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The development of primers and the installation of PCR for the detection of coronavirus SARS-CoV-2

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Abstract. The relevance of this study stems from the need to improve the accuracy and sensitivity of laboratory diagnostics for COVID-19, particularly in the early stages of infection and with low viral loads. The aim of the study was to validate and experimentally evaluate the performance of a pair of primers targeting the SARS-CoV-2 nucleocapsid gene using a plasmid positive control. The study utilised computer-aided primer design using standard criteria, testing their specificity against nucleotide sequence databases, modelling a plasmid construct with the target fragment, and performing one-step reverse transcription followed by polymerase chain reaction and agarose gel analysis of the products. Primers N9171F and N9368R, 20-22 nucleotides in length, with optimal GC content and consistent melting temperatures, were developed and characterised. Bioinformatics analysis revealed a lack of significant tendency to form stable hairpins and dimers, and confirmed minimal homology with off-target sequences, which increases amplification specificity. Recombinant plasmid DNA pJET1.2, containing a 197-bp insert of the target fragment, was used as a positive control. Visualisation of the construct map confirmed the presence of the diagnostic insert and its ease of use for reaction control. Experimental results demonstrated the production of

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a specific product of the expected size (197 bp) during SARS-CoV-2 RNA analysis, while the negative amplification control did not produce any, confirming the accuracy of the reaction and reducing the risk of false negative results with a valid control. The practical value of this work lies in the potential for using the proposed primer pair and plasmid control in laboratories for RT-PCR testing in laboratory diagnostics, epidemiological monitoring, and the development of diagnostic test systems for detecting the coronavirus pathogen

Keywords: plasmid; nucleotide; diagnostics; amplification; BLAST

Introduction

The need to develop and optimise primers for the SARS-CoV-2 nucleocapsid (N) gene stems from the virus's continued circulation, the emergence of new genetic variants, and the need to ensure reliable laboratory diagnostics at the national level. Despite a decline in global incidence compared to the peak levels of 2020-2022, COVID-19 remains a significant respiratory infection causing severe complications in vulnerable population groups. Given the genetic variability of the virus, the effectiveness of existing test systems may decline, requiring regular revision of primer and probe designs, particularly for conserved regions of the genome such as the N gene. D. Dutta *et al.* (2022) analysed the diagnostic performance of RT-PCR in clinical samples from 312 patients and demonstrated that test systems targeting the N gene provided a detection limit of up to 10 RNA copies/reaction at a specificity of 99.3%, which exceeded the performance of tests targeting the S gene exclusively. The authors emphasised that the high transcriptional activity of the N gene results in a greater quantity of subgenomic RNA, increasing the likelihood of virus detection in the early stages of infection.

In their study, A. Mentes *et al.* (2022) proposed an *in silico* pipeline for identifying genomic variants that overlap with the target regions of widely used SARS-CoV-2 PCR primer sets, based on large datasets including sequences from GISAID. They found that mutations affecting primer target sites – particularly in Omicron lineages – impair detection by some assays, increasing the proportion of samples classified as misclassified. These findings underscore the need for regular *in silico* assessment of primer-template complementarity as circulating variants evolve. D. Negrón *et al.* (2022) conducted a large-scale *in silico* analysis of over 1.6 million SARS-CoV-2 genomes and demonstrated that the accumulation of mutations in primer and probe binding regions can lead to a reduction in the sensitivity of PCR assays. This indicates a potential decline in assay sensitivity over time and highlights the need for continuous monitoring and redesign of primers. H. Li *et al.* (2020) developed a modified set of primers targeting a conserved region of the N2 region and tested it on 186 clinical samples. The sensitivity of the method was 98.9%, and the limit of detection was 5 RNA copies per reaction. Compared with the reference protocol, sensitivity increased by 6.3%, particularly in samples with a viral load of less than 10^3 copies/mL.

In their review of COVID-19, M. Cascella *et al.* (2025) provided a comprehensive overview of the clinical features, epidemiology and diagnostic methods for SARS-CoV-2, including a discussion of molecular diagnostics using PCR. The authors noted that SARS-CoV-2, like other RNA viruses, rapidly accumulates mutations in its genome, which influences the virus's evolution and requires careful consideration when selecting targets for diagnostic assays, as changes in target sequences can potentially reduce the sensitivity of RT-qPCR tests. This highlights the importance of monitoring circulating variants to maintain the effectiveness of existing diagnostic primers. Research by R. Wang *et al.* (2020) demonstrates that the N gene remains one of the most stable and diagnostically significant targets of SARS-CoV-2. The constant evolution of the virus necessitates regular analysis of genomic data, optimisation of primer sequences, and experimental validation of their efficacy. Furthermore, the one-step RT-PCR format is more cost-effective and technologically convenient for routine use in clinical diagnostic laboratories. Combining the reverse transcription and amplification steps in a single reaction tube reduces the duration of the assay by an average of 30-40% compared to two-step protocols, reduces the consumption of enzymes and plasticware, and minimises the risk of contamination. This is particularly important during mass testing and when handling a high throughput of clinical samples. Reducing the number of steps decreases staff workload and improves the reproducibility of results, making one-step RT-PCR the optimal tool for rapid and reliable laboratory diagnosis of SARS-CoV-2.

According to the WHO (2022), equitable distribution of and access to COVID-19 diagnostic tools, including molecular tests such as PCR kits, remain inadequate in many low- and middle-income countries. The report highlights persistent gaps in regulation, supply and domestic delivery mechanisms that hinder timely and reliable access to diagnostic tools, underscoring the ongoing challenges countries face in maintaining a stable diagnostic capacity for SARS-CoV-2. For example, not all laboratories in the Republic of Kazakhstan and the Kyrgyz Republic have stable and timely access to commercial diagnostic kits for detecting SARS-CoV-2. Constraints related to supply logistics, currency dependence and periodic disruptions in the global reagent market may reduce the efficiency of laboratory surveillance of infectious diseases, particularly in remote regions. Given the ongoing circulation of the virus and the need to monitor new variants, such reliance on imported test kits poses a potential epidemiological risk. In this regard, the development in such countries of test systems based on their own molecular genetic solutions, including the design of primers and probes targeting conserved regions of the SARS-CoV-2 N gene, takes on particular significance. The creation of local diagnostic methods makes laboratory diagnostics more accessible, ensures flexibility in adapting to new variants of the virus, and reduces the cost of testing. Furthermore, the implementation of nationally developed technologies helps to strengthen the region's scientific and technological capacity and establish a sustainable biosafety system.

The optimisation of primers for the SARS-CoV-2 N gene in a one-step RT-PCR format is of not only scientific and methodological but also strategic importance, ensuring laboratories' independence from external suppliers and enhancing the preparedness of the healthcare systems in Kazakhstan and Kyrgyzstan for current and future epidemiological challenges. The aim of this study was to develop and experimentally optimise primers for conserved regions of the SARS-CoV-2 N gene, taking into account current genomic data on circulating variants of the virus, and to evaluate their analytical sensitivity and specificity in a one-step RT-PCR assay.

Materials and Methods

The research was conducted at the Research Institute for Biological Safety Issues of the QazBioPharm National Holding (Republic of Kazakhstan) in 2025. The SARS-CoV-2 strain SARS-CoV-2/human/KAZ/Delta-020/2021 was used in the study. Viral RNA was isolated under BSL-2 biosafety conditions using the innuPREP Virus DNA/RNA Kit (IST Innuscreen GmbH, Berlin, Germany) in accordance with the manufacturer's instructions. The concentration and quality of the isolated RNA were assessed using a NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, USA). The A260/A280 and A260/A230 ratios were used to assess the purity of the preparation, with values in the range of 1.8-2.0 and > 1.8, respectively, being considered acceptable.

A constructed plasmid DNA containing a fragment of the SARS-CoV-2 N gene was used as a positive control. A 197-base-pair (bp) nucleotide sequence corresponding to the SARS-CoV-2 N-gene fragment was cloned into the pJET1.2 plasmid vector using the CloneJET PCR Cloning Kit (Thermo Fisher Scientific Baltics, Lithuania). Transformation was carried out in competent E. coli DH5α cells, and recombinant clones were selected on LB agar supplemented with ampicillin (100 μg/mL). Plasmid DNA was isolated using a plasmid extraction kit and verified by Sanger sequencing. The resulting recombinant plasmid was used as a positive control in the OT-PCR assay. A model of the pJET1.2 plasmid construct with the N-gene fragment inserted was generated using PlasMapper 3.0 software.

Primers for the detection of SARS-CoV-2 were selected based on multiple alignment of the nucleotide sequences of the relevant viral genes. Sequences of SARS-CoV-2 isolates from various geographical regions, available in the GenBank (n.d.) database, were used for the analysis. The N-gene sequences of the SARS-CoV-2 virus available in GenBank were used for alignment (Table 1).

Table 1. GenBank accession numbers for the N gene of the SARS-CoV-2 virus

Name of the gene and virus	Identification numbers of SARS-CoV-2 virus sequences in the GenBank database
The N gene of the SARS-CoV-2 virus	Severe acute respiratory syndrome coronavirus 2 isolate SARS-CoV-2/human/KAZ/Omicron-XBB.1.9.1-399/2023 [Genbank: OR485702.1, Kazakhstan], Severe acute respiratory syndrome coronavirus 2 isolate SARS-CoV-2/human/KAZ/Omicron-XBB.1.9-400/2023 [Genbank: OR485705.1, Kazakhstan], Isolate SARS-CoV-2/human/KAZ/AST-S396/2023 [Genbank: PP905483.1, Kazakhstan], isolate SARS-CoV-2/HUMAN/CHN/Delta CS/2021[Genbank: PX952996.1, China], isolate SARS-CoV-2/Vero E6/CHN/Delta CAS1\2/2024 1 [Genbank: PX952990.1, China], isolate SARS-CoV-2/human/CHN/CCS12-BA.2/2022 [Genbank: PX587945.1, China], isolate SARS-CoV-2/human/RUS/P693/2024 [Genbank: PQ510397.1, Russia]

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

Nucleotide sequences in FASTA format were imported into MEGA version 11.0 (Molecular Evolutionary Genetics Analysis) via the Align → Edit/Build Alignment module. Multiple alignment was performed using the ClustalW algorithm. Alignment parameters: gap opening penalty – 15, gap extension penalty – 6.66. Conservative regions selected for primer design were defined as areas with a sequence identity of at least 95% among the isolates analysed.

Primer pairs were designed using the Vector NTI Advance™ software (Thermo Fisher Scientific, USA) in the "Primer Design" section. The target nucleotide sequence was imported in FASTA format into the Vector NTI → Tools → Primer Design module for the automatic selection of optimal primers. The criteria for primer selection were: length 18-24 nucleotides, guanine-cytosine (GC) content 40-60%, annealing temperature 55-65°C, absence of significant secondary structures (ΔG > -3 kcal/mol for hairpins and dimers), and an amplicon size of 150-300 bp. Primer specificity was verified using the BLAST (Basic Local Alignment Search Tool) algorithm against the NCBI (n.d.) nucleotide sequence database to exclude cross-reactivity with the genomes of other microorganisms and humans.

For the detection of viral RNA by RT-PCR, primers N9171F and N9368R, targeting the SARS-CoV-2 N gene, were used. The primers were synthesised by Metabion International AG (Germany) to HPLC-grade purity. The total reaction volume was 25 μL and comprised: 12.5 μL of 2× buffer, 1 μL of enzyme mix, 1 μL each of forward and reverse primers (10 nmol), 2 μL of RNA template (5-50 ng) and deionised water to the final volume. The composition of the 2× buffer included Tris-HCl (pH 8.3), KCl, $MgCl_2$ (concentration 3 mM in the final reaction) and dNTPs (0.4 mM of each). The enzyme mix comprised reverse transcriptase, which facilitates the synthesis of complementary DNA (cDNA) from the RNA template, and Taq DNA polymerase, which carries out the amplification of the cDNA.

The RT-PCR temperature-time profile comprised a reverse transcription step at 58°C for 30 seconds, an initial denaturation step at 94°C for 1 minute, followed by 40 cycles: denaturation at 94°C for 15 s, annealing/extension at 58°C for 30 s. Amplification was performed on a SimpliAmp Thermal Cycler (Thermo Fisher Scientific, USA). The amplification products were analysed by electrophoresis in a 2% agarose gel (SeaKem LE Agarose, Lonza) with the addition of ethidium bromide (0.5 μg/mL) in 1× TAE buffer. Electrophoresis was performed at 120 V for 40 minutes. The GeneRuler 100 bp DNA Ladder (Thermo Fisher Scientific) was used as a molecular weight marker. Visualisation and documentation of the results were carried out using a gel documentation system with a UV transilluminator.

The specificity of the primers developed was analysed using the NCBI BLAST online tool. All experiments were conducted in triplicate. No statistical analysis was performed due to the qualitative nature of the RT-PCR method.

Results and Discussion

The primers were designed in accordance with standard PCR design criteria: primer length ranged from 18 to 24 nucleotides, GC content was between 40% and 60%, and the melting temperatures (Tm) of the forward and reverse primers differed by no more than 5°C. To enhance specificity, a GC-clamp was introduced at the 3′ end and the propensity for secondary structure formation was minimised. Homology with off-target sequences was checked *in silico* using nucleotide sequence databases. Table 2 lists the characteristics of the selected primers.

Table 2. Characteristics of the selected primers N9171F and N9368R for the N gene of SARS-CoV-2

Name of the primer	Nucleotide sequence (5′ → 3′)	Length, nt	GC, %	Tm, °C	Amplicon size, bp
N9171F	CATTGGCCGCAAATTGCACA	20	50.0	59	197
N9368R	TGGTGGGAATGTTTTGTATGCG Complementary: CGCATACAAAACATTCCCACCA	22	45.5	60	

Note: nt – nucleotides; GC – percentage of guanine (G) and cytosine (C) nucleotides; Tm – primer melting temperature; bp – base pairs

Source: compiled by the authors

The N9171F and N9368R primers have an optimal length (20-22 nt) and GC content (45-50%), ensuring stable and specific amplification. Melting temperature calculations showed good agreement in Tm values between the primers (difference < 2°C). Analysis of secondary structures revealed no stable hairpins or significant dimers capable of inhibiting PCR, allowing these primers to be recommended for use in PCR. Figure 1 shows the localisation of the primers on the nucleotide sequence of the coronavirus genome.

The pJET1.2 plasmid DNA is used as a positive control in PCR, as it contains the target nucleotide sequence of the SARS-CoV-2 virus's N gene. The presence of amplification when using this control confirms the correctness of the reaction conditions, the functionality of the primers and the enzyme system, and also allows false-negative test results to be ruled out (Fig. 2).

Modelling has yielded a circular map of the recombinant pJET1.2 plasmid containing an insert of the SARS-CoV-2 N gene, with a total length of 3,205 bp. The 197-bp insert, cloned into plasmid DNA, contains the target fragment of the SARS-CoV-2 N gene and is used as a positive control in PCR. The results obtained confirm that RT-PCR targeting the N gene allows for the effective detection of viral RNA, including at low viral loads, which is particularly important for the early diagnosis of COVID-19 and screening studies. The results of RT-PCR using the N9171F and N9368R primers for the detection of the SARS-CoV-2 N gene are presented in Figure 3.

The RT-PCR results for the identification of the SARS-CoV-2 virus showed that a specific PCR product of 197 bp in size was amplified using SARS-CoV-2 viral RNA. The selection of the N gene as a target for SARS-CoV-2 diagnosis is scientifically justified. As noted by P. Zhou *et al.* (2020), SARS-CoV-2 exhibits 96% identity in its whole-genome sequence with the bat coronavirus RaTG13 and 79.6% with SARS-CoV, indicating the phylogenetic proximity of this virus to coronaviruses of animal origin. Furthermore, as shown in the study by F. He *et al.* (2020), coronaviruses are a highly diversified group of RNA-containing viruses that can cause respiratory, intestinal, hepatic and neurological diseases of varying severity in humans and animals. In this regard, the selection of conserved genomic regions for diagnostic purposes becomes of critical importance. The SARS-CoV-2 coronavirus nucleocapsid protein N plays a key role in the packaging of viral RNA and viral replication, which further confirms the stability and diagnostic significance of the gene encoding it (Chang *et al.*, 2006; Dangi *et al.*, 2021; Chen *et al.*, 2022). W. Song *et al.* (2023) emphasise that the N gene is highly conserved across different viral strains and is expressed in large quantities in infected cells, which increases the sensitivity of the detection method. Using the N gene as a target reduces the likelihood of false-negative results, particularly when analysing samples with a low viral load, which is of fundamental importance for the early diagnosis of infection.

