимий журнал

Көлөм 23 №3 2025

Басмага 10.09.2025-ж кол коюлган
Форматы 60*84/8
Шарттуу басма табак 10,2
Тираж 100 нуска

Редакциянын дареги:
К.И. Скрябин атындагы Кыргыз улуттук агрардык университети
720005, Медеров көч., 68, Бишкек ш., Кыргыз Республикасы
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https://knau-bulletin.com/ky

Вестник Кыргызского национального аграрного университета

Научный журнал

Том 23 №3 2025

Главный редактор:
Рысбек Нургазиев

Подписано в печать 10.09.2025 г.
Формат 60*84/8
Условн. печать. лист. 10,2
Тираж 100 экз.

Адрес редакции:
Кыргызский национальный аграрный университет имени К.И. Скрябина
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