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29641 atagcaatct ttaatcagtg tgtaacatta gggaggactt gaaagagcca ccacatttc
```

Figure 1. Localisation of primers on the nucleotide sequence of the SARS-CoV-2 coronavirus genome
Source: compiled by the authors based on NCBI (n.d.)

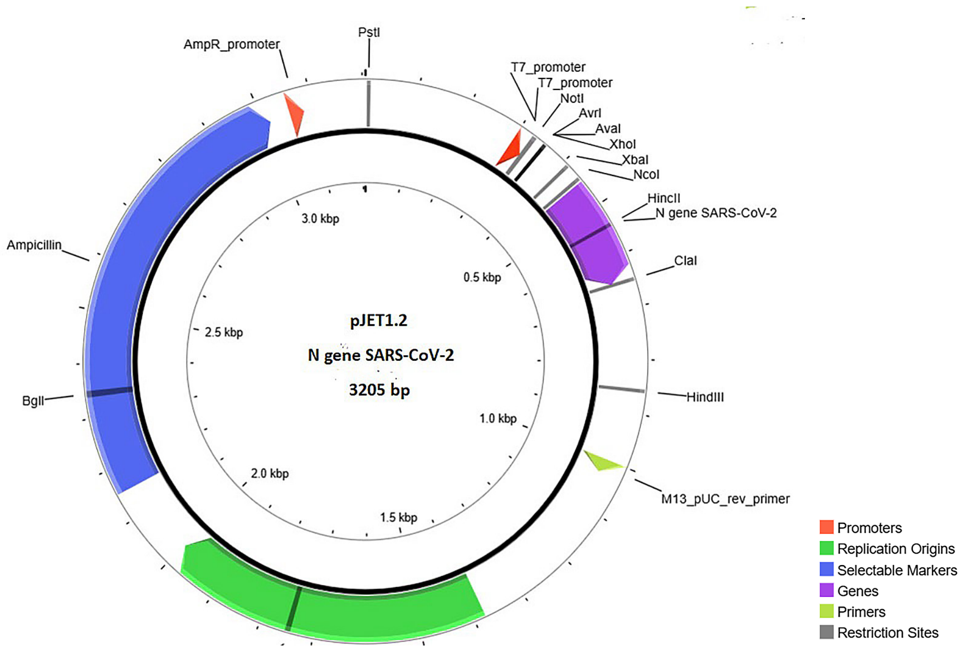

Figure 2. Circular map of the recombinant plasmid pJET1.2 containing the N gene fragment of the SARS-CoV-2 virus
Source: compiled by the authors using PlasMapper 3.0

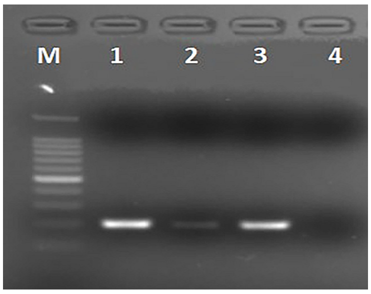

Figure 3. Results of PCR testing using the N9171F and N9368R primers for the diagnosis of SARS-CoV-2

Note: M – DNA molecular weight marker; 1 – positive control; 2, 3 – SARS-CoV-2 viral RNA; 4 – negative control

Source: compiled by the authors

The use of MEGA 11.0 software for multiple alignment of nucleotide sequences is consistent with modern approaches to bioinformatics analysis (Tamura *et al.*, 2021). This software package is widely used for phylogenetic analysis and enables the identification of conserved genomic regions that are optimal for the design of diagnostic primers. When developing PCR systems for the detection of SARS-CoV-2, the envelope protein (E) and RNA-dependent RNA polymerase (RdRp) genes are also widely used as diagnostic targets (Chu *et al.*, 2020; Pabbaraju *et al.*, 2021). The E gene is highly conserved among members of the Sarbecovirus subgenus and is frequently used in screening PCR tests due to its stability (Rangaiah *et al.*, 2021). I. Barjaktarović *et al.* (2023) highlight the diagnostic importance of detecting the E gene of the SARS-CoV-2 genome in the comprehensive diagnosis of COVID-19. The RdRp gene, which encodes a key enzyme in viral genome replication, exhibits high specificity for SARS-CoV-2 and is frequently used in confirmatory diagnostic tests (Abbasi *et al.*, 2022). Compared to the E and RdRp genes, the N gene is characterised by a combination of high conservation, specificity and expression levels. The N gene is widely used as the primary or one of the key targets in commercial and research diagnostic kits for the detection of SARS-CoV-2 (Corman *et al.*, 2020; Hu *et al.*, 2022).

A. Nalla *et al.* (2020) conducted a comparative evaluation of the effectiveness of SARS-CoV-2 detection using seven different pairs of primers and probes, including kits targeting the N gene. The results demonstrated that N-gene-based systems provide high sensitivity and specificity in the detection of viral RNA in clinical samples. The importance of accurate laboratory diagnosis of COVID-19 is also emphasised in the broader context of the pandemic's development. S. Perlman (2020) noted in his editorial that, a decade after the SARS outbreak and seven years after the emergence of MERS, humanity is facing yet another coronavirus, which highlights the need to develop reliable and accessible diagnostic systems. B. Udugama *et al.* (2020) emphasised in their review the central role of molecular diagnostics, in particular RT-PCR, as the gold standard for detecting SARS-CoV-2, whilst noting the need for validated diagnostic tools. T. Dong *et al.* (2023), in a comprehensive review of SARS-CoV-2 diagnostic and analytical methods, noted that PCR-based molecular detection methods remain the most reliable for the early detection of infection, particularly when combined with the use of multiple targets, including the N gene.

Overall, the results of this study confirm that the developed one-step PCR system, utilising the N9171F and N9368R primers targeting the conserved region of the N gene, is an effective tool for the detection of SARS-CoV-2. The use of a one-step RT-PCR format reduces analysis time, lowers the risk of contamination and simplifies the protocol compared to two-step methods, making this approach optimal for routine laboratory diagnostics. The use of the recombinant plasmid pJET1.2 containing a cloned fragment of the N-gene as a positive control allows the reaction setup procedure to be standardised and ensures the validity of the results obtained. The combination of bioinformatic analysis for primer selection and experimental verification of their efficacy demonstrates a comprehensive approach to the development of diagnostic systems. The data obtained can be used in the development of domestic diagnostic kits for the detection of SARS-CoV-2, which will help to increase the availability of laboratory diagnostics for COVID-19 in the region and reduce dependence on imported test systems.

Conclusions

As a result of the study, specific primers for the detection of SARS-CoV-2 using a one-step reverse transcription polymerase chain reaction (RT-PCR) method were developed and experimentally validated, which is of practical significance for the laboratory diagnosis of COVID-19 in the Republic of Kazakhstan and the Kyrgyz Republic. Based on bioinformatic analysis of multiple alignment of N-gene nucleotide sequences of SARS-CoV-2 isolates from various geographical regions, as presented in the GenBank database, conserved regions of the genome with a sequence identity of at least 95% were identified. Using Vector NTI Advance software, primers N9171F (20 nucleotides) and N9368R (22 nucleotides) were developed, characterised by an optimal GC content of 45-50%, melting temperatures differing by less than 2°C, and no tendency to form stable secondary structures. Verification of primer specificity using the BLAST method confirmed minimal homology with off-target sequences, which reduces the risk of non-specific amplification.

A recombinant pJET1.2 plasmid containing a 197-base-pair target fragment of the SARS-CoV-2 N gene was constructed and used as a positive control for the validation of the RT-PCR assay. The use of a plasmid control ensures standardisation of the reaction and helps to eliminate false-negative results, which is critical for the reliability of laboratory diagnostics. The performance of the developed primers has been demonstrated experimentally: when analysing RNA from the SARS-CoV-2/human/KAZ/Delta-020/2021 strain using a one-step RT-PCR method, a specific amplification product of the expected size of 197 base pairs was obtained, visualised by agarose gel electrophoresis. The absence of amplification in the negative control confirms the specificity of the reaction and the correctness of the selected conditions.

Future research plans include validating the developed method on an expanded panel of clinical samples from patients with confirmed COVID-19, determining the analytical sensitivity and specificity of the method, assessing its effectiveness in detecting new genetic variants of SARS-CoV-2, adapting the protocol for real-time PCR with fluorescent detection, and developing a multiplex test system with simultaneous detection of several target genes (N, E, RdRp) to improve the reliability of diagnosis and differentiation of SARS-CoV-2 from other respiratory pathogens.

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SARS-CoV-2 коронавирусун аныктоо үчүн Праймерлерди иштеп чыгуу жана Птрди коюу

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Аннотация. Бул изилдөөнүн актуалдуулугу COVID-19 үчүн лабораториялык диагностиканын тактыгын жана сезгичтигин жогорулатуу зарылдыгынан келип чыгат, айрыкча инфекциянын алгачкы этаптарында жана вирустук жүктөмү төмөн болгондо. Изилдөөнүн максаты SARS-CoV-2 нуклеокапсид генин плазмиддик позитивдүү башкарууну колдонуу менен бутага алган бир жуп праймердин иштешин текшерүү жана эксперименталдык түрдө баалоо болгон. Изилдөөдө стандарттуу критерийлерди колдонуу менен компьютердик жардам менен праймердин дизайны колдонулган, алардын нуклеотиддик ырааттуулук маалымат базаларына карата спецификалуулугун текшерген, максаттуу фрагмент менен плазмиданын конструкциясын моделдеген жана бир баскычтуу тескери транскрипцияны, андан кийин полимераз чынжыр реакциясын жана продуктулардын агароз гелинин анализин жүргүзгөн. Узундугу 20-22 нуклеотидден турган, оптималдуу GC курамы жана туруктуу эрүү температурасы бар N9171F жана N9368R праймерлери иштелип чыккан жана мүнөздөлгөн. Биоинформатикалык анализ туруктуу чач тырмактарын жана димерлерди түзүү тенденциясынын жоктугун көрсөттү жана максаттан тышкаркы ырааттуулуктар менен минималдуу гомологияны тастыктады, бул амплификациянын спецификалуулугун жогорулатат. Максаттуу фрагменттин 197-bp кошумчасын камтыган рекомбинанттык плазмидалык ДНК pJET1.2 оң контроль катары колдонулган. Конструкция картасын визуалдаштыруу диагностикалык кошумчанын бар экендигин жана аны реакцияны башкаруу үчүн колдонуунун оңойлугун тастыктады. Эксперименталдык жыйынтыктар SARS-CoV-2 РНК анализи учурунда күтүлгөн өлчөмдөгү (197 bp) белгилүү бир продуктунун өндүрүлгөнүн көрсөттү, ал эми терс күчөтүү контролу эч кандай натыйжа берген жок, бул реакциянын тактыгын тастыктап, жарактуу контроль менен жалган терс натыйжалардын коркунучун азайтты. Бул иштин практикалык баалуулугу сунушталган праймер жубун жана плазмидалык контролду лабораториялык диагностикада, эпидемиологиялык мониторингде жана коронавирустун козгогучун аныктоо үчүн диагностикалык тест системаларын иштеп чыгууда RT-ПЦР тестирлөө үчүн лабораторияларда колдонуу мүмкүнчүлүгүндө жатат

Негизги сөздөр: плазмид; нуклеотид; диагностика; күчөтүү; BLAST

Разработка праймеров и постановка ПЦР для выявления коронавируса SARS-CoV-2 на основе N-гена

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Аннотация. Актуальность работы обусловлена необходимостью повышения точности и чувствительности лабораторной диагностики COVID-19, особенно на ранних стадиях инфекции и при низкой вирусной нагрузке. Целью исследования было обосновать и экспериментально оценить работоспособность пары праймеров, нацеленных на нуклеокапсидный ген SARS-CoV-2, с использованием плазмидного положительного контроля. В работе применяли компьютерный дизайн праймеров по стандартным критериям, проверку их специфичности по базам нуклеотидных последовательностей, моделирование плазмидной конструкции с целевым фрагментом, а также проведение одношаговой обратной транскрипции с последующей полимеразной цепной реакцией и анализ продуктов в агарозном геле. Были разработаны и охарактеризованы праймеры N9171F и N9368R длиной 20-22 нуклеотида с оптимальным содержанием GC и согласованными температурами плавления. При биоинформатической оценке установлено отсутствие выраженной склонности к образованию устойчивых шпилек и димеров, а также подтверждена минимальная гомология с внецелевыми последовательностями, что повышает специфичность амплификации. В качестве положительного контроля использована рекомбинантная плазмидная ДНК pJET1.2, содержащая вставку целевого фрагмента длиной 197 пар оснований; визуализация карты конструкции подтверждала наличие диагностической вставки и удобство ее применения для контроля постановки реакции. Экспериментально показано получение специфического продукта ожидаемого размера 197 пар оснований при анализе РНК SARS-CoV-2, тогда как отрицательный контроль амплификации не давал, что свидетельствует о корректности реакции и снижает риск ложноотрицательных результатов при валидном контроле. Практическая ценность работы заключается в возможности использования предложенной пары праймеров и плазмидного контроля в лабораториях для проведения ОТ-ПЦР-метода в лабораторной диагностике, эпидемиологическом мониторинге и при создании диагностических тест-систем для выявления возбудителя коронавирусной инфекции

Ключевые слова: плазмида; нуклеотид; диагностика; амплификация; BLAST

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Digital transformation of land resource management and development of the national spatial data infrastructure using artificial intelligence

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Abstract. In the context of the digitalisation of the economy of the Kyrgyz Republic, the transformation of the land resource management system has become strategically important, as the efficient use of the national land fund is directly linked to ensuring the sustainable development of the agricultural sector, increasing the investment attractiveness of territories, and improving public regulatory mechanisms. The purpose of this study was to assess the role of artificial intelligence technologies and the national spatial data infrastructure in enhancing the efficiency of land resource management in the Kyrgyz Republic. The methodological framework of the study was based on system analysis, comparative analysis, economic and statistical methods, as well as geoinformation modelling and spatial data analysis. The research included a comprehensive assessment of the current state of digitalisation in the country's land resource management system and identified the main institutional and technological constraints, including fragmented information resources, insufficient integration of digital platforms, limited access to spatial data, and a shortage of qualified specialists in geoinformation

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technologies. The findings demonstrated that the implementation of artificial intelligence tools improves the accuracy of land resource monitoring, automates spatial data processing, supports forecasting of land-use changes, and enhances the validity of managerial decision-making. The results also indicated that integrating geographic information systems with intelligent algorithms increases the transparency of land resource management, reduces the risks of inefficient land use, and optimises government control and regulatory processes. Priority directions for the development of the national spatial data infrastructure had been identified, including the standardisation of information flows, integration of digital services, expansion of interagency cooperation, and improvement of access to geospatial information resources. The practical significance of the study lay in the possibility of applying its findings in the development and implementation of national digital strategies for land resource management in the Kyrgyz Republic

Keywords: geographic information systems; digital cadastre; intelligent data analysis; land relations; territorial monitoring; management automation

Introduction

Against the backdrop of the digital transformation of the economy and mounting global challenges linked to climate change, land degradation and the need to ensure food security, the issue of improving the efficiency of land resource management is becoming particularly pressing. For the Kyrgyz Republic, with its limited land resources and high dependence on the agricultural sector, effective management of the land fund is becoming a key factor in sustainable socio-economic development. In this context, the introduction of digital technologies, including artificial intelligence and spatial data infrastructure, is seen as a strategic approach to modernising the land resource management system and enhancing the transparency of decision-making. Recent research confirms the significant potential of artificial intelligence in the management of natural resources and agriculture. I. Bhat *et al.* (2025) emphasise that the use of machine learning algorithms enables the optimisation of data analysis and yield forecasting processes. A study by A. Mana *et al.* (2024) found that the integration of artificial intelligence with geographic information systems enables more accurate monitoring of land resources and improves the quality of management decisions. P. Ruksar *et al.* (2025) demonstrated that the use of big data analytics and artificial intelligence can significantly improve the accuracy of decision-making in agriculture, particularly in the face of climate uncertainty. Y. Yang & Y. Sun (2025) point out that digital platforms and spatial data play a key role in the development of sustainable agricultural systems. A study by S. Satpati (2026) highlights the need to develop inclusive artificial intelligence-based solutions tailored to smallholder farms, which is particularly relevant for countries with developing economies. At the same time, K. Chowdhury *et al.* (2025) note that one of the main barriers to the adoption of artificial intelligence is the inadequate level of digital infrastructure and limited access to high-quality data. A. Atapattu *et al.* (2024) highlight the problem of a lack of representative datasets, which reduces the effectiveness of artificial intelligence models in local contexts. Despite the rapid development of digital technologies, the scientific literature does not devote sufficient attention to the integration of artificial intelligence specifically into the land resource management system and the development of the national spatial data infrastructure in the Kyrgyz Republic. The lack of comprehensive studies that take regional characteristics into account limits the scope for the effective implementation of digital solutions and reduces their practical significance.

Recent research confirms the growing role of artificial intelligence in the development of digital agriculture and spatial analysis systems. For instance, A. Adewusi *et al.* (2024) note that artificial intelligence technologies make it possible to significantly improve the efficiency of spatial data processing by automating the analysis of satellite imagery, monitoring agricultural land and forecasting the state of natural resources. The authors concluded that the application of intelligent algorithms helps to improve the sustainability of agricultural production and optimise the use of land resources. In the study by L. Chen *et al.* (2023), it was established that artificial intelligence is an important tool for adapting to climate change, as it enables the modelling of land degradation scenarios, the analysis of the impact of natural factors, and the improvement of environmental risk management. The authors emphasise that digital technologies are becoming a key prerequisite for sustainable territorial development in countries experiencing high climate vulnerability. C. Ge *et al.* (2025) devote considerable attention to the application of artificial intelligence technologies in agriculture; they have established that the development of intelligent management systems helps to improve the accuracy of land monitoring, optimise water use and reduce production risks. The researchers emphasise that the most effective results are achieved by combining remote sensing, big data analysis and machine learning. K. Wu *et al.* (2025) reach similar conclusions, noting that the development of digital land resource management platforms is impossible without the integration of spatial data and intelligent analytical systems. Of particular significance to this study are the findings of the FAO (n.d.), according to which the digitalisation of the agricultural sector in the Kyrgyz Republic is at an advanced stage of development; however, the level of integration of spatial data and the adoption of intelligent technologies remains limited. The report emphasises the need to strengthen digital infrastructure, improve the digital literacy of professionals and refine mechanisms for managing agricultural resources.

Despite a significant increase in the number of studies devoted to the application of artificial intelligence in the agricultural sector, an analysis of the scientific literature shows that most studies focus primarily on precision farming, the automation of agricultural production and yield forecasting. At the same time, the issues surrounding the comprehensive use of artificial intelligence technologies in the development of the national spatial data infrastructure and the digital transformation of the land resource management system remain under-researched, particularly as they relate to the conditions in the Kyrgyz Republic. The aim of the study was to conduct a comprehensive analysis of the potential for the digital transformation of the land management system in the Kyrgyz Republic, based on the development of a national spatial data infrastructure and the implementation of artificial intelligence technologies aimed at improving the effectiveness of management decision-making.

Literature Review

In recent years, the digital transformation of the land management system has been regarded as one of the most promising avenues for improving the efficiency of public administration, ensuring sustainable land use and minimising the negative impact of climate change on the agricultural sector. Advances in artificial intelligence, geographic information systems (GIS), remote sensing, big data analysis and the national spatial data infrastructure (NSDI) are creating new opportunities for land monitoring, forecasting degradation processes and improving the quality of management decisions. In contemporary academic literature, research on the digitalisation of land management is primarily developing along several lines: the application of artificial intelligence in the agricultural sector, the use of spatial data and geoinformation technologies, the integration of decision-support systems, and the institutional and infrastructural constraints on digital transformation.

Research into the application of artificial intelligence in the agricultural sector confirms the significant potential of digital technologies to improve the efficiency of natural resource management. For instance, I. Gryshova *et al*. (2024) point out that the introduction of intelligent technologies helps to enhance the sustainability of agricultural production by automating information processing, optimising resource use and improving the adaptability of agricultural systems to climate change (Wu *et al.*, 2025). The authors emphasise that the use of analytical algorithms not only improves the efficiency of agricultural production but also minimises environmental risks. A similar view is held by I. Bhat *et al*. (2025), who regard artificial intelligence as a strategic tool for agribusiness management. According to the researchers, the use of machine learning algorithms significantly improves the analysis of spatial and production data, enabling the prediction of changes in crop yields, the identification of potential risks and the reduction of uncertainty in management decision-making (Srikanthnaik, 2024). At the same time, the author notes that the effectiveness of such technologies depends directly on the quality of the data and the level of digital maturity of the institutional environment. A. Mana *et al*. (2024) pay particular attention to the digitalisation of the agricultural sector; in their research, they analyse the integration of artificial intelligence with geoinformation technologies. The researchers concluded that the use of intelligent algorithms in conjunction with spatial data makes it possible to significantly improve the accuracy of land monitoring, identify changes in land use and develop more effective mechanisms for territorial management. P. Ruksar *et al*. (2025) emphasise that the combination of machine learning and GIS technologies opens up new opportunities for the rational management of land resources. L. Chen *et al*. (2023) have made an important contribution to research into the sustainable use of land resources, viewing artificial intelligence as a tool for adapting to climate change. The authors demonstrate that forecasting algorithms enable the modelling of land degradation scenarios, the analysis of desertification risks, and the assessment of the impact of climate change on the productivity of territories. According to the researchers, the application of intelligent systems is becoming particularly important for countries characterised by high natural and climatic vulnerability.

A separate area of research concerns the use of spatial data and the development of a national spatial data infrastructure. M. Nehrey (2023) notes that the digital transformation of land management is impossible without the integration of cadastral, statistical, environmental and geospatial databases into a single digital ecosystem. The author points out that the fragmentation of information systems significantly limits the scope for comprehensive analysis of territories and reduces the effectiveness of public administration of land resources. Continuing this line of research, K. Wu *et al*. (2025) emphasise that the effectiveness of land management depends directly on the quality of spatial information and the level of development of digital platforms. The researchers conclude that the integration of artificial intelligence technologies into spatial analysis systems enables the automatic processing of large volumes of data in real time, thereby significantly improving the quality of management decisions. A. Adewusi *et al.* (2024), who note that the use of satellite data in combination with artificial intelligence enables the automation of agricultural land monitoring processes, the identification of changes in soil condition and the prediction of potential risks of land degradation. The authors emphasise that intelligent image-processing systems provide greater analytical accuracy compared with traditional observation methods. Similar conclusions are presented in the work by S. Saha *et al.* (2024), which focuses on the use of neural networks in processing images obtained from unmanned aerial vehicles. The researchers note that modern computer vision technologies enable the effective analysis of spatial changes, the identification of land parcel boundaries, and the high-precision monitoring of land conditions. At the same time, A. Atapattu *et al.* (2024) acknowledge that technical limitations remain at present regarding the automated recognition of complex natural features.

Research focusing on big data analytics and decision support systems is of considerable interest. P. Ruksar *et al.* (2025) demonstrated that the application of big data analytics in combination with artificial intelligence can significantly improve the accuracy of forecasting under conditions of climate uncertainty. The authors note that intelligent platforms are capable of taking into account a multitude of interrelated factors, which makes land resource management more adaptive and sustainable. Similar results are demonstrated by Y. Yang & Y. Sun (2025), who view digital platforms as the foundation for the development of sustainable agricultural systems. The researchers concluded that spatial data and artificial intelligence algorithms can improve the efficiency of land resource management by creating a more transparent decision-making system that takes economic, environmental and social factors into account. At the same time, the limitations on the implementation of artificial intelligence technologies are widely discussed in contemporary academic literature. For instance, K. Chowdhury *et al.* (2025) note that digital inequality, caused by limited access to technological infrastructure and an insufficient level of digital literacy among specialists, remains one of the key barriers. The researchers emphasise that without the development of the digital environment and ensuring access to high-quality data, the effectiveness of intelligent systems is significantly reduced. This view is supported by A. Atapattu *et al.* (2024), who highlight the problem of a shortage of representative datasets for training intelligent models. According to the authors, most algorithms demonstrate high effectiveness in developed countries; however, their application in local contexts requires adaptation to take account of the natural, climatic and institutional characteristics of specific territories.

Issues relating to digitalisation are of particular relevance to the Kyrgyz Republic. According to the findings of the FAO (n.d.), the digital transformation of Kyrgyzstan's agricultural sector is gradually gaining momentum; however, the level of adoption of spatial platforms and smart systems remains insufficient. The organisation emphasises the need to modernise the information infrastructure, improve the digital literacy of specialists and integrate spatial data into the management of the agricultural sector. Furthermore, D. Sakkaraeva & M. Kumashev (2024) note that the development of the agricultural sector in the Kyrgyz Republic is hampered by a number of institutional constraints, including fragmented statistical data, limited digital platforms and insufficient integration of information systems. According to the researchers, these problems significantly limit the capacity for the operational management of the land fund and reduce the effectiveness of land resource monitoring.

Despite the significant body of research devoted to the application of artificial intelligence in agriculture and the digitalisation of the agricultural sector, an analysis of the scientific literature shows that the majority of studies focus primarily on precision farming, the automation of production processes and yield forecasting (Ye *et al.*, 2024). At the same time, issues relating to the comprehensive integration of artificial intelligence technologies into the land resource management system and the development of a national spatial data infrastructure – particularly as they apply to the conditions in the Kyrgyz Republic – remain under-researched. There is a limited number of studies in the scientific literature dedicated to assessing the effectiveness of the interaction between spatial data, digital platforms and intelligent algorithms within the state land resource management system, which highlights the need for further scientific analysis in this area (Polwaththa *et al.*, 2024). For their part, A. Hamrani *et al.* (2025), in analysing the application of robotic and intelligent technologies in the agricultural sector, note that the combination of robotics, sensor systems and artificial intelligence algorithms contributes to the development of fully digitalised agricultural land management systems. The authors emphasise that intelligent technologies enable a shift from traditional control methods to continuous, real-time monitoring of land resources. Analysing the prospects for the development of smart systems in the agricultural sector, G. Gupta & S. Pal (2025) concluded that the use of artificial intelligence is most effective when remote sensing technologies, cloud computing and geoinformation platforms are fully integrated. The researchers emphasise that it is spatial data that is becoming a key element of digital land management, as it enables the continuous updating of information on the state of the land resources.

Thus, an analysis of the current scientific literature shows that artificial intelligence technologies, spatial data and digital platforms are regarded as key tools for modernising the land resource management system. At the same time, the majority of existing studies focus primarily on precision farming, increasing crop yields and the automation of specific agricultural processes. Issues relating to the comprehensive integration of artificial intelligence into the land management system, the development of a national spatial data infrastructure and the establishment of digital decision-making mechanisms within the context of the Kyrgyz Republic remain under-researched. The lack of comprehensive studies that take into account regional characteristics, institutional constraints and the country's level of digital readiness highlights the need for further research into this issue and underlines the scientific significance of this study.

Materials and Methods

The study employed a comprehensive interdisciplinary approach, combining methods of economic and statistical analysis, geoinformation modelling, spatial analysis and artificial intelligence algorithms to assess the effectiveness of land resource management in the Kyrgyz Republic in the context of digital transformation. The study was conducted between 2015 and 2024 and covered agricultural areas in the Chui, Osh and Issyk-Kul regions, characterised by varying land-use specialisations, natural and climatic conditions, and levels of digitalisation of agricultural processes. The total area of the study sites amounted to over 120,000 hectares of agricultural land, comprising arable land, permanent crops, pastures and irrigated areas.

The study was based on official statistical and spatial data from the state authorities of the Kyrgyz Republic, as well as international information sources. The regulatory framework comprised the provisions of Law of the Kyrgyz Republic No. 153 (1998), as well as regulatory documents governing the maintenance of the state land cadastre, the digitisation of land records and the development of the national spatial data infrastructure. Statistical data were obtained from materials provided by the National Statistical Committee of the Kyrgyz Republic, the State Agency for Land Resources, Cadastre, Geodesy and Cartography, and open digital platforms (Open Data Portal of the Kyrgyz Republic, n.d.). In addition, analytical materials from the FAO (n.d.) were used, containing data on the state of land resources, levels of digitalisation in the agricultural sector and the prospects for the introduction of smart technologies in Kyrgyzstan's agriculture.

Geoinformation modelling methods based on the use of remote sensing data were applied to analyse the spatial characteristics of land resources (Bhat *et al.*, 2025). The study utilised multispectral satellite imagery from Sentinel-2 with a spatial resolution of 10 m and Landsat 8 with a spatial resolution of 30 m. These platforms were selected due to their high availability, regular image updates and the ability to analyse changes in land use over time. To minimise seasonal and atmospheric distortions, images acquired predominantly during the growing season (April-September) with cloud cover of less than 10% were used. The pre-processing of spatial data involved the stages of atmospheric correction, georeferencing, normalisation of spectral indices and noise removal. The processing was carried out using QGIS 3.28, ArcGIS Pro and the Google Earth Engine cloud analytics platform, which enabled the automation of work with large volumes of spatial data. Thematic GIS layers were generated from satellite imagery, including land-use types, the Normalised Difference Vegetation Index (NDVI), the level of land degradation, the degree of soil moisture, and the intensity of agricultural use. To identify spatial changes in land-use patterns, an overlay analysis method was applied, involving the sequential overlay of thematic maps from different time periods (Mana *et al.*, 2024). This approach made it possible to identify changes in the area of agricultural land, pinpoint areas of land degradation and determine zones of intensive land use (Rudoy *et al.*, 2023).

Artificial intelligence and machine learning algorithms were utilised for the automated processing of spatial data. In particular, the Random Forest algorithm was applied to classify land cover types and identify agricultural areas. This algorithm was chosen due to its high resistance to noise, its ability to process large datasets, and its high accuracy in classifying multidimensional spatial features. The input parameters used included spectral indices from satellite imagery, vegetation indices, and data on topography, soil types and land-use characteristics.

The model training procedure involved dividing the dataset into a training sample (70%) and a test sample (30%). Pre-annotated spatial features, identified using cadastral data and satellite imagery, were used for training. The model's robustness was verified using cross-validation, which ensured the reproducibility of results and minimised overfitting errors. Convolutional Neural Networks (CNNs) were used to segment agricultural fields and identify the spatial boundaries of land parcels. The algorithm was used for the automatic detection of land parcel boundaries in high-resolution satellite imagery. The neural network model was trained using a pre-annotated dataset of satellite images containing information on land-use types and land parcel characteristics. The quality of the classification was assessed by analysing the error matrix, the accuracy coefficient and the F1-score, which enabled an objective evaluation of the algorithms' effectiveness.

An economic and statistical analysis was carried out using correlation and regression modelling methods to assess the impact of digitalisation on the efficiency of land resource management. The dependent variable (Y) was an integrated indicator of the efficiency of land resource use, comprising indicators of crop yield, land productivity and the economic return on agricultural production. The independent variables were derived from statistical data and included: X_1 – the level of digitalisation in land resource management (proportion of digitalised cadastral processes, %); X_2 – intensity of land resource use (level of agricultural pressure per 1 ha); X_3 – investment in digital technologies (volume of financial investment in digital infrastructure, million KGS).

Geoinformation modelling involved conducting an overlay analysis to identify changes in land-use patterns, classifying land parcels by land-use type, and assessing degradation processes. Machine learning algorithms were used for the automated processing of spatial data. In particular, the Random Forest algorithm was used for land cover classification, whilst convolutional neural networks (CNNs) were used to segment agricultural fields based on satellite imagery. Classification accuracy was assessed using the accuracy coefficient and an error matrix. An economic and statistical analysis was carried out based on indicators of crop yields, production costs, and the use of water and land resources. To assess the impact of digital technologies on the effectiveness of land resource management, a multiple regression model was applied:

$$Y = 12.54 + 0.68X_1 + 0.43X_2 + 0.57X_3 + \varepsilon, \quad (1)$$

where Y is the indicator of land resource utilisation efficiency; X_1 is the level of digitalisation of management processes; X_2 is the intensity of land resource utilisation; X_3 is investment in digital technologies; ε is the random error of the model.

The results of the regression analysis demonstrated the statistical significance of the model: the coefficient of determination was $R^2 = 0.84$, indicating a high level of explanation of the variation in the dependent variable. A p-value of <0.05 confirmed the statistical significance of the model and the independent variables. The digitalisation level indicator had the greatest influence on the efficiency of land resource use ($\beta_1 = 0.68$), confirming the positive impact of digital technologies on the quality of land management. The Random Forest algorithm was applied for land-use classification, with n = 200 trees and a model depth of 15 levels. The training sample comprised 1,250 spatial objects. The model's accuracy was 91.4%, and the F1-score was 0.89. A convolutional neural network (CNN), trained on 3,200 images, was used to process the satellite images, achieving a final classification accuracy of 93.2%. Regression modelling yielded a coefficient of determination of $R^2 = 0.84$ and an RMSE of 0.18.

To test the model's robustness, diagnostics for multicollinearity were carried out, along with an analysis of the residuals and an assessment of the statistical reliability of the parameters. Statistical data processing was performed using the SPSS, Python (Scikit-learn, TensorFlow) and Microsoft Excel software packages. In addition, the study employed the SWOT analysis method, which enabled an assessment of the strengths and weaknesses of introducing artificial intelligence into land resource management, as well as the identification of institutional, technological and economic constraints on digital transformation. Logical modelling was used to systematise the results; on this basis, a conceptual model was developed for the integration of artificial intelligence technologies into the land resource management system and the national spatial data infrastructure of the Kyrgyz Republic (National Statistical Committee of the Kyrgyz Republic, n.d.).

A comparative analysis was carried out between traditional and digital approaches to land resource management based on the following criteria: yield (kg/ha), water consumption (m^3/ha), production costs (KGS/ha) and the level of digitalisation of processes (%). Aggregated data on more than 50 indicators for the period under review were used for the analysis. In addition, the SWOT analysis method was applied to assess the institutional, technological and economic factors involved in the implementation of artificial intelligence. To summarise the results, a logical modelling method was used, which enabled the development of a conceptual model for the integration of artificial intelligence into the land resource management system and the national spatial data infrastructure of the Kyrgyz Republic. Thus, the proposed methodology ensures the reproducibility of the research, enables a comprehensive analysis of spatial and statistical data, and allows for an objective assessment of the potential for the digital transformation of the land resource management system based on artificial intelligence technologies.

Results and Discussion

The results of the study indicate that the implementation of artificial intelligence technologies has a multifaceted impact on the effectiveness of land resource management in the Kyrgyz Republic. Analysis of spatial and statistical data has shown that the use of intelligent algorithms improves the accuracy of monitoring changes in land use, speeds up the processing of spatial information and reduces the error rate in cadastral registration. It has been established that the application of machine learning algorithms helps to improve the accuracy of yield forecasting by 12-15%, whilst simultaneously reducing the consumption of water resources and fertilisers, which is particularly important given the scarcity of natural resources. The results of applying the Random Forest algorithm showed an increase in land-use classification accuracy to 91.4%, as confirmed by a high F1-score (0.89). The use of a CNN enabled satellite image recognition accuracy of 93.2% to be achieved, particularly in the identification of degraded land. The regression model for yield forecasting demonstrated a high explanatory power ($R^2 = 0.84$), which indicates that the forecast results are reliable.

The results obtained are consistent with the research by I. Bhat *et al.* (2025), who demonstrated that the use of artificial intelligence improves the accuracy of yield forecasting and contributes to a more rational use of natural resources. Similar conclusions are presented by A. Mana *et al.* (2024), who highlight the effectiveness of integrating AI with geographic information systems (GIS) for analysing changes in land use. A. Adewusi *et al.* (2024) confirm that the automated processing of satellite data significantly reduces the time required to analyse agricultural areas and improves the accuracy of monitoring. In turn, D. Akhmatova (2023) points out that the low level of digital maturity in the countries of the Eurasian Economic Union is due to institutional constraints, whilst D. Sakkaraeva & M. Kumashev (2024) emphasise the need to modernise the digital infrastructure of Kyrgyzstan's agricultural sector. Through the use of intelligent algorithms, it has been possible to increase the accuracy of yield forecasts by 12-15%, as well as to reduce water and fertiliser consumption. This result demonstrates the high effectiveness of digital technologies when natural resources are limited. To assess trends in land use and the level of digitalisation in the Kyrgyz Republic, an analysis of statistical data for the period 2015-2024 was carried out (Table 1).

Table 1. Trends in land use in the Kyrgyz Republic (2015-2024)

Indicator	2015	2020	2024
Area of agricultural land, thousand hectares	10,650	10,720	10,830
Irrigated land, thousand hectares	1,020	1,045	1,060
Degraded land, thousand hectares	1,200	1,350	1,500
Proportion of land recorded digitally, %	25	45	65

Source: authors' calculations based on data from the National Statistical Committee of the Kyrgyz Republic (n.d.)

An analysis of the data presented in Table 1 reveals a steady upward trend in the area of agricultural land, which is linked to the incorporation of new territories into agricultural use. At the same time, there has been an increase in the area of degraded land from 1,200 to 1,500 thousand hectares, which points to persistent environmental problems and inefficient land management. A significant development is the increase in the level of digital land registration from 25% to 65%, reflecting the gradual development of the national spatial data infrastructure in the Kyrgyz Republic. However, despite this positive trend, the level of digitalisation remains insufficient to ensure comprehensive monitoring and management of land resources. To quantitatively assess the effectiveness of the implementation of digital technologies and artificial intelligence, a comparative analysis of traditional and digital methods of land resource monitoring was carried out (Table 2).

Table 2. Effectiveness of land resource monitoring (traditional vs digital approach)

Indicator	Traditional approach	GIS+AI	Change
Accuracy of change detection	70-75%	85-95%	+15-20%
Data processing time	10-15 days	1-3 days	-80%
Data update frequency	Once a year	Monthly	↑
Cadastral data errors	15-20%	5-10%	-50%

Note: GIS – geographic information systems; AI – artificial intelligence
Source: authors' calculations based on analysis of Sentinel-2 satellite data and FAO (n.d.)

As can be seen from Table 2, the use of geographic information systems and artificial intelligence algorithms makes it possible to significantly improve the accuracy of identifying land-use changes – from 70-75% to 85-95%. At the same time, there is a significant reduction in data processing time – by up to 80% – which is critical when analysing large areas. There is also a reduction in errors in cadastral data of approximately 50%, confirming the effectiveness of automated methods for processing spatial information. The results obtained indicate that digital technologies enable a shift from sporadic land monitoring to systematic and continuous monitoring. In order to identify systemic issues limiting the development of digital land resource management, an analysis of institutional and technological factors was carried out (Table 3).

Table 3. Key challenges in land resource management in the Kyrgyz Republic

Challenge	Manifestation	Consequences
Data fragmentation	Disparate departmental databases	Poor coordination
Lack of standards	GIS incompatibility	Analytical errors

Table 3. Continued

Challenge	Manifestation	Consequences
Staff shortages	Shortage of GIS specialists	Limited implementation of AI
Restricted access to data	Closed databases	Reduced transparency
Land degradation	Erosion, salinisation	Reduced crop yields

Note: GIS – geographic information systems; AI – artificial intelligence
Source: developed by the authors

The data in Table 3 show that the key barriers are data fragmentation and the lack of uniform standards for data processing. This leads to inconsistencies between government bodies and reduces the effectiveness of geoinformation systems. Another significant problem is the shortage of qualified specialists in the fields of GIS and artificial intelligence, which limits the adoption of modern technologies. Furthermore, the issue of land degradation is highlighted, which requires the implementation of monitoring systems based on satellite data and intelligent analysis. Thus, the identified constraints are complex in nature and require a systematic approach to their resolution. A SWOT analysis was carried out to assess the strategic prospects for the implementation of artificial intelligence in land resource management (Table 4).

Table 4. SWOT analysis of the implementation of AI in land resource management in the Kyrgyz Republic

Strengths (S)	Weaknesses (W)
Improved monitoring accuracy	Shortage of specialists
Automation of the land register	High costs
Improved data analysis	Limited data
Opportunities (O)	**Threats (T)**
Development of the National Spatial Data Infrastructure (NSDI)	Cyber risks
Attracting investment	Technological dependence
Digitalisation of management	Social inequality

Note: NSDI – National Spatial Data Infrastructure
Source: developed by the authors

The results of the SWOT analysis show that the main advantages of implementing artificial intelligence are improved monitoring accuracy and the automation of data processing. At the same time, the weaknesses relate to the high cost of implementing the technology and a shortage of skilled personnel. Opportunities for development include the digitalisation of public administration and the integration of the National Land Use Plan, which could significantly improve the transparency and efficiency of land resource management. However, risks relating to cybersecurity and technological dependence remain, necessitating the development of a comprehensive strategy for AI implementation. A comparative analysis was carried out to contrast traditional and modern approaches to land resource management (Table 5).

Table 5. Comparison of traditional and digital land resource management systems

Criterion	Traditional system	Digital (GIS + AI)
Data management	Paper-based/disparate	Centralised
Monitoring	Manual	Automated
Accuracy	Average	High
Processing speed	Low	High
Decision-making	Intuitive	Data-driven

Note: GIS – geographic information systems; AI – artificial intelligence
Source: developed by the authors

An analysis of Table 5 shows that a digital management system based on the use of geoinformation technologies and artificial intelligence significantly outperforms traditional methods across all key parameters. In particular, process automation enables faster data processing and improves the quality of decision-making. Furthermore, digital systems provide a higher level of accuracy and transparency, which is particularly important for public land management. This confirms the need to transition to digital management platforms. To assess the potential for applying artificial intelligence in the land management system, a model of the impact of digital technologies was developed (Table 6).

Table 6. Potential impact of AI technologies on land resource management in the Kyrgyz Republic

Indicator	Without AI	With AI	Change
Accuracy of change monitoring	70-80%	85-95%	+15-25%
Data processing time	100%	10-30%	-70-90%
Errors in cadastral data	100%	40-60%	-40-60%
Data update speed	Low	High	↑
Identification of land degradation	Limited	Automated	Significant improvement

Note: AI – artificial intelligence
Source: authors' calculations based on the Open Data Portal of the Kyrgyz Republic (n.d.), National Statistical Committee of the Kyrgyz Republic (n.d.)

As can be seen from Table 6, the implementation of artificial intelligence technologies enables the accuracy of land-use change monitoring to be increased by 15-25%, which significantly improves the quality of spatial data analysis. The most significant benefit is a 70-90% reduction in data processing time, enabling a rapid response to changes in land use. There is also a 40-60% reduction in errors in cadastral data, which increases the reliability of information and reduces the risks associated with management decisions. Furthermore, the use of AI enables the automated detection of land degradation, which is an important tool for the sustainable management of natural resources (Skvortsov, 2020). Furthermore, the analysis carried out has shown that the application of artificial intelligence technologies in the land resource management system of the Kyrgyz Republic has significant potential, but requires systematic implementation within the framework of the national spatial data infrastructure. In particular, the use of satellite data and machine learning algorithms enables the automation of processes for identifying changes in land use, including illegal land use, soil degradation and changes in the structure of agricultural land (Srinivasu *et al.*, 2026).

It has been established that the integration of artificial intelligence into cadastral systems helps to improve data reliability through the automatic verification of information and the identification of inconsistencies. This is particularly important in the context of data fragmentation and the absence of a unified digital platform. Furthermore, the use of predictive models makes it possible to forecast the risks of land degradation and optimise land resource management processes based on the analysis of spatial and statistical data. Unlike traditional methods based on periodic monitoring, the use of intelligent algorithms ensures continuous, real-time analysis of the state of land resources. This enables more timely management decision-making and reduces the incidence of human error (Eze *et al.*, 2025).

Particular attention should be paid to the identified opportunities and limitations of AI applications, including an analysis of their strengths and weaknesses, as well as potential threats and prospects, which is consistent with the findings of I. Gryshova *et al.* (2024) and P. Srinivasu *et al.* (2026). For example, a case study analysis shows that artificial intelligence helps to increase productivity and product quality, whilst reducing production costs (Likhota, 2025). Nevertheless, the widespread adoption of AI faces a number of constraints, such as slow rates of technology adoption, which highlights the need for further study of these limitations (Skvortsov, 2020). Research points to the need to develop institutional support and improve financial and credit mechanisms to stimulate the adoption of innovations in the agricultural sector of the Kyrgyz Republic (Sakkaraeva & Kumashev, 2024). It is important to note, however, that the use of AI not only improves agricultural production through real-time crop monitoring, but also opens up new opportunities for the digital transformation of agriculture, including the optimisation of resource use and increased profitability (Bhat *et al.*, 2025). In this context, AI enables agricultural enterprises to monitor climate change and fluctuations in market demand in real time, whilst optimising resource utilisation and inventory management through modelling, forecasting and intelligent analytics (Zhang *et al.*, 2026). Furthermore, the capabilities of AI include the ability to self-learn, which is particularly relevant for recognising uncalibrated objects or building models of agricultural development that depend on various factors (Skvortsov *et al.*, 2020). Furthermore, the integration of AI with the IoT and robotic systems enables the automation of processes, reduces labour costs and minimises environmental impact (Lebid *et al.*, 2023; Shevchenko *et al.*, 2024).

Artificial intelligence applied to the sustainable development of agricultural systems encompasses a wide range of technologies, such as satellite data, soil sensors and weather data, enabling the precise management of farms (Bhat *et al.*, 2025). In particular, systems based on machine learning and deep neural networks help to improve the accuracy of yield forecasting and optimise irrigation schedules, which is critically important for water-stressed regions (Bachu *et al.*, 2024).

Such technologies also deliver significant reductions in fertiliser use of up to 28% and water use of 22%, whilst increasing crop yields by up to 25%, as noted by O. Ugwu *et al*. (2025). Such intelligent systems make it possible to identify the optimal time for harvesting, minimise waste and effectively monitor soil and crop conditions (Mana *et al.*, 2024). Consequently, AI helps to improve the adaptability of agricultural systems to climate change through the introduction of new plant varieties resistant to weather anomalies and the application of precision irrigation methods (Perekhodov, 2025). The integration of AI with Internet of Things and machine vision tools enables the collection and analysis of large volumes of data, allowing farmers to make more informed decisions regarding resource management and risk minimisation (Akintuyi, 2024). The use of machine learning algorithms to predict crop behaviour under various environmental conditions, based on the analysis of large volumes of data generated by IoT sensors and climate information systems, contributes to a significant improvement in the efficiency of agricultural production (Yparraguirre *et al.*, 2026). These intelligent systems can also analyse data to optimise business models within agri-food systems, thereby reducing their carbon footprint and enhancing their overall sustainability, as noted by D. Olawade *et al*. (2024). However, in order to generate instructions, information, forecasts and support for decision-making, AI requires data from its computing environment, which is most often provided via IoT sensors, satellites and weather stations (Assis *et al.*, 2024). Furthermore, AI can be used to reduce the use of herbicides, pesticides and other fertilisers by 25-35%, whilst increasing crop yields by 3-4%. These figures highlight the significant potential of AI in achieving more sustainable and productive agriculture, particularly in the context of resource constraints and the need to adapt to changing climatic conditions (Sherstiuk, 2025). AI also enables the optimisation of fertiliser application by analysing soil composition, nutrient levels and historical yield data, thereby helping to reduce environmental impact and improve economic efficiency (Adewusi *et al.*, 2024; Truflyak & Ragozin, 2025). The use of AI also allows for more precise application of pesticides, targeting only affected areas, which significantly reduces the overall chemical load on the ecosystem and preserves biodiversity (Lebid *et al.*, 2023; Polwaththa *et al.*, 2024). Such technologies enable a differentiated approach to field management, minimising losses and maximising the efficiency of every resource invested (Gryshova *et al.*, 2024; Çokkızgın *et al.*, 2025). Furthermore, the integration of Internet of Things (IoT) sensors with artificial intelligence systems is transforming precision farming, enabling intelligent monitoring and adaptive management of agricultural processes, as noted by V. Eze *et al*. (2025). This enables farmers to obtain continuous data on soil conditions, crop growth and environmental conditions, which, combined with advanced machine learning algorithms, facilitates predictive analytics and real-time decision-making to optimise resource use (Wei *et al.*, 2024). Thanks to its predictive analytical capabilities, AI is becoming the 'cornerstone' of decision-support systems, analysing historical data, weather conditions and crop-specific parameters, thereby providing valuable insights for resource optimisation and contributing to the long-term sustainability of agricultural systems (Truflyak & Ragozin, 2025). The use of AI also facilitates more accurate forecasting of plant diseases and pests, enabling a rapid response to minimise crop losses and reduce the need for pesticides, as noted by O. Lebid *et al*. (2023). For example, the use of AI systems to identify and predict the spread of pests makes it possible to reduce pesticide use by more than 50%, thereby minimising environmental damage (Ye *et al.*, 2024). K. Polwaththa *et al*. (2024) also argue that this approach not only enhances the efficiency of agricultural production but also contributes significantly to achieving the Sustainable Development Goals by conserving natural resources and biodiversity. This transition to an AI-driven agricultural model promises significant benefits for both agricultural productivity and environmental sustainability, as traditional farming methods often result in the inefficient use of resources.

A study by L. Chen *et al*. (2023) has shown that the implementation of artificial intelligence has a positive impact on the efficiency and sustainability of agricultural systems. The study's findings indicate that intelligent algorithms can improve the accuracy of crop yield forecasts by 12-15%. Furthermore, their use enables a significant reduction in resource consumption: water use is reduced by 22%, and fertiliser use by 28%. An increase in crop yields of 20-25% was also observed. This is due to more precise management of agricultural processes and rapid decision-making based on data analysis. Through the use of machine learning, IoT sensors and predictive analytics, it is possible to monitor soil conditions, plant health and weather conditions in real time (Yparraguirre *et al.*, 2026). A study by P. Perekhodov (2025) also identified key areas where AI can be effectively applied in agriculture. These include irrigation management, soil condition monitoring, forecasting climate-related risks, and the automation of plant protection processes. The findings confirm that AI is a valuable tool for increasing crop yields and the sustainability of agriculture. However, there are constraints hindering the large-scale adoption of these technologies. The most significant of these include a lack of digital infrastructure, limited access to reliable data, and low levels of digital skills among agricultural producers (Sakkaraeva & Kumashev, 2024).

Research by A. Adewusi *et al*. (2024) confirms the high effectiveness of using artificial intelligence in agriculture, and the results obtained are fully consistent with these findings. Increased yields and reduced resource costs point to a transition towards a more sustainable and economically viable model of agriculture (Mana *et al.*, 2024). However, the limitations identified highlight the need for a comprehensive approach to the implementation of AI. To this end, it is necessary to develop digital infrastructure, create agricultural databases and enhance staff skills (Wu *et al.*, 2025). Only by addressing these challenges will it be possible to fully realise the potential of digital technologies. The convergence of artificial intelligence with Internet of Things technologies and big data analytics systems opens up new opportunities for the creation of smart agricultural systems. Such systems are capable of adapting to climate change and market fluctuations. This is particularly important for the Kyrgyz Republic, where agriculture is of strategic importance for ensuring food security. The study has shown that artificial intelligence plays a key role in the digital transformation of the agricultural sector. However, the successful implementation of AI requires institutional support, investment and the development of tailored solutions that take into account the specific characteristics of agriculture in different regions.

Conclusions

The study conducted has established that the digital transformation of the land management system in the Kyrgyz Republic is a prerequisite for improving the efficiency of land use and ensuring sustainable socio-economic development. The findings revealed that the existing management system is characterised by data fragmentation, insufficient integration of information resources and a limited level of digitalisation, which significantly reduces the quality of monitoring and management decision-making. Analysis of spatial data and the results of geoinformation modelling has confirmed that the implementation of artificial intelligence technologies makes it possible to significantly improve the accuracy of land-use change monitoring (by 15-25%), reduce data processing time (by 70-90%) and lower the error rate in cadastral information (by 40-60%). This demonstrates the high effectiveness of using machine learning algorithms and satellite data in land resource management systems. It has been established that the development of a national spatial data infrastructure plays a key role in enhancing the transparency and consistency of public administration. The integration of geographic information systems and digital platforms provides access to up-to-date information, reduces data duplication and contributes to the creation of a unified information space. The study identified the main barriers to digital transformation, including the lack of uniform data processing standards, inadequate digital infrastructure and a shortage of qualified specialists in the fields of GIS and artificial intelligence. These constraints require a comprehensive solution at the level of public policy and institutional reform.

The practical significance of this study lies in the development of recommendations for improving the land resource management system in the Kyrgyz Republic, including the introduction of intelligent spatial data analysis systems, the development of a national spatial data infrastructure, the standardisation of geoinformation resources, and the enhancement of human resource capacity. Implementing the proposed measures will improve the efficiency of land use, ensure environmental sustainability and accelerate the digital transformation of the agricultural sector. Prospects for further research include the development of applied artificial intelligence models for predicting land degradation, as well as the creation of integrated digital platforms for land resource management at the national level.

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Conflict of Interest

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Аннотация. Кыргыз Республикасынын экономикасын санариптештирүү шарттарында жер ресурстарын башкаруу системасын трансформациялоо стратегиялык мааниге ээ болууда, анткени жер фондун натыйжалуу пайдалануу агрардык сектордун туруктуу өнүгүшүн камсыз кылуу, аймактардын инвестициялык жагымдуулугун жогорулатуу жана мамлекеттик жөнгө салуу механизмдерин өркүндөтүү менен түздөн-түз байланыштуу. Изилдөөнүн максаты жасалма интеллект технологияларынын жана улуттук мейкиндиктик маалыматтар инфраструктурасынын Кыргыз Республикасынын жер ресурстарын башкаруунун натыйжалуулугун жогорулатуудагы ролун баалоо болгон. Изилдөөнүн методологиялык негизин системалык, салыштырма жана экономикалык-статистикалык талдоо ыкмалары, ошондой эле геомаалыматтык моделдөө жана мейкиндиктик маалыматтарды талдоо ыкмалары түздү. Изилдөөнүн жүрүшүндө өлкөдөгү жер ресурстарын башкарууну санариптештирүүнүн учурдагы абалына комплекстүү баа берилип, негизги институционалдык жана технологиялык чектөөлөр аныкталды. Аларга маалыматтык ресурстардын бөлүнүп-жарылышы, санариптик платформалардын интеграциясынын жетишсиз деңгээли, мейкиндиктик маалыматтарга жеткиликтүүлүктүн чектелиши жана геомаалыматтык технологиялар жаатындагы квалификациялуу адистердин жетишсиздиги кирет. Жасалма интеллект инструменттерин киргизүү жер ресурстарына мониторинг жүргүзүүнүн тактыгын жогорулатууга, мейкиндиктик маалыматтарды иштетүү процесстерин автоматташтырууга, жер пайдалануудагы өзгөрүүлөрдү болжолдоого жана башкаруучулук чечимдердин негиздүүлүгүн жогорулатууга өбөлгө түзөрү аныкталды. Изилдөөнүн жыйынтыктары көрсөткөндөй, геомаалыматтык системаларды жана интеллектуалдык алгоритмдерди интеграциялоо жер ресурстарын башкаруунун ачыктыгын жогорулатууга, аларды натыйжасыз пайдалануу тобокелдиктерин азайтууга, ошондой эле мамлекеттик көзөмөлдөө жана жөнгө салуу процесстерин оптималдаштырууга мүмкүндүк берет. Улуттук мейкиндиктик маалыматтар инфраструктурасын өнүктүрүүнүн артыкчылыктуу багыттары жалпыланып, алар маалымат агымдарын стандартташтырууну, санариптик сервистерди интеграциялоону, ведомстволор аралык өз ара аракеттенүүнү кеңейтүүнү жана геомаалыматтык ресурстардын жеткиликтүүлүгүн жогорулатууну камтыйт. Изилдөөнүн практикалык мааниси алынган жыйынтыктарды Кыргыз Республикасынын жер ресурстарын башкаруу чөйрөсүндөгү мамлекеттик санариптик стратегияларды иштеп чыгууда жана ишке ашырууда колдонуу мүмкүнчүлүгү менен аныкталат

Негизги сөздөр: геомаалыматтык системалар; санариптик кадастр; маалыматтарды интеллектуалдык талдоо; жер мамилелери; аймактарга мониторинг жүргүзүү; башкарууну автоматташтыруу

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Аннотация. В условиях цифровизации экономики Кыргызской Республики трансформация системы управления земельными ресурсами приобретает стратегическое значение, поскольку эффективное использование земельного фонда напрямую связано с обеспечением устойчивого развития аграрного сектора, повышением инвестиционной привлекательности территорий и совершенствованием механизмов государственного регулирования. Целью исследования являлась оценка роли технологий искусственного интеллекта и национальной инфраструктуры пространственных данных в повышении эффективности управления земельными ресурсами Кыргызской Республики. Методологическую основу исследования составили методы системного, сравнительного и экономико-статистического анализа, а также методы геоинформационного моделирования и пространственного анализа данных. В ходе исследования проведена комплексная оценка современного состояния цифровизации управления земельными ресурсами страны, выявлены основные институциональные и технологические ограничения, включая фрагментацию информационных ресурсов, недостаточный уровень интеграции цифровых платформ, ограниченность доступа к пространственным данным и дефицит квалифицированных специалистов в области геоинформационных технологий. Установлено, что внедрение инструментов искусственного интеллекта способствует повышению точности мониторинга земельных ресурсов, автоматизации процессов обработки пространственной информации, прогнозированию изменений землепользования и повышению обоснованности принимаемых управленческих решений. Результаты исследования показали, что интеграция геоинформационных систем и интеллектуальных алгоритмов позволяет повысить прозрачность управления земельными ресурсами, снизить риски их неэффективного использования, а также оптимизировать процессы государственного контроля и регулирования. Обобщены приоритетные направления развития национальной инфраструктуры пространственных данных, предусматривающие стандартизацию информационных потоков, интеграцию цифровых сервисов, расширение межведомственного взаимодействия и повышение доступности геоинформационных ресурсов. Практическая значимость исследования заключается в возможности применения полученных результатов при разработке и реализации государственных цифровых стратегий в сфере управления земельными ресурсами Кыргызской Республики

Ключевые слова: геоинформационные системы; цифровой кадастр; интеллектуальный анализ данных; земельные отношения; мониторинг территорий; автоматизация управления

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Digital transformation and agricultural competitiveness in Central Asia: A comparative empirical analysis

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Abstract. Digital transformation has become a key driver of agricultural development in Central Asia, where enhancing the competitiveness of the agricultural sector is of strategic importance for ensuring sustainable economic growth and food security. This study aimed to assess the relationship between digitalisation and agricultural competitiveness through a comparative analysis of Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan. The empirical analysis was based on statistical data for the period 2010-2023 obtained from the World Development Indicators database, FAOSTAT, and official national statistical sources. To evaluate the study variables, composite indices of digitalisation and agricultural competitiveness were developed using the Min-Max normalisation method. The relationship between the indices was examined using descriptive statistics, comparative cross-country analysis, and Pearson correlation analysis. The findings indicate that digitalisation increased steadily across all four countries, whereas the dynamics of agricultural competitiveness differed substantially. A strong positive correlation between the two indices was identified for Kazakhstan ($r = 0.97$), Uzbekistan ($r = 0.99$), and Tajikistan ($r = 0.98$), while Kyrgyzstan exhibited a strong negative correlation ($r = -0.95$). The findings suggest that the impact of digitalisation on agricultural competitiveness depends not only on the diffusion of digital technologies but also on the quality of the institutional environment, the structural characteristics of the agricultural sector, and the efficiency of resource utilisation. The novelty of the study lies in the comprehensive assessment of the relationship between digitalisation and agricultural competitiveness in Central Asian countries based on the proposed composite indices, which made it possible to demonstrate that this relationship is shaped by country-specific characteristics of agricultural development. The findings may support the formulation of public policies and digital transformation strategies aimed at improving resource efficiency, strengthening agricultural competitiveness, and promoting the sustainable development of rural areas

Keywords: digitalisation; agricultural competitiveness; Central Asia; information and communication technologies; digital transformation; Pearson correlation analysis

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Introduction

Digital transformation has become one of the main drivers of efficiency, resilience, and competitiveness in agrifood systems worldwide. As noted by R. Birner *et al.* (2021), digital technologies are increasingly reshaping agrifood systems by improving productivity, strengthening resilience, and enhancing the overall competitiveness of the agricultural sector. R. Abbasi *et al.* (2022) further emphasised that advances in information and communication technologies, artificial intelligence, big data analytics, the Internet of Things, and digital platforms create new opportunities for modernising agriculture, improving the management of land, water, and labour resources, and enhancing decision-making processes. Against the backdrop of climate change, growing global food demand, and the need for sustainable rural development, digital technologies are increasingly recognised not only as instruments of technological modernisation but also as key enablers of productivity growth, food security, and long-term agricultural competitiveness.

For the countries of Central Asia, the adoption of digital technologies is of strategic importance, as agriculture remains a major source of employment, rural household income, and food security. According to S. Wang *et al.* (2025), the region has experienced steady progress in digital infrastructure development, expanded access to information and communication technologies, and the gradual adoption of digital solutions across the agrifood sector. A. Kadyraliev *et al.* (2024) demonstrated that the application of digital technologies and automated management systems improves the efficiency of agricultural management in the Kyrgyz Republic. Taken together, these studies suggest that digital technologies contribute to higher agricultural productivity, improved management practices, reduced production risks, and more sustainable agricultural development. However, the pace of digital technology adoption, the quality of the institutional environment, and the progress of digital transformation differ considerably across Central Asian countries, highlighting the need for comparative analysis. S. Wang *et al.* (2025) highlighted that recent research has increasingly shifted from examining individual digital technologies to assessing their broader impact on the resilience and competitiveness of agrifood systems, with particular attention devoted to the effects of digitalisation on agricultural productivity, resource-use efficiency, value chain resilience, human capital development, and public governance. Similarly, R. Abbasi *et al.* (2022) concluded that digital transformation promotes economic efficiency, accelerates innovation, strengthens the adaptive capacity of the agricultural sector, and supports its long-term sustainable development.

Despite the growing body of research on digital transformation in agriculture, several important issues remain insufficiently explored. Most existing studies focus on individual countries, specific digital technologies, or particular areas of their application. Comparative analyses covering Central Asian countries remain limited, while the relationship between digital development and agricultural competitiveness has rarely been examined using composite indicators that enable consistent cross-country comparisons. Although the countries of Central Asia share a common historical background, they differ substantially in their levels of digital development, institutional quality, and the pace of agricultural modernisation. These differences underscore the need for an integrated analytical framework capable of assessing the relationship between digital development and agricultural competitiveness across the region. Accordingly, the present study aimed to assess the relationship between digital development and agricultural competitiveness in the countries of Central Asia through a comparative analysis.

Literature Review

Agriculture has traditionally played an important role in the economies of Central Asian countries; however, its contribution to gross domestic product (GDP) varies considerably across the region. According to the World Development Indicators (World Bank, 2024), agriculture accounts for less than 5% of GDP in Kazakhstan, whereas its contribution remains substantially higher in Kyrgyzstan and Uzbekistan despite a gradual decline over the study period. Tajikistan exhibits the highest dependence on agriculture, with the sector consistently contributing more than 20% of national GDP. These differences reflect variations in economic structure, the pace of industrialisation, and natural resource endowments, creating distinct conditions for digital transformation and the development of agricultural competitiveness.

The literature considers agriculture in Central Asia not only as a productive sector but also as a key driver of regional socio-economic development. R. Pomfret (2019) argues that improvements in agricultural productivity contribute to higher labour productivity, rural development, and better living standards for rural populations. Similarly, the World Bank (n.d.) emphasises that agriculture continues to play a crucial role in employment generation and rural household income despite its declining share in GDP across the region. Over the past decade, growing attention has been devoted to the role of digital technologies in transforming agrifood systems. S. Wolfert *et al.* (2017) were among the first to demonstrate that precision agriculture, big data analytics, and digital platforms improve farm management and enhance resource-use efficiency. Expanding this perspective, B. Basso & J. Antle (2020) argued that digital agriculture represents an essential pathway toward the design of sustainable agrifood systems by simultaneously improving productivity and environmental sustainability. J.C. Aker (2011) showed that information and communication technologies substantially improve farmers' access to information and advisory services, whereas E. Nakasone *et al.* (2014) demonstrated that digital technologies facilitate access to financial services and agricultural markets, thereby reducing transaction costs and increasing the transparency of agrifood value chains.

Despite the considerable potential of digital technologies, recent studies indicate that the effectiveness of digital transformation depends on more than technological progress alone. L. Klerkx *et al.* (2019) emphasise the importance of institutional quality, infrastructure development, and agricultural knowledge and advisory systems in facilitating the adoption of digital innovations. R. Birner *et al.* (2021) further argue that successful digital transformation depends largely on human capital, institutional capacity, and farmers' ability to adapt to emerging technologies. These findings suggest that, particularly in emerging and transition economies, the outcomes of digital transformation are shaped by the interaction of technological, institutional, and organisational factors.

Although research on agricultural digital transformation has expanded rapidly in recent years, empirical evidence remains concentrated on either developed economies or individual developing countries. Comparative studies focusing on Central Asia are still limited. Moreover, existing research has primarily examined specific dimensions of digitalisation, including information and communication technologies, digital infrastructure, and individual digital solutions, whereas comprehensive assessments of the relationship between digital development and agricultural competitiveness remain scarce. Cross-country differences in this relationship, particularly those associated with institutional quality, agricultural structure, and the level of digital maturity, have received limited scholarly attention. These research gaps provide the rationale for the present study, which evaluates the relationship between digital development and agricultural competitiveness across Central Asian countries using composite indices.

Materials and Methods

Data sources. The empirical analysis was based on statistical data for four Central Asian countries – Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan – covering the period from 2010 to 2023. These countries were selected because they share a common historical background, similar institutional settings, and a significant role of agriculture in their national economies, thereby ensuring the comparability of the cross-country analysis. The study draws on data from the World Development Indicators (World Bank, n.d.) database, FAOSTAT (FAO, n.d.), and official publications of the national statistical agencies of the selected countries. The World Development Indicators database was used to construct the digitalisation index, while FAOSTAT provided the agricultural indicators used to develop the agricultural competitiveness index. National statistical sources were employed to verify and complement selected statistical indicators. The use of internationally comparable statistical data ensures the reliability of cross-country comparisons of digitalisation and agricultural competitiveness. The study covers the period from 2010 to 2023 because, at the time of the analysis, internationally comparable data for all selected indicators were consistently available for all four countries only up to 2023. Data for 2024-2025 have been released at different times by international organisations and national statistical agencies, preventing their consistent use in a comparative cross-country analysis.

Construction of the Digitalisation Index (DI). To quantify the level of digitalisation, a Digitalisation Index was developed by combining indicators that characterise digital infrastructure and the diffusion of information and communication technologies. The conceptual framework of the Digitalisation Index was based on internationally recognised approaches to measuring digital development, particularly the ICT Development Index (IDI) developed by the International Telecommunication Union (ITU, 2017) and the methodological principles for constructing composite indicators presented in the OECD Handbook on Constructing Composite Indicators (OECD & Joint Research Centre of the European Commission, 2008). These frameworks identify Internet connectivity, access to communication infrastructure, and broadband development as the core dimensions of national digital development. Rather than reproducing the original international indices, the present study adapted their conceptual principles to the objectives of a comparative assessment of digitalisation in the agricultural sector of Central Asian countries.

The selection of indicators was additionally guided by OECD & Joint Research Centre of the European Commission (2008), which recommends that composite indicators should be based on conceptually relevant, statistically reliable, and internationally comparable variables. Because not all indicators included in the original ITU methodology were consistently available for all four countries throughout the entire study period (2010-2023), only indicators meeting these methodological requirements and ensuring complete cross-country comparability were retained. The indicators were selected based on three criteria: their relevance to the research objectives, their ability to capture key dimensions of digital development, and the availability of internationally comparable data for all four countries throughout the study period. The index was constructed by aggregating normalised indicators into a composite measure following the approach commonly applied in the development of composite digitalisation indices. This approach ensures the comparability of indicators expressed in different units of measurement.

The Digitalisation Index includes the following indicators: Internet users (% of the population); Mobile cellular subscriptions (per 100 inhabitants); Fixed broadband subscriptions (per 100 inhabitants). Together, these indicators provide a comprehensive assessment of the level of digital development in the countries under study. To ensure cross-country comparability, all variables were normalised using the Min-Max normalisation method. Min-Max normalisation ensured the comparability of indicators measured in different units. The Digitalisation Index was calculated as the arithmetic mean of the normalised indicators:

$$X_{ij}^{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}, \quad (1)$$

where digitalisation Index for country *j*; number of indicators included in the index; normalised value of indicator *i* for country *j*.

Following the methodological guidance presented in the OECD Handbook on Constructing Composite Indicators (OECD & Joint Research Centre of the European Commission, 2008), equal weights were assigned to all indicators because no robust theoretical or empirical evidence justified differential weighting. This approach enhances methodological transparency, ensures the consistency and comparability of the composite index across countries, and reduces potential bias associated with subjective weighting schemes.

Construction of the Agricultural Competitiveness Index (ACI). To assess the level of agricultural competitiveness, a Composite Agricultural Competitiveness Index (ACI) was developed. The conceptual framework of the Agricultural Competitiveness Index was informed by the multidimensional concept of agricultural competitiveness proposed by L. Latruffe (2010) and the Food and Agriculture Organisation of the United Nations (FAO, 2017). These approaches consider agricultural competitiveness as a multidimensional concept that should be assessed through a combination of indicators reflecting the economic contribution of agriculture, production efficiency, productivity, and export performance rather than by a single measure.

In this study, agricultural competitiveness is defined as a multidimensional concept reflecting the economic performance of the agricultural sector. Following these methodological principles, the composite index was designed to capture the principal dimensions of agricultural competitiveness while ensuring international comparability and consistent data availability for all four Central Asian countries throughout the study period. The selected indicators were chosen because they collectively reflect the sector's contribution to the national economy, production efficiency, export capacity, and labour productivity, which are widely recognised as key dimensions of agricultural competitiveness. The selection of indicators was guided by the need to provide a comprehensive assessment of agricultural competitiveness and covers the key dimensions of the sector, including its contribution to the national economy, production efficiency, export performance, and labour productivity. Collectively, these indicators provide a comprehensive assessment of agricultural competitiveness and enable meaningful cross-country comparisons.

The Agricultural Competitiveness Index comprises the following indicators: Agriculture, forestry, and fishing, value added (% of GDP); Crop yield (t/ha); Agricultural exports (million USD); Agricultural labour productivity (agriculture, forestry, and fishing value added per worker, constant 2015 USD). All indicators were normalised using the Min-Max normalisation method and aggregated into a composite index:

$$ACI_j = \frac{1}{n}\sum_{i=1}^{n} X_{ij}^{norm}, \quad (2)$$

where ACI_j – Agricultural Competitiveness Index for country *j*; *n* – number of indicators included in the index; X_{ij}^{norm} – normalised value of indicator *i* for country *j*.

Following the methodological guidance provided in (OECD & Joint Research Centre of the European Commission, 2008), equal weights were assigned to all indicators because no robust theoretical or empirical evidence justified differential weighting. This approach enhances methodological transparency, ensures the consistency and comparability of the composite index across countries, and reduces potential bias associated with subjective weighting schemes.

Data analysis. The empirical analysis was conducted in three stages. First, the dynamics of the Digitalisation Index and the Agricultural Competitiveness Index were analysed over the period 2010-2023. Second, a comparative cross-country analysis was carried out to identify differences in the levels of digital development and agricultural competitiveness among the Central Asian countries. Third, the relationship between digitalisation and agricultural competitiveness was assessed using the Pearson correlation coefficient:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}, \quad (3)$$

where *r* – Pearson correlation coefficient; *x* – Digitalisation Index (DI); *y* – Agricultural Competitiveness Index (ACI); $\bar{x}$ – mean value of the Digitalisation Index; $\bar{y}$ – mean value of the Agricultural Competitiveness Index. The Pearson correlation coefficient was employed to evaluate the strength and direction of the linear relationship between the Digitalisation Index and the Agricultural Competitiveness Index. The estimated correlation coefficients describe the statistical association between the two indices and should not be interpreted as evidence of a causal relationship.

Study limitations. Despite the methodological robustness of the proposed approach, several limitations should be considered when interpreting the findings. First, the Min-Max normalisation method is sensitive to extreme values, which may influence the resulting composite index scores. Second, equal weights were assigned to all indicators when constructing the composite indices. Although this approach ensures methodological transparency and facilitates cross-country comparability, it does not account for potential differences in the relative importance of individual indicators. Third, the analysis is based on aggregated macroeconomic data, which limits the ability to capture regional disparities within individual countries and sector-specific characteristics of agricultural production. Fourth, Pearson correlation analysis identifies statistical associations between digitalisation and agricultural competitiveness but does not establish causal relationships between the variables. Finally, the study covers the period from 2010 to 2023 because, at the time of the analysis, internationally comparable data for all selected indicators were consistently available for all four countries only up to 2023. Data for 2024-2025 had not yet been released simultaneously by international organisations and national statistical agencies, preventing their inclusion in a consistent cross-country analysis.

Results

Dynamics of digitalisation in Central Asia

The analysis of the Digitalisation Index revealed a steady increase in the level of digitalisation across all Central Asian countries during the period 2010-2023. Despite this overall upward trend, the pace and extent of digital transformation differed substantially among the countries under study. These differences reflect the heterogeneous nature of digitalisation processes across the region, as well as variations in digital infrastructure development and the adoption of information and communication technologies. Table 1 presents the calculated values of the Digitalisation Index.

Table 1. Digitalisation Index in Central Asia, 2010-2023

Year	Kazakhstan	Kyrgyzstan	Uzbekistan	Tajikistan
2010	0.37	0.17	0.13	0.09
2011	0.42	0.20	0.15	0.11
2012	0.47	0.23	0.18	0.13
2013	0.52	0.27	0.21	0.16
2014	0.57	0.31	0.26	0.19
2015	0.66	0.32	0.30	0.20
2016	0.69	0.35	0.33	0.22
2017	0.71	0.39	0.36	0.24
2018	0.73	0.43	0.40	0.27
2019	0.75	0.48	0.44	0.30
2020	0.77	0.52	0.47	0.33
2021	0.79	0.57	0.50	0.36
2022	0.80	0.62	0.55	0.39
2023	0.81	0.67	0.62	0.46

Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

Throughout the study period, Kazakhstan maintained the highest level of digitalisation among the four countries. The Digitalisation Index increased from 0.37 in 2010 to 0.81 in 2023, representing more than a twofold increase over the initial level. This trend reflects the continuous development of digital infrastructure and the rapid adoption of information and communication technologies. Kyrgyzstan and Uzbekistan also recorded substantial progress in digitalisation over the study period. In Kyrgyzstan, the Digitalisation Index increased from 0.17 to 0.67, while in Uzbekistan it rose from 0.13 to 0.62, indicating continued improvements in digital infrastructure and wider adoption of digital technologies. However, the trajectories of digitalisation differed between the two countries. In Uzbekistan, the index increased at a relatively steady pace throughout the study period, whereas in Kyrgyzstan the most pronounced growth occurred after 2015, which may reflect the acceleration of digital transformation and broader access to information and communication technologies.

Although Tajikistan consistently recorded the lowest Digitalisation Index among the Central Asian countries throughout the study period, its index increased from 0.09 in 2010 to 0.46 in 2023. This trend indicates gradual improvements in digital infrastructure and the increasing adoption of digital technologies. The remaining gap relative to the other countries highlights the need for further investment in digital infrastructure and improved access to digital services. Figure 1 illustrates the dynamics of the Digitalisation Index across the four Central Asian countries during 2010-2023.

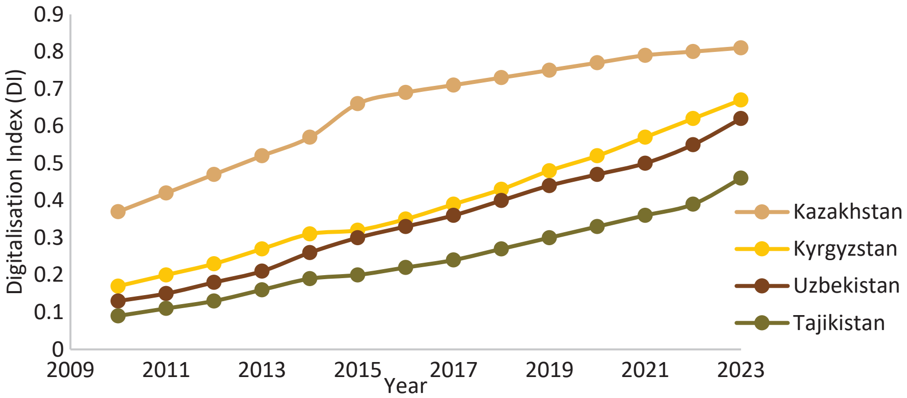

Figure 1. Dynamics of the Digitalisation Index in Central Asia, 2010-2023

Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

Overall, the analysis indicates that, despite the steady progress in digitalisation across all Central Asian countries, the pace of digital transformation differed substantially, resulting in persistent cross-country disparities in the level of digital development.

Trends in agricultural competitiveness

The analysis of the Agricultural Competitiveness Index revealed substantial differences in both the level and dynamics of agricultural competitiveness across the Central Asian countries. Although several countries exhibited improvements in agricultural performance during the study period, the trajectories of the ACI differed considerably, reflecting differences in the effectiveness of agricultural development and structural characteristics of the sector. The calculated values of the Agricultural Competitiveness Index are presented in Table 2.

Table 2. Agricultural Competitiveness Index in Central Asia, 2010-2023

Year	Kazakhstan	Kyrgyzstan	Uzbekistan	Tajikistan
2010	0.24	0.30	0.55	0.28
2011	0.27	0.29	0.56	0.28
2012	0.29	0.29	0.58	0.28
2013	0.29	0.29	0.59	0.29
2014	0.31	0.28	0.59	0.29
2015	0.29	0.27	0.59	0.30
2016	0.29	0.27	0.59	0.30
2017	0.31	0.27	0.60	0.31
2018	0.31	0.26	0.61	0.32
2019	0.33	0.26	0.62	0.32
2020	0.35	0.26	0.63	0.33
2021	0.38	0.26	0.65	0.34
2022	0.40	0.23	0.66	0.34
2023	0.42	0.20	0.67	0.35

Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

Uzbekistan consistently recorded the highest ACI values throughout the study period. The index increased from 0.55 in 2010 to 0.67 in 2023, indicating a gradual strengthening of agricultural competitiveness. Minor fluctuations observed during the study period suggest the stability of key indicators reflecting agricultural productivity and export performance. Kazakhstan also exhibited a steady upward trend in the Agricultural Competitiveness Index, particularly after 2016. Over the study period, the index increased from 0.24 to 0.42, indicating a gradual improvement in agricultural competitiveness.

Tajikistan likewise demonstrated positive growth, with the ACI increasing from 0.28 in 2010 to 0.35 in 2023. Although the rate of growth was more moderate than in Kazakhstan and Uzbekistan, the observed trend indicates a gradual improvement in agricultural competitiveness. At the same time, the relatively low index values point to persistent constraints related to resource-use efficiency and export performance while also indicating considerable potential for further sectoral development.

Unlike the other countries in the region, Kyrgyzstan exhibited a declining trend in the Agricultural Competitiveness Index. During the study period, the index decreased from 0.30 in 2010 to 0.20 in 2023, indicating a deterioration in the composite assessment of agricultural competitiveness despite continued progress in digital infrastructure development. Figure 2 illustrates the differences in the dynamics of the Agricultural Competitiveness Index across the Central Asian countries.

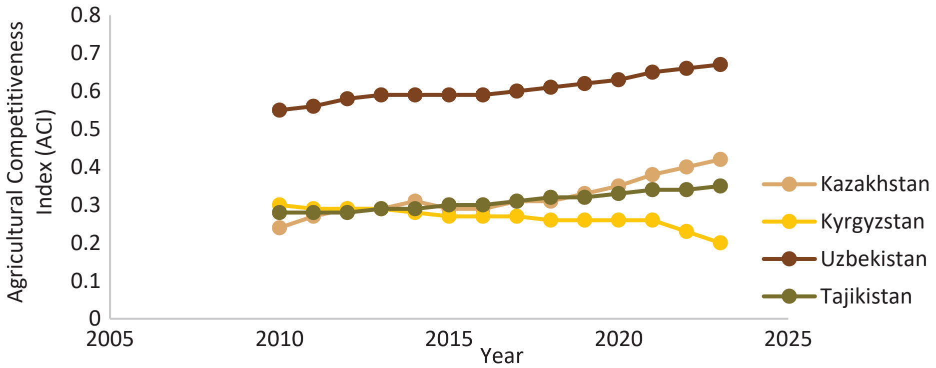

Figure 2. Dynamics of the Agricultural Competitiveness Index in Central Asia, 2010-2023
Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

Overall, the analysis revealed substantial cross-country differences in the dynamics of agricultural competitiveness. While Kazakhstan, Uzbekistan, and Tajikistan experienced increases in the Agricultural Competitiveness Index, Kyrgyzstan recorded a decline. These findings indicate that agricultural development in Central Asia does not follow a uniform trajectory and highlight the importance of considering country-specific characteristics when interpreting the relationship between digitalisation and agricultural competitiveness. To provide a more comprehensive explanation of the observed differences in the Agricultural Competitiveness Index, it is necessary to examine the composition of its underlying indicators. A comparison of the average values of the indicators included in the index provides insights into the determinants of agricultural competitiveness in the countries under study and identifies the factors contributing most to cross-country differences (Table 3).

Table 3. Average values of the components of the Agricultural Competitiveness Index in Central Asian countries, 2010-2023

Indicator	Kazakhstan	Kyrgyzstan	Uzbekistan	Tajikistan
Agriculture, forestry, and fishing, value added (% of GDP)	4.43	20.66	27.01	24.02
Cereal yield (kg/ha)	1,005.1	2,689.2	4,828.1	3,127.8
Agricultural exports (million USD)	2,685.7	625.0	3,764.3	474.3
Agricultural labour productivity (USD per worker, constant 2015 prices)	6,664.3	1,470.0	2,112.9	1,400.0

Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

The results presented in Table 3 indicate that agricultural competitiveness in Central Asian countries is shaped by different structural factors. Kazakhstan records the highest level of agricultural labour productivity (USD 6,664.3 per worker) together with a substantial volume of agricultural exports. These indicators reflect more efficient resource utilisation and a stronger export orientation of the agricultural sector despite the relatively small contribution of agriculture to national GDP. Uzbekistan demonstrates the highest values for most components of the Agricultural Competitiveness Index. The country ranks first in the share of agriculture in GDP (27.01%), cereal yield (4,828.1 kg/ha), and agricultural exports (USD 3,764.3 million), indicating that its agricultural competitiveness is supported by multiple complementary factors.

In both Kyrgyzstan and Tajikistan, agriculture continues to play an important role in the national economy. However, relatively low levels of labour productivity and limited export volumes point to structural constraints that continue to limit improvements in agricultural competitiveness. Overall, the cross-country differences observed in the components of the Agricultural Competitiveness Index indicate that agricultural competitiveness depends not only on the scale of agricultural production but also on labour productivity, resource-use efficiency, and export performance. These structural differences provide an important basis for interpreting the cross-country variation in the relationship between digitalisation and agricultural competitiveness discussed in the following section.

Relationship between digitalisation and agricultural competitiveness

To assess the relationship between digitalisation and agricultural competitiveness, a Pearson correlation analysis was performed using the Digitalisation Index and the Agricultural Competitiveness Index for the Central Asian countries. The graphical representation of the observed relationships is presented in Figure 3.

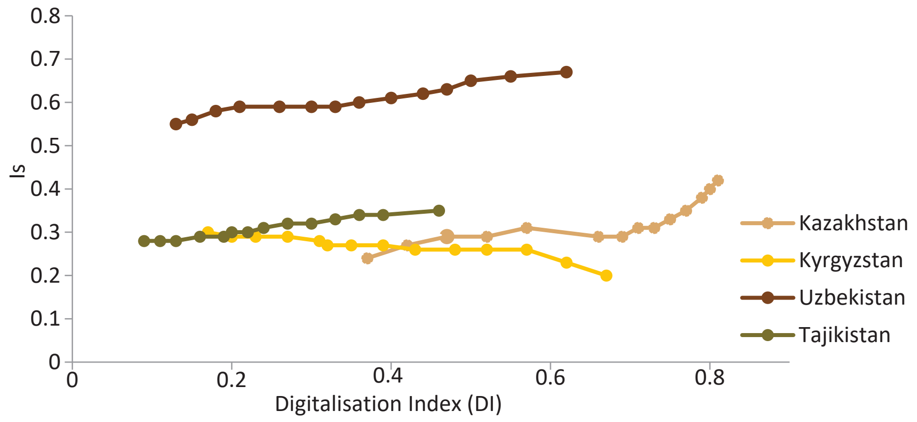

Figure 3. Relationship between digitalisation and agricultural competitiveness in Central Asia, 2010-2023
Source: compiled by the authors based on World Bank (n.d.), FAO (n.d.)

The analysis revealed substantial cross-country differences in both the direction and strength of the relationship between digitalisation and agricultural competitiveness. In Kazakhstan, a very strong positive correlation was observed between the Digitalisation Index and the Agricultural Competitiveness Index ($r \approx 0.97$), indicating a high degree of consistency between digital development and improvements in agricultural competitiveness. However, this relationship is correlational and should not be interpreted as evidence of causality. Similarly strong positive correlations were observed in Uzbekistan ($r \approx 0.99$) and Tajikistan ($r \approx 0.98$). These high correlation coefficients indicate that improvements in digitalisation were accompanied by higher levels of agricultural competitiveness over the study period. Nevertheless, these relationships should also be interpreted as statistical associations rather than evidence of causal effects.

In contrast, Kyrgyzstan exhibited a strong negative correlation between the Digitalisation Index and the Agricultural Competitiveness Index ($r \approx -0.95$). This indicates that, during the study period, progress in digitalisation was accompanied by a decline in the composite measure of agricultural competitiveness. This pattern may reflect a structural mismatch between digital transformation processes and the development of the agricultural sector. As with the other countries, this finding reflects a statistical relationship and does not imply causality.

The Pearson correlation coefficients obtained for the four countries were as follows: Kazakhstan: $r \approx 0.97$; Kyrgyzstan: $r \approx -0.95$; Uzbekistan: $r \approx 0.99$; Tajikistan: $r \approx 0.98$. The correlation coefficients should be interpreted as measures of the strength and direction of the statistical association between the variables and do not imply statistical significance or causal relationships. Overall, the correlation analysis demonstrates that the relationship between digitalisation and agricultural competitiveness varies substantially across the Central Asian countries. These cross-country differences underscore the importance of considering national socio-economic and institutional conditions when interpreting the role of digitalisation in agricultural development.

Discussion

The findings of this study demonstrate that the relationship between digitalisation and agricultural competitiveness is heterogeneous across the Central Asian countries. These findings are consistent with those reported by R. Amoussouhoun *et al.* (2024) and L. Klerkx *et al.* (2019), who argue that the effectiveness of digital transformation depends not only on the level of information and communication technology infrastructure but also on the quality of the institutional environment, the availability of digital services, and farmers' readiness to adopt innovative technologies. The strong positive relationship observed in Kazakhstan may be explained by the country's relatively advanced digital infrastructure, consistent public policies supporting digital transformation, and a higher level of technological modernisation in the agricultural sector. Similar conclusions were reported by N.M. Trendov *et al.* (2019), who demonstrated that digital technologies improve farmers' access to information, financial services, and agricultural markets. These findings suggest that digitalisation should be viewed as an enabling factor for improving agricultural performance, provided that appropriate institutional and economic conditions are in place. Furthermore, digital technologies contribute to lower transaction costs, greater market transparency, and more efficient information systems (Nakasone *et al.*, 2014).

The positive relationship between digitalisation and agricultural competitiveness observed in Uzbekistan and Tajikistan is likely to reflect the gradual development of the digital environment and the expanding adoption of digital technologies in agriculture. This interpretation is supported by R. Fabregas *et al.* (2019), who showed that digital technologies enhance agricultural productivity, resilience, and production efficiency in developing countries, particularly where access to information and modern agricultural technologies is limited. At the same time, the effectiveness of digital transformation depends on the availability of innovation infrastructure, access to agricultural advisory services, and the effectiveness of institutional support mechanisms for farmers (Fielke *et al.*, 2020). Previous studies have also shown that the adoption of digital technologies in agriculture is constrained by high implementation costs, insufficient digital infrastructure, and limited digital literacy among farmers (Dibbern *et al.*, 2024). These constraints remain relevant for the countries of Central Asia, where agricultural digitalisation is progressing at different rates. Similar observations have been reported in studies of Kyrgyzstan, emphasising that the successful adoption of digital technologies depends largely on improvements in the regulatory framework, the development of institutional support mechanisms, and the implementation of coherent public policies for agricultural digital transformation (Dzhumagulov & Mistriukova, 2025).

The identification of a negative relationship between digitalisation and agricultural competitiveness in Kyrgyzstan represents one of the principal findings of this study. However, this relationship should not be interpreted as evidence that digital development has an adverse effect on the agricultural sector. Rather, it is more likely to reflect a structural mismatch between the expansion of digital infrastructure and the effective adoption of digital technologies in agricultural production. Several factors may explain this pattern. First, digital services in Kyrgyzstan remain concentrated primarily in urban areas, whereas rural regions, where most agricultural production takes place, have more limited access to modern digital infrastructure and digital services (National Statistical Committee of the Kyrgyz Republic, 2024). Second, the predominance of small and medium-sized farms constrains the adoption of capital-intensive digital technologies. Third, institutional constraints, insufficiently developed agricultural advisory services, and limited access to financial resources may further hinder the diffusion of digital innovations in agriculture. These findings suggest that investments in digital infrastructure should be complemented by institutional reforms, strengthened agricultural extension services, and capacity-building initiatives to facilitate the effective adoption of digital technologies in agriculture. These findings are consistent with previous studies demonstrating that the effectiveness of digital transformation is shaped by a combination of socio-economic, institutional, and behavioural factors (Cui & Wang, 2023). In many developing countries, digital infrastructure has expanded more rapidly in urban areas than in rural regions, limiting the practical benefits of digital technologies for agricultural development (Birner *et al.*, 2021). Furthermore, the success of digital transformation depends on human capital, institutional quality, and farmers' capacity to adopt and effectively use new technologies (Rotz *et al.*, 2019).

Farmer digital literacy and effective knowledge transfer mechanisms also play an important role. Previous studies have shown that digital skills, agricultural advisory services, and efficient agricultural knowledge systems are critical for the successful adoption of innovation (Rose & Chilvers, 2018; Ingram & Maye, 2020). In addition, farmers' willingness to adopt digital tools is influenced by their perceived usefulness, trust in new technologies, and access to the necessary financial and technical resources (Diaz *et al.*, 2021). Economic and behavioural factors likewise affect the adoption of digital and financial technologies in agriculture (Sharma *et al.*, 2025). In the absence of these enabling conditions, rapid expansion of digital infrastructure does not necessarily translate into higher agricultural competitiveness.

Conclusions

The findings demonstrate that, despite the overall progress of digital transformation across the Central Asian countries, changes in agricultural competitiveness followed different trajectories. This indicates that there is no universal pattern linking digital transformation to agricultural development. A comparison of the composite indices showed that digital development was accompanied by improvements in agricultural competitiveness in Kazakhstan, Uzbekistan, and Tajikistan, whereas Kyrgyzstan exhibited a negative correlation between the two indicators. The results suggest that the effects of digital transformation depend on country-specific characteristics of the agricultural sector, the quality of the institutional environment, and the capacity to effectively adopt digital technologies. Digital transformation should therefore be regarded as a necessary, but not sufficient, condition for enhancing agricultural competitiveness.

The achievement of positive economic outcomes depends not only on the level of digital development but also on a broader set of institutional, structural, and socio-economic factors, including institutional quality, human capital, access to digital services, and the effectiveness of digital technology adoption mechanisms. The proposed framework for assessing digital development and agricultural competitiveness expands the possibilities for comparative cross-country analysis by accounting for the specific characteristics of agricultural development. From a practical perspective, the proposed approach can support the design of public policies for agricultural digital transformation, the development of digital infrastructure programmes, and the improvement of mechanisms for promoting digital technology adoption in Central Asian countries. Future research should extend the geographical scope of the analysis, incorporate panel econometric models, and examine the causal effects of digitalisation on agricultural competitiveness.

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Аннотация. Санариптик трансформация Борбордук Азия өлкөлөрүндө айыл чарбасын өнүктүрүүнүн негизги факторлорунун бири болуп калды, анткени агрардык сектордун атаандаштыкка жөндөмдүүлүгүн жогорулатуу туруктуу экономикалык өсүштү жана азык-түлүк коопсуздугун камсыз кылууда стратегиялык мааниге ээ. Изилдөөнүн максаты Казакстан, Кыргызстан, Өзбекстан жана Тажикстандын мисалында санариптештирүү менен айыл чарбасынын атаандаштыкка жөндөмдүүлүгүнүн өз ара байланышын салыштырма талдоонун негизинде баалоо болду. Эмпирикалык талдоо 2010-2023-жылдардагы World Development Indicators маалымат базасынан, FAOSTATтан жана улуттук расмий статистикалык булактардан алынган маалыматтарга негизделди. Изилденип жаткан көрсөткүчтөрдү баалоо үчүн Min-Max нормалдаштыруу ыкмасы аркылуу санариптештирүүнүн жана айыл чарбасынын атаандаштыкка жөндөмдүүлүгүнүн интегралдык индекстери түзүлдү. Индекстердин өз ара байланышы сүрөттөөчү статистиканын, өлкөлөр аралык салыштырма талдоонун жана Пирсондун корреляциялык талдоосунун жардамы менен изилденди. Натыйжалар төрт өлкөнүн тең санариптештирүү деңгээли туруктуу өскөнүн, бирок айыл чарбасынын атаандаштыкка жөндөмдүүлүгүнүн динамикасы олуттуу айырмаланганын көрсөттү. Казакстан ($r = 0,97$), Өзбекстан ($r = 0,99$) жана Тажикстан ($r = 0,98$) үчүн эки индекстин ортосунда күчтүү оң корреляция аныкталса, Кыргызстан үчүн күчтүү терс корреляция ($r = -0,95$) байкалды. Алынган жыйынтыктар санариптештирүүнүн айыл чарбасынын атаандаштыкка жөндөмдүүлүгүнө тийгизген таасири санариптик технологиялардын жайылышы менен гана эмес, институционалдык чөйрөнүн сапатына, агрардык сектордун түзүмдүк өзгөчөлүктөрүнө жана ресурстарды пайдалануунун натыйжалуулугуна да көз каранды экенин көрсөтөт. Изилдөөнүн илимий жаңылыгы сунушталган интегралдык индекстердин негизинде Борбордук Азия өлкөлөрүндөгү санариптештирүү менен айыл чарбасынын атаандаштыкка жөндөмдүүлүгүнүн өз ара байланышын комплекстүү баалоодо жатат. Бул байланыш ар бир өлкөнүн айыл чарбасын өнүктүрүүдөгү өзгөчөлүктөрүнө жараша өзгөрөрү көрсөтүлдү. Изилдөөнүн жыйынтыктары ресурстарды пайдалануунун натыйжалуулугун жогорулатууга, айыл чарбасынын атаандаштыкка жөндөмдүүлүгүн бекемдөөгө жана айыл аймактарынын туруктуу өнүгүшүн камсыз кылууга багытталган мамлекеттик саясатты жана санариптик трансформация стратегияларын иштеп чыгууда колдонулушу мүмкүн

Негизги сөздөр: санариптештирүү; айыл чарбасынын атаандаштыкка жөндөмдүүлүгү; Борбордук Азия; маалыматтык-коммуникациялык технологиялар; санариптик трансформация; Пирсондун корреляциялык талдоосу

Цифровая трансформация и конкурентоспособность сельского хозяйства в Центральной Азии: сравнительный эмпирический анализ

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Аннотация. Цифровая трансформация стала одним из ключевых факторов развития сельского хозяйства в странах Центральной Азии, где повышение конкурентоспособности аграрного сектора имеет стратегическое значение для обеспечения устойчивого экономического роста и продовольственной безопасности. Целью исследования являлась оценка взаимосвязи между цифровизацией и конкурентоспособностью сельского хозяйства на основе сравнительного анализа Казахстана, Кыргызстана, Узбекистана и Таджикистана. Эмпирический анализ основан на статистических данных за 2010-2023 гг., полученных из базы данных World Development Indicators, FAOSTAT и официальных национальных статистических источников. Для оценки исследуемых переменных были разработаны композитные индексы цифровизации и конкурентоспособности сельского хозяйства с использованием метода нормализации Min-Max. Взаимосвязь между индексами исследовалась с помощью методов описательной статистики, сравнительного межстранового анализа и корреляционного анализа Пирсона. Полученные результаты свидетельствуют о том, что уровень цифровизации во всех четырех странах стабильно возрастал, тогда как динамика конкурентоспособности сельского хозяйства существенно различалась. Сильная положительная корреляция между двумя индексами выявлена для Казахстана ($r = 0,97$), Узбекистана ($r = 0,99$) и Таджикистана ($r = 0,98$), тогда как для Кыргызстана установлена сильная отрицательная корреляция ($r = -0,95$). Полученные результаты свидетельствуют о том, что влияние цифровизации на конкурентоспособность сельского хозяйства определяется не только распространением цифровых технологий, но и качеством институциональной среды, структурными особенностями аграрного сектора и эффективностью использования ресурсов. Научная новизна исследования заключается в комплексной оценке взаимосвязи между цифровизацией и конкурентоспособностью сельского хозяйства стран Центральной Азии на основе предложенных композитных индексов, что позволило показать обусловленность данной взаимосвязи специфическими особенностями развития сельского хозяйства каждой страны. Результаты исследования могут быть использованы при разработке государственной политики и стратегий цифровой трансформации, направленных на повышение эффективности использования ресурсов, укрепление конкурентоспособности сельского хозяйства и обеспечение устойчивого развития сельских территорий

Ключевые слова: цифровизация; конкурентоспособность сельского хозяйства; Центральная Азия; информационно-коммуникационные технологии; цифровая трансформация; корреляционный анализ Пирсона

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Research and improvement of water metering structures for irrigation systems with non-steady flow conditions in agricultural water use

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Abstract. This article examined the problem of improving the accuracy of water metering at water-metering facilities in irrigation systems operating under variable head conditions and subject to intensive siltation. The relevance of this research stems from the need to ensure accurate water flow measurement under unstable hydraulic conditions and the accumulation of bed sediments, which significantly affect the reliability of the structures and the efficiency of water resource allocation. The accuracy of water metering is of vital importance to agriculture, as it affects compliance with irrigation regimes, the rational use of water and the sustainable water supply to the agricultural sector. Insufficient measurement accuracy can lead to water wastage, disruption to irrigation schedules and reduced crop yields. The aim of this study was to develop and provide a hydraulic justification for an improved diaphragm design that ensures measurement stability and reduces the impact of sediment. The study utilised methods of hydraulic calculation, comparative design analysis and modelling of the structure's operation under various flow regimes and head levels. The influence of the orifice geometry, the position of the bottom opening and the diaphragm configuration on the flow pattern and sediment accumulation processes was assessed. The results showed that, to improve the accuracy of water metering, it is advisable to use two types of diaphragm: a flat plate with an adjustable bottom opening and a design with a fixed opening. It was established that the adjustable opening reduces silting, prevents the cross-section from becoming blocked and stabilises the flow characteristics. The design with a fixed orifice is effective under stable operating conditions. Calculation data confirm a reduction

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in measurement error, an increase in the stability of the flow coefficient and an improvement in the long-term operational reliability of the structure. The practical value of this work lies in the ability to adapt water metering units to various conditions without complicating the design. The proposed solutions contribute to improving water use efficiency and enhancing water distribution management in irrigation systems

Keywords: water metering structure; adjustable diaphragm; bottom outlet; sedimentation; water metering accuracy; Chüy Valley

Introduction

Rational management of water resources is a key factor in the sustainable development of agriculture in Kyrgyzstan, where agricultural production is directly dependent on irrigation systems and limited water resources. The efficiency of water supply affects crop yields, economic stability and food security, and in the context of climate variability, there is a growing need for accurate water metering and rational water distribution. Research by M. Ubaydullaev *et al.* (2024) shows that the main problems relate to the dilapidated state of irrigation networks, insufficient funding and shortcomings in water management, which reduce the efficiency of land use. Consequently, there is a need to modernise existing systems, develop new irrigation networks and improve funding mechanisms. According to FAO (2022), over 90% of agricultural production in Kyrgyzstan depends on irrigated land. The intensification of climate change is leading to water shortages, which have already caused significant crop losses during periods of drought. This is linked to rising temperatures, increased water consumption by crops and a reduction in river flow. Under these conditions, the role of modern monitoring systems, which enable more accurate accounting of water resources, is becoming increasingly important. At the same time, the operation of irrigation canals involves complex hydraulic processes, including fluctuations in water levels, backwater effects and the accumulation of bed sediments. Siltation of the canals alters the flow pattern and reduces flow capacity, which adversely affects the accuracy of water-metering facilities. Additional errors arise due to changes in hydraulic conditions, under which traditional measuring devices do not always function correctly. The operation of irrigation systems is accompanied by complex hydraulic processes, including fluctuations in water levels, non-uniform flow velocities and the influence of head in the lower reach. A significant factor is the transport and accumulation of bed sediments, whilst the silting up of river channels reduces flow capacity and alters the hydraulic characteristics of the flow. Water gauging structures are particularly sensitive to these changes, as the accuracy of water flow measurement depends on their precise operation. In his research, K. Beishekeev (2010) notes the need to develop improved water gauges for channels with extremely turbulent flow and proposes a new design, the effectiveness of which has been confirmed by laboratory studies.

N. Li *et al.* (2026) established that the presence of bed sediments in the vicinity of water-measuring devices leads to a distortion of the flow velocity profile and a redistribution of energy, causing deviations in actual water flow rates from calculated values. Backwater from the downstream reach also has a significant effect, altering the hydraulic flow regime and reducing the reliability of measurements. In this regard, water-metering structures must not only meet accuracy requirements but also ensure strength, stability and durability when subjected to hydraulic loads, filtration processes and possible deformations, which is a prerequisite for their effective and safe operation in irrigation systems. The paper notes that sediment deposition is one of the key factors affecting the accuracy of water metering in irrigation canals. The authors established that sediment concentration determines the thickness of the deposits, whilst the hydraulic parameters of the flow – discharge and bed gradient – regulate the rate at which they accumulate. At the same time, sediment accumulation leads to a rise in the water level and a systematic overestimation of the calculated discharge, with errors potentially reaching significant values under unfavourable hydraulic conditions. The results obtained confirm that channel siltation significantly distorts the relationship between water level and discharge, a factor that must be taken into account in the operation and design of water-measuring structures.

An important avenue for improving the efficiency of water use is the refinement of the designs of water-measuring structures used in irrigation canals, as traditional devices, such as diaphragms and weirs, do not always ensure accuracy under unstable hydraulic conditions, siltation and variable head. W. Liang *et al.* (2026) highlight the need to develop new or upgraded design solutions. As a promising approach, a deformation device has been developed for measuring flow rate in open channels, combining accuracy, portability and low cost. A theoretical model demonstrated a parabolic relationship between velocity and the square root of deformation, whilst the optimal plate parameters ensured an average error of less than 5%, outperforming traditional propeller flowmeters. Such a device is particularly relevant for Kyrgyzstan's irrigation systems, where outdated hydraulic structures lead to water losses, uneven flow and limited controllability, thereby reducing the overall efficiency of water use.

Recent studies, including the work of A. Batykova *et al*. (2024), note that soil cover forms the basis of sustainable agriculture and depends to a large extent on rational water management. Disruptions to irrigation regimes lead to waterlogging or water shortages, causing salinisation, soil degradation and a decline in soil fertility. These problems are particularly acute in irrigation systems with non-steady-state flow regimes, where fluctuations in water levels and flow rates make it difficult to regulate water supply accurately. Inadequate accuracy in water metering under such conditions leads to uneven water distribution and exacerbates negative processes in the soil. In this regard, improving the design of water metering structures that operate effectively under non-steady-state hydraulic conditions is a key area for enhancing the accuracy of water metering, optimising water distribution and ensuring the sustainability of irrigated land. In the work by A. Sabitov & I. Uraiimov (2023), it is noted that the use of accurate and real-time methods for measuring water flow in open channels and pipelines is key to the effective management of water resources. One such method is point-based flow measurement in trapezoidal channels and circular pipes, which enables the collection of real-time data for adjusting water distribution and improving the accuracy of metering under actual operating conditions. Research by A. Batykova *et al*. (2023) notes that organising the efficient use of land and water resources within a system of water users' associations requires a comprehensive approach combining rational land use and sustainable water distribution. In the current context, the development of irrigation systems is focused not only on improving organisational management mechanisms (such as hydro-units and water users' association service zones), but also on the introduction of innovative engineering solutions.

The development of irrigation systems in the Kyrgyz Republic requires the introduction of modern water resource management technologies and the improvement of hydraulic structures. In this regard, the development of innovative engineering solutions aimed at improving water use efficiency and the sustainability of irrigation systems takes on particular significance. Of particular importance in this regard is the development of water-metering devices capable of adapting to changing flow conditions and ensuring the stability of hydraulic characteristics in irrigation networks. Taking into account factors such as variable head, channel siltation and flow irregularities is becoming an important part of both the technical and organisational aspects of water management. Despite the progress made, issues concerning the operational stability of water metering structures when exposed to these factors remain insufficiently studied, which necessitates further research aimed at improving the accuracy of metering and the rational allocation of water resources in irrigated agriculture. A number of studies have examined the use of new types of flow meters. In their paper, Y. Sun *et al*. (2024) note that the vane flowmeter offers an effective method for measuring water flow in small-diameter channels. Thanks to its simple design, resistance to silting and the stable relationship between deflection angle and flow rate, this device demonstrates high potential for improving measurement accuracy.

The aim of this study was to provide a hydraulic justification for improved designs of water meter diaphragms, aimed at enhancing their operational stability and the accuracy of water flow measurement under conditions of variable hydraulic regimes and severe silting.

Materials and Methods

The study was conducted under laboratory and semi-industrial conditions to assess the hydraulic efficiency of improved designs for water-metering structures with diaphragms, intended for measuring water flow in open irrigation canals. The experimental part of the study was carried out on a hydraulic test rig simulating the operating conditions of on-farm irrigation systems in the Kyrgyz Republic, taking into account the characteristic parameters of channel flow, sediment content and water level variability. The experimental setup comprised inlet and outlet channels with rectangular cross-sections, a water-measuring diaphragm with adjustable and fixed water-passage openings, water-level gauges for determining the hydraulic parameters of the flow, and a device to ensure a submerged flow regime. The length of the test section was 6.0 m, the channel width was 0.8 m, and the average flow depth varied between 0.30 and 1.00 m. The water-level gauges were installed in the upper and lower reaches directly adjacent to the diaphragm, and water-level readings were taken after the flow had stabilised, i.e. once a steady-state flow regime had been reached for each specified opening of the outlet. The flow velocity was regulated by varying the head and the water discharge in the system. As part of the study, two modifications of the diaphragms were developed and tested.

An adjustable diaphragm in the form of a flat metal plate 3-5 mm thick, fitted with a rounded lower element of radius $R = 0.15$ m, designed to reduce turbulence and minimise local hydraulic losses. A non-adjustable diaphragm in the form of a fixed wall, made of metal, reinforced concrete or concrete, with a separately mounted rounded element secured by bolted connections.

The geometric characteristics of the structures were determined taking into account the typical operating conditions of the irrigation canals in the Chüy Valley. The height of the water outlet varied between 0.30 and 0.40 m, whilst the length of the outlet was taken to be equal to the width of the channel at the bottom, which prevented lateral compression of the water jet. The radius of curvature of the lower edge was calculated based on the maximum water depth in the upper reach and determined by the following equation:

$$R \approx 0{,}2H_{Bmax}, \tag{1}$$

where R is the radius of curvature of the lower edge, and H_{Bmax} is the maximum water depth in the upper reach.

The experimental studies were carried out sequentially in several stages. In the first stage, the initial hydraulic parameters of the flow were determined: water discharge, depth, flow velocity and the head difference between the upper and lower reaches. In the second stage, the diaphragm structure under investigation was installed and various flow regimes were modelled, including free-flow and submerged-flow conditions. The submerged flow regime was created and maintained using a weir and a depression in the riverbed in the lower reach; the submerged nature of the flow was monitored visually by checking the water level in the intake section of the structure relative to the weir crest elevation before each series of measurements. During the third stage, multiple measurements of flow parameters were carried out at various values of the orifice opening and head level. The study is based on an analysis of existing water-measuring structures with diaphragms, the hydraulic behaviour of flow through openings under submerged conditions, and calculations of the discharge coefficient using formula (1): The main parameters measured were: water discharge (Q, m^3/s); head (Z, m); height of the water passage opening (h_(op), m); effective cross-sectional area of the flow (ω, m^2); discharge coefficient (μ); stability of the hydraulic regime; and the rate of sediment accumulation upstream of the structure. The water discharge Q at each measurement stage was determined by calculation using Equation (1), based on directly measured values of the head Z and the effective cross-sectional area ω, whilst the obtained values of the discharge coefficient μ were used for the subsequent assessment of the hydraulic efficiency of the diaphragm structures under investigation.

The water flow rate was determined using the following relationship:

$$Q = \mu\omega\sqrt{(2gz)}, \tag{2}$$

where Q is the water flow rate (m^3/s), μ is the discharge coefficient, ω is the effective cross-sectional area of the flow (m^2), g is the acceleration due to gravity (9.81 m/s^2), and z is the difference in water levels between the upper and lower reaches, m.

To improve the reliability of the measurements, each experiment was repeated at least five times, after which the mean values of the measured parameters were calculated. The reproducibility of the results was verified by comparing the experimental data from repeated tests and analysing measurement deviations. The permissible error in determining water flow did not exceed ±3-5%, which meets the requirements for hydrometric studies of open irrigation channels. A comparative assessment of the effectiveness of the proposed designs was carried out according to the following criteria: the value of the discharge coefficient (μ); stability of the hydraulic regime; the extent of local energy losses; resistance to silting; accuracy of water flow measurement; and operational reliability of the structure. Methods of hydraulic analysis, comparative modelling and statistical processing of experimental data were used to analyse the results. Calculations and the processing of measurement data were carried out in Microsoft Excel, which made it possible to identify patterns in the variation of the discharge coefficient under different operating conditions of the structure and to verify the results obtained by comparing them with existing hydraulic models and data from recent studies.

Bernoulli's equation was formulated for cross-sections 1-1 and 2-2, which pass through the free surface of the flow in the upper and lower reaches, respectively. The reference plane 0-0 was taken at the level of the excavation (sump) of the water-measuring structure. To analyse the hydraulic conditions, a free-flow scheme is considered, reflecting the main characteristics of flow motion in the absence of head. Figure 1 shows the free-flow scheme.

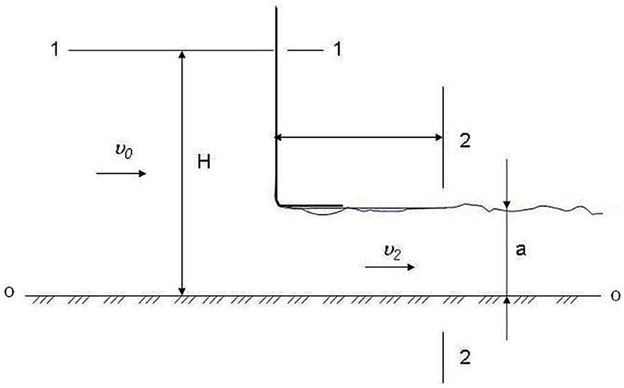

Figure 1. Free-flow diagram

Source: compiled by the authors

The flow rate of the submerged flow through the water meter:

$$Q = \mu\omega_2\sqrt{2gz}, \tag{3}$$

where Q – water flow rate through the water metering structure, m^3/s; μ – discharge coefficient; ω_2 – area of the outlet orifice, m^2; z – effective head, m; g – acceleration due to gravity, 9.81 m/s^2.

Results and Discussion

Traditional diaphragm designs used in open-channel water metering structures are characterised by a number of design features that limit their hydraulic efficiency. These features include the presence of a sill beneath the flow opening, jet constriction around the perimeter of the opening, and a relatively short length of the opening relative to the channel width. Taken together, these factors lead to a reduction in the structure's flow capacity and a decrease in the accuracy of water flow measurement. Hydraulic studies of water-metering structures have noted that the presence of a sill and sharp edges causes additional local energy losses, as well as contributing to an uneven distribution of velocities within the flow. Recent laboratory studies by Z. Wenzheng *et al.* (2024) also confirm that the geometry of the restricting elements and the nature of the inlet weirs significantly influence velocity distribution, turbulence and the actual flow rate in critical sections of the channels, leading to flow rates lower than theoretical values, all other things being equal.

A schematic diagram of an improved water-measuring structure with a diaphragm, comprising inlet and outlet channels, a depression in the riverbed, a diaphragm with a water-passage opening, and level gauges installed in the upper and lower reaches. Figure 2 illustrates the structural features of the structure and the relative positions of its main components.

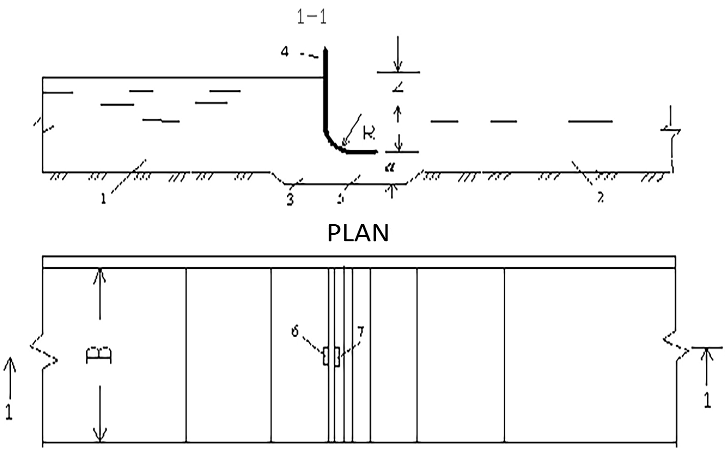

Figure 2. Schematic diagram of an improved water-measuring structure with a diaphragm

Note: 1 – inlet channel; 2 – outlet channel; 3 – recess in the channel bed; 4 – diaphragm; 5 – water passage; 6 – water level gauge in the upper reach; 7 – water level gauge in the lower reach

Source: developed by the authors

The design features of the improved formwork developed by M.V. Butyrin, as well as its spatial configuration and main elements, are shown in Figure 3, which illustrates front and side views of the structure.

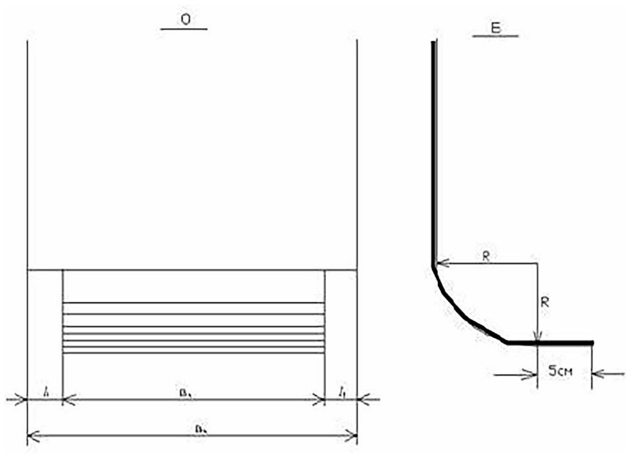

Figure 3. Improved shield designed by M.V. Butyrin

Note: a – front view; b – side view

Source: prepared by the authors

To ensure a submerged flow regime, special design solutions are employed to regulate flow conditions and enhance the stability of the hydraulic regime. Figure 4 shows diagrams of the device for ensuring a submerged flow regime, including a sluice gate and a depression in the riverbed.

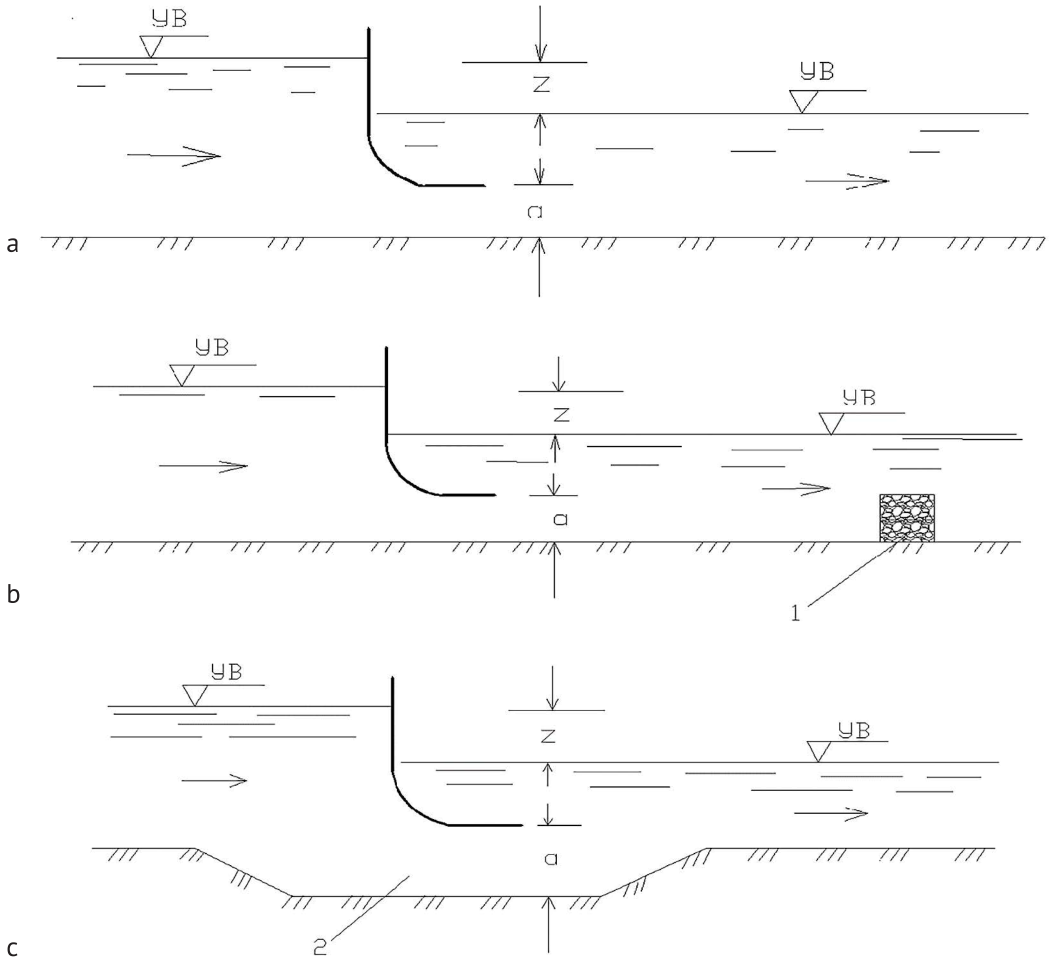

Figure 4. Schematic diagrams of devices for ensuring a submerged flow regime
Note: 1 – sluice weir; 2 – depression in the riverbed
Source: compiled by the authors

The paper by A. Nicosia *et al.* (2023) demonstrates that the outflow process from a linear constriction under free-flow conditions can be modelled using dimensional analysis and conditions of incomplete self-similarity. The proposed equation relating flow rate to the stage is characterised by an exponent close to 2 and a coefficient dependent on the angle of inclination of the device's side walls relative to the channel bank, which provides an accurate estimate of the flow rate with an error of less than ±3% in 93.7% of cases. In conventional water-meter diaphragm designs, the water flow passing through the orifice experiences jet compression along the vertical and horizontal boundaries, which leads to a reduction in the effective flow area. The presence of sharp edges and weirs increases flow turbulence and energy losses. This is particularly noticeable in irrigation canals with high levels of bed sediment: sediment deposition upstream of the weir gradually alters the geometry of the structure and impairs flow conditions. The proposed linear constriction device is characterised by its simple design, ease of installation, low cost and high measurement accuracy, making it an effective solution for practical water metering.

In later designs of water-measuring diaphragms, improvements were proposed aimed at eliminating these shortcomings. In the improved designs (Fig. 3), the sill beneath the orifice was completely removed, and the lower edge of the orifice was formed as a smooth radial curve. The radius of curvature is taken to be approximately $R \approx 0.2H_{Bmax}$, where H_{Bmax} is the maximum water depth in the upper reach. Furthermore, the length of the opening was increased to match the width of the channel at the bottom, which made it possible to virtually eliminate lateral compression of the jet. These design modifications significantly improved the hydraulic performance of the structure.

Furthermore, box-type spillway stabilisers are widely used in the irrigation systems of the Kyrgyz Republic; these stabilise the water flow and reduce local hydraulic losses. The use of such devices ensures a uniform distribution of flow even when the water level in the canal fluctuates. Mathematical modelling of the proposed spillway stabiliser has made it possible to determine a pressure range of $H_{max}/H_{min} = 3.0$ and a hydraulic coefficient of c = 2 m/s. The results of the study confirm the high efficiency of the stabilisers in reducing turbulence and maintaining a steady water flow rate, complementing the effects achieved by improved water meter diaphragm designs. Based on experimental measurements of flow rates and water levels, flow coefficient values were obtained for various operating modes of the structure. The results of the calculations are presented in Table 1.

Table 1. Results of determining the discharge coefficient μ

Experiment No.	Head difference Z, m	Opening height h_(op), m	Flow rate Q, m³/s	Area ω, m₂	Discharge coefficient μ
1	0.20	0.30	0.125	0.090	0.95
2	0.25	0.30	0.145	0.090	0.96
3	0.30	0.35	0.180	0.105	0.97
4	0.35	0.35	0.205	0.105	0.98
5	0.40	0.40	0.240	0.120	0.99

Source: developed by the authors based on the results of experimental studies

As can be seen from Table 1, the obtained values of the discharge coefficient lie within the range $\mu \approx 0.95$-0.99, which confirms the high hydraulic efficiency of the proposed designs. There is a consistent trend towards an increase in μ as the head difference increases and the orifice parameters are optimised. The calculations presented directly confirm the experimental and theoretical principles of the research methodology and demonstrate its applicability for evaluating the performance of water-measuring structures with a rounded lower edge and box-type structures.

When analysing water flow through a diaphragm, Bernoulli's equation, expressed for the cross-sections upstream and downstream of the nozzle, is taken as the basis. Since the pressure in both cross-sections is the same (atmospheric), and given that, with a submerged outlet, the water depths in the upper and lower reaches are similar and the channel width remains constant, the velocity head at the inlet can be disregarded. As a result, the equation is significantly simplified. Under these conditions, the difference in water levels between the upper and lower reaches is effectively equal to the head loss. In other words, the entire difference in water levels is expended on overcoming local resistance as the flow passes through the nozzle. Energy losses are determined by the total coefficient of local resistance, which is the sum of the resistance at the inlet to the nozzle and at its outlet. For the design under consideration, this coefficient is small (approximately 0.13), indicating relatively favourable hydraulic flow conditions. By equating the difference in levels to the head loss, an expression for the average flow velocity within the nozzle is obtained. Analysis shows that the velocity is slightly less than the theoretical (ideal) velocity of free flow. This reduction is accounted for by the velocity coefficient, which in this case is approximately 0.94. Since there is no jet compression (the compression coefficient is taken to be equal to one), the discharge coefficient coincides with the velocity coefficient. Consequently, the actual flow rate through the nozzles is approximately 94% of the theoretical value, which indicates a sufficiently high hydraulic efficiency of the design under consideration. Consequently, when determining the flow rate of submerged flow, there is no need to take into account the approach velocity υ_0. Knowing the flow equations for free and submerged flow, it is possible to determine the head H_1 in the upper reach of the weir, since under actual operating conditions it is precisely through this value that the construction height of the hydraulic structure with the weir can be determined. The head (or water depth) upstream of the diaphragm is determined at the maximum flow rate of the hydraulic structure as the sum of the difference in water levels between the upper and lower reaches and the water depth downstream of the nozzles (in the intake section of the structure). Thus, the water level upstream of the diaphragm depends on both the hydraulic head and the conditions in the lower reach. The head difference, in turn, is related to the water flow rate through the opening (nozzles), with the flow rate being determined taking into account the discharge coefficient, which reflects the effects of jet compression and hydraulic losses. The geometric characteristics of the opening, in particular its area, also have a direct influence on the structure's flow capacity.

The opening in question is rectangular in shape, with its width taken to be equal to the width of the channel, which ensures a uniform flow and simplifies the hydraulic calculations. The water depth in the lower reach (intake) is determined as the sum of the so-called service depth in the discharge channel and the additional depth resulting from the operating conditions of the intake section of the structure. The design depth is determined using established hydraulic equations for uniform water flow, in particular using equations of the Chazé type, which take into account the effective cross-sectional area, the hydraulic radius and the channel gradient. The depth of the receiving section, given a fixed outlet height, must ensure that the intake is submerged from the downstream side even at minimum flow rates. This condition is important for the stable operation of the structure and accurate water metering. O. Baev (2023) notes that, when designing and operating irrigation canals and water-metering structures, it is necessary to take into account the interrelationship between the hydraulic parameters of the flow and the structural characteristics of the structures, drawing on classical methods of hydraulic calculation. In particular, research into the hydraulics of irrigation canals has demonstrated the applicability of various types of design problems, enabling the determination of flow capacity, gradient, roughness coefficient, flow depth and the dimensions of the canal's cross-section, which together provide a reliable description of the hydraulic regime. Under steady-state flow conditions in the inlet, the intake depth must be determined taking into account the geometric parameters of the structure, the normal water depth in the channel and an additional depth margin, as specified by regulatory guidelines. This margin is necessary to ensure that the inlet is fully submerged and to prevent disruption of the hydraulic regime. Overall, the analysis carried out shows that the flow parameters, including water depth, discharge and channel characteristics (including the roughness coefficient), are interrelated and must be considered holistically – taking into account both the hydraulic behaviour of the flow and the structural features of the water-measuring structure, which is in line with modern approaches to the calculation and design of irrigation systems. The energy state of the water flow in the nozzle can be determined by comparing the height of the orifice (nozzle)α with the critical depth, which is determined using the following formula:

$$h_{np} = \sqrt[3]{\frac{\alpha \cdot q^2}{g}}, \tag{4}$$

where h_{np} is the critical flow depth; α is the Coriolis coefficient, $\alpha = 1.08/52/$; q is the specific water flow rate, $g = \frac{Q}{b}$; g is the acceleration due to gravity, $g = 9.81$ m/s^2.

If the orifice height $a > h_{np}$, the flow condition in the nozzle is laminar; if $a < h_{np}$, it is turbulent. The energy state of the flow in the nozzle can also be determined by the Froude number – *Fr.* In the case of turbulent flow in the nozzle below the diaphragm, the task of measuring flow rate becomes more complicated, as a hydraulic jump occurs in the lower run-out section of the water meter. When the surface roller of the hydraulic jump is positioned above the orifices of the proposed water meter, a flow regime known as "submerged flow" arises, which is intermediate between free and submerged flow. In this regime, the flow rate for submerged flow is determined by the formula:

$$Q = \mu \cdot a \cdot b\sqrt{2g \cdot (H_0 - h_z)}, \tag{5}$$

where Q is the volumetric flow rate of the fluid; μ is the discharge coefficient; a is the orifice height; b is the orifice width; g is the acceleration due to gravity; H_0 is the head taking into account the approach velocity in the upper stilling basin; h_z is the depth at the outlet of the nozzle.

As can be seen from the equation, determining the flow rate under this flow regime becomes ambiguous. In addition to the dimensions of the orifices a and b, the flow coefficient of the nozzle and the geometric head in the upper reach H, it is also necessary to know the approach velocity υ_0 (which, in the case of a submerged flow, has practically no effect on the determination of the flow rate) and the depth at the centreline of the hydraulic channel h_z. When considering the hydraulic scheme of a submerged outflow through the proposed water-measuring device with a diaphragm and bottom nozzles, the elimination of the trapezoidal channel cross-section presents certain specific challenges. In particular, the bottom nozzle is limited by the width of the channel at the bottom, i.e. it has a cross-sectional dimension of $a \cdot b$, whilst the side sections on the channel slopes are covered by an impermeable diaphragm. When analysing the flow scheme, these additional side walls must be taken into account, as they may lead to a slight reduction in the flow meter's discharge coefficient. Parabolic flume channels and the structures installed within them possess specific hydraulic characteristics, and their actual flow capacity depends on the roughness coefficient of the watercourses, as well as the design features of the bottom inserts and diaphragms. The authors emphasise that, when designing and operating water-metering, water-release and network structures, it is necessary to take into account the influence of lateral constraints on the accuracy of water flow measurements, which is particularly important for the sustainable operation of irrigation systems in the Kyrgyz Republic (Mambetov *et al.*, 2022). If the bottom orifice of the nozzle extends across the entire lower part of the channel cross-section, i.e. has a trapezoidal shape, then the theory presented here also requires refinement, as the flow rate through a narrow orifice cannot be determined using the small-orifice model when $a < 0.1$H. In this case, the flow rate through a large trapezoidal orifice can be determined using:

$$Q = \mu \cdot \sqrt{2g} \int_{H_1}^{H_2} b_2 \cdot \sqrt{2 \cdot d_z}, \tag{6}$$

where Q is the fluid flow rate (volumetric flow rate, m^3/s); μ is the discharge coefficient; g is the acceleration due to gravity (≈9.81 m/s^2); H_1 and H_2 – integration limits corresponding to the head at the upper and lower edges of the orifice (nozzle); b_2 – variable width of the trapezoidal orifice; z – current depth.

The results of hydraulic studies show that the use of rounded lower edges on water-measuring diaphragms and the use of box-type spillway stabilisers make it possible to reduce local energy losses and increase the discharge coefficient. Most experimental studies note that the discharge coefficient in designs with a rounded edge can increase by 5-10% compared with designs with sharp edges. Calculations carried out as part of this study confirm these findings: the obtained values of the discharge coefficient lie within the range $\mu \approx 0.95$-0.99. This indicates the high hydraulic efficiency of the proposed solutions and their stability under various flow conditions, whilst the combined use of a box-type stabiliser provides additional flow stabilisation and reduces pressure fluctuations.

A diagram of the improved water-measuring structure with a diaphragm is shown in Figure 2. The design comprises inlet and outlet channels, a recess in the channel bed, a diaphragm and a water passage. Water levels are monitored using level measuring rods in the upper and lower reaches. The depression in the channel bed ensures a submerged flow regime. The submerged regime is considered one of the most stable operating regimes for water gauging structures, as the influence of external factors on the flow rate is reduced by the head, which stabilises the flow. Under these conditions, the discharge coefficient becomes more constant and is less dependent on fluctuations in water levels, whilst the error in discharge measurement is reduced by 10-15% compared with free flow. This is particularly important for water metering in irrigation systems. For instance, in their paper, P. Sultanbekova *et al.* (2025) note that, in conditions of freshwater scarcity, there is a growing need for the rational use of collector-drainage water, significant volumes of which, if managed inefficiently, can deteriorate the ecological and land-improvement conditions of the areas concerned. Similar patterns are observed in closed irrigation systems. For instance, J. Ishanov (2025) notes in his work that the uniformity of water distribution in pipelines is determined by their diameter, length, flow rate, pressure and the gradient of the terrain. The proposed mathematical model, based on the 10% criterion, enables the optimisation of water distribution and an increase in the efficiency of irrigation systems. Despite the improvements made, issues relating to the detailed design of the diaphragm remain insufficiently studied. In existing solutions, the main focus is on the geometry of the orifice, whilst the design and methods of fixing the diaphragm are considered only to a limited extent. As part of this study, two modifications of the diaphragms have been developed, differing in design and operational characteristics.

The first variant consists of an adjustable diaphragm in the form of a flat plate (Fig. 4). The design comprises an upper flat metal plate 3-5 mm thick and a lower rounded element with a radius of R = 0.15 m. This radius has been chosen on the basis of the average hydraulic conditions in mountainous and foothill watercourses, where the water depth is typically between 0.6 and 1.0 m. The rounded element consists of two short sections: a vertical section and a horizontal section. The vertical section is used to bolt the element to the shield, whilst the horizontal section ensures that the flow is directed in a parallel jet pattern. A sealing gasket is used to ensure a watertight connection between the structural elements. The main advantage of the adjustable orifice is the ability to vary the height of the water passage. This allows the structure to be used not only for measuring water flow rate but also for regulating water distribution within the channel. Water flow is determined by the relationship Q (Z, h_(open)), where Z is the difference in water levels between the upper and lower reaches, and h_(open) is the height of the opening. This approach allows for changes in hydraulic conditions to be taken into account and enables the water supply to be adjusted promptly.

The second variant consists of a non-adjustable diaphragm in the form of a wall (Fig. 4). The design comprises a main wall made of metal, concrete or reinforced concrete, as well as a separately manufactured rounded element which is attached to the wall by bolted connections. Various design options are possible, including rigid or removable fastening of the element, as well as its installation on the front or rear side of the wall. A. Churaev & L. Yuchenko (2022) note that, in the context of open irrigation networks, the main problems remain the poor technical condition of water metering points, a lack of measuring instruments and limited financial resources, which hinder the implementation of complex and costly water flow measurement systems. In this regard, it is advisable to use simple, reliable and affordable hydrometric structures, in particular the "fixed channel" type, which have proven their effectiveness. The main advantage of the design in question is its ease of operation: unlike adjustable orifices, it contains no moving parts, which increases the structure's reliability and reduces the need for maintenance. Determining the water flow rate in this case is reduced to measuring only the difference in water levels Z, which significantly simplifies operation, particularly in remote and hard-to-reach sections of irrigation systems, where the use of complex equipment is difficult or economically unfeasible. A comparison of the results obtained with data from other studies shows that the proposed designs offer a number of advantages. In most previously developed water-metering structures, the discharge coefficient varies widely depending on flow conditions and the degree of silting in the channel. In some cases, its value may fall to $\mu \approx 0.80$-0.85. In the proposed designs, the absence of a weir, the increased length of the orifice and the rounded lower edge ensure a more stable value for the discharge coefficient.

Of particular importance is the structure's resistance to silting and sediment accumulation. In traditional water-measuring structures, the presence of a sill in front of the orifice promotes sediment accumulation and the formation of deposits, which over time leads to a reduction in the effective cross-sectional area of the orifice. In the proposed designs, this drawback is eliminated by the absence of a sill and the use of a rounded edge. The water flow passes freely through the orifice without creating conditions for sediment accumulation

(Vatankhah & Ghaderinia, 2018). Practical calculations and analysis of the hydraulic characteristics show that the proposed designs maintain a high stability of the discharge coefficient even under variable inundation conditions and partial silting of the channel. The discharge coefficient values range from $\mu \approx 0.95$-0.99, which corresponds to the best performance figures reported in contemporary hydraulic studies.

The proposed design solutions are particularly promising for on-farm irrigation channels in the Chüy Valley. These channels are characterised by unsteady hydraulic conditions, significant fluctuations in water levels and an intense inflow of sediment. Under such conditions, the use of traditional water-metering structures is often accompanied by a reduction in the accuracy of water flow measurements and the need for regular canal cleaning. As noted in the research by B. Kurumshiev *et al*. (2021), the water supply system for the irrigation networks of the Kyrgyz Republic comprises a complex network of hydraulic structures that ensure the supply of water from mountain rivers to main and distribution canals. The authors emphasise that the parameters of hydraulic structures and water supply schemes are shaped by natural conditions, topography and the characteristics of mountain rivers, which determine the specific nature of irrigation systems' operation and necessitate the refinement of engineering solutions during the operation of water management facilities. The paper by R. Aliev & A. Djalilov (2024) examines two methods for determining water flow in open irrigation systems: the "velocity-area" and "gradient-area" methods, as well as issues relating to the modernisation of the "gradient-area" method with a view to the remote transmission of parameters and the improvement of their processing. Based on experimental studies, the authors demonstrated that the maximum error of the "gradient-area" method compared with the "velocity-area" method is 0.7%, which confirms its high accuracy and importance for modern water metering systems. The use of improved diaphragms in water metering installations makes it possible to further enhance the reliability of the systems and reduce operating costs.

Improvements to the diaphragm design, achieved by eliminating the threshold, increasing the length of the orifice and using a rounded lower edge, ensure a significant increase in the hydraulic efficiency of the water metering structure. The proposed adjustable and non-adjustable diaphragm designs ensure stable operation of the structure under various hydraulic conditions and can be recommended for use in irrigation systems with high silt content.

Conclusions

As a result of the research carried out, two modifications of water-measuring diaphragms for open irrigation channels were developed and analysed: an adjustable diaphragm in the form of a flat shield and a non-adjustable diaphragm in the form of a wall with a rounded bottom element. The proposed design solutions are aimed at increasing the hydraulic efficiency of water-measuring structures, improving flow conditions and enhancing the accuracy of water flow measurement in irrigation systems. Calculation of the discharge coefficient for vertical sluice gates with a wide weir crest in freely submerged flows using the best-subset regression method. An accurate determination of the discharge coefficient is possible by taking into account both free-flow and submerged-flow conditions, which is important for irrigation, water supply and the safety of structures. The hydraulic analysis carried out confirmed that the main factors in improving the gate's efficiency are the removal of the sill in front of the water passage, increasing the length of the passage to the width of the channel at the bottom, and the use of a rounded lower edge to the passage. Calculations showed that with these design solutions, the discharge coefficient μ reaches 0.95-0.99, which is 5-10% higher than that of traditional diaphragms with sharp edges and a sill, whilst the reduction in hydraulic losses contributes to an increase in flow capacity and greater stability of the flow characteristic as water levels change. The method proposed by the authors ensures a high level of calculation accuracy (coefficient of determination 0.993, root mean square error 5.04%), which confirms its practical applicability for the design of water metering structures.

An analysis of flow regimes has shown that ensuring the orifice operates in a submerged mode stabilises the hydraulic parameters of the flow and reduces the impact of water level fluctuations on the accuracy of flow measurement. Under conditions of variable head, the calculated error in flow rate determination can be reduced by approximately 10-15% compared with traditional water meter designs. The proposed adjustable diaphragm allows the height of the water passage to be varied within a range of 3-5 cm or more, enabling simultaneous regulation and measurement of water flow according to the relationship $Q(Z, h_{(op)})$. The non-adjustable diaphragm design is characterised by ease of operation and enhanced reliability, as determining the flow rate requires only the measurement of the water level difference Z. The absence of a threshold and the presence of a rounded bottom edge also help to reduce sediment accumulation and minimise the likelihood of the water meter structure becoming silted up.

The proposed designs are particularly effective for on-farm canals in irrigation systems, where unsteady hydraulic conditions and significant sediment inflow are typical. Under such conditions, the use of the developed diaphragms can improve the stability of the structure's hydraulic characteristics and reduce operational maintenance costs. The results of this study support the recommendation to implement the developed designs in the design and reconstruction of water gauging stations for irrigation systems in the Kyrgyz Republic.

The use of these improved water gauging devices may contribute to a more rational distribution of water resources and an increase in the efficiency of agricultural production. Further research should focus on conducting field experiments under real-world operating conditions in irrigation canals, as well as on refining the flow characteristics of the structure under various flooding regimes and degrees of siltation.

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Айыл чарба сууну пайдалануу шарттарындагы агымдын стационардык эмес режиминде иштеген сугат системалары үчүн суу эсептөөчү конструкцияларды изилдөө жана өркүндөтүү

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Аннотация. Макалада өзгөрмө подпордук режимдерде жана интенсивдүү ылай басуу шарттарында иштеген ирригациялык системалардын суу өлчөөчү курулмаларында суу эсебинин тактыгын жогорулатуу маселеси каралат. Изилдөөнүн актуалдуулугу туруксуз гидравликалык шарттарда жана түпкү чөкмөлөрдүн топтолушу учурунда суунун чыгымын ишенимдүү эсепке алууну камсыз кылуу зарылдыгы менен негизделет, анткени бул факторлор курулмалардын ишенимдүүлүгүнө жана суу ресурстарын бөлүштүрүүнүн натыйжалуулугуна олуттуу таасир этет. Суу эсебинин тактыгы айыл чарбасы үчүн өзгөчө мааниге ээ, себеби ал сугаруу режимдеринин сакталышына, сууну сарамжалдуу пайдаланууга жана агрардык секторду туруктуу суу менен камсыздоого түздөн-түз таасир этет. Өлчөөлөрдүн жетишсиз тактыгы суунун ашыкча сарпталышына, сугаруу графиктеринин бузулушуна жана түшүмдүүлүктүн төмөндөшүнө алып келиши мүмкүн. Изилдөөнүн максаты өлчөөлөрдүн туруктуулугун камсыз кылган жана чөкмөлөрдүн таасирин азайткан өркүндөтүлгөн диафрагма конструкциясын иштеп чыгуу жана анын гидравликалык негиздемесин берүү болгон. Изилдөөдө гидравликалык эсептөө, конструкцияларды салыштырмалуу талдоо жана курулманын ар кандай агым режимдеринде жана подпор деңгээлдеринде иштөөсүн моделдөө ыкмалары колдонулган. Тешиктин геометриясынын, түпкү өтмөктүн жайгашуусунун жана диафрагманын конфигурациясынын агым түзүмүнө жана чөкмөлөрдүн топтолуу процесстерине тийгизген таасири бааланган. Изилдөөнүн жыйынтыктары суу эсебинин тактыгын жогорулатуу үчүн диафрагмалардын эки түрүн колдонуу максатка ылайыктуу экенин көрсөттү: жөңгө салынуучу түпкү тешиги бар жалпак калкан жана туруктуу тешиги бар конструкция. Жөңгө салынуучу тешик ылай басууну азайтып, өтмөктүн жабылып калышын алдын алып, суу чыгымынын мүнөздөмөлөрүнүн туруктуулугун камсыздай турганы аныкталды. Туруктуу тешиги бар конструкция эксплуатациянын туруктуу шарттарында натыйжалуу болуп саналат. Эсептик маалыматтар өлчөө каталарынын азайышын, чыгым коэффициентинин туруктуулугунун жогорулашын жана курулманын узак мөөнөттүү ишенимдүүлүгүнүн өсүшүн тастыктады. Иштин практикалык мааниси суу өлчөө түйүндөрүн конструкцияны татаалдаштырбастан ар кандай шарттарга ылайыкташтыруу мүмкүнчүлүгүндө турат. Сунушталган чечимдер сууну пайдалануунун натыйжалуулугун жогорулатууга жана ирригациялык системаларда суу бөлүштүрүүнү башкарууну жакшыртууга көмөктөшөт

Негизги сөздөр: суу өлчөөчү курулма; жөңгө салынуучу диафрагма; түпкү тешик; чөкмөлөр; суу эсебинин тактыгы; Чүй өрөөнү

Исследование и совершенствование конструкций водоучета для ирригационных систем с нестационарным режимом течения в условиях сельскохозяйственного водопользования

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Аннотация. В статье рассматривается проблема повышения точности водоучета на водомерных сооружениях ирригационных систем, функционирующих в условиях переменных подпорных режимов и интенсивного заиления. Актуальность исследования обусловлена необходимостью обеспечения достоверного учета расхода воды при нестабильных гидравлических условиях и накоплении донных наносов, что существенно влияет на надежность сооружений и эффективность распределения водных ресурсов. Точность водоучета имеет важное значение для сельского хозяйства, так как влияет на соблюдение режимов орошения, рациональное использование воды и устойчивое водообеспечение аграрного сектора. Недостаточная точность измерений может приводить к перерасходу воды, нарушению графиков полива и снижению урожайности. Целью работы были разработка и гидравлическое обоснование усовершенствованной конструкции диафрагмы, обеспечивающей стабильность измерений и снижение влияния наносов. В исследовании использованы методы гидравлического расчета, сравнительного анализа конструкций и моделирования работы сооружения при различных режимах течения и уровнях подпора. Оценено влияние геометрии отверстия, положения донного проема и конфигурации диафрагмы на структуру потока и процессы накопления наносов. Результаты показали, что для повышения точности водоучета целесообразно применение двух типов диафрагм: плоского щита с регулируемым донным отверстием и конструкции с фиксированным отверстием. Установлено, что регулируемое отверстие снижает заиление, предотвращает перекрытие сечения и стабилизирует расходные характеристики. Конструкция с фиксированным отверстием эффективна при стабильных условиях эксплуатации. Расчетные данные подтверждают снижение погрешности измерений, повышение стабильности коэффициента расхода и увеличение надежности функционирования сооружения в долгосрочной перспективе. Практическая ценность работы заключается в возможности адаптации водомерных узлов к различным условиям без усложнения конструкции. Предложенные решения способствуют повышению эффективности использования воды и улучшению управления водораспределением в ирригационных системах

Ключевые слова: водомерное сооружение; регулируемая диафрагма; донное отверстие; наносы; точность водоучета; Чуйская долина

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Palynological analysis of honey produced in the East Kazakhstan Region of the Republic of Kazakhstan

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Abstract. Verifying the botanical origin of natural honey is one of the key tasks in modern quality control of beekeeping products, as the reliability of information regarding its floral origin determines its consumer value, confirms its authenticity and helps to prevent adulteration. This issue is of particular relevance to regions with high floristic diversity, including the East Kazakhstan Region of the Republic of Kazakhstan, where natural conditions give rise to a wide range of honey-producing vegetation and create favourable conditions for the production of honey of various botanical origins. The aim of the study was to establish the actual botanical origin of samples of natural honey based on a palynological analysis of their pollen composition, and to assess the consistency of the results obtained with the floral composition declared by the producers. The study focused on 18 samples of natural honey obtained from various districts of the East Kazakhstan Region and labelled by the producers as polyfloral, buckwheat and sunflower honey. The study was carried out using light microscopy, followed by the identification of pollen grains based on a set of morphological characteristics. For each sample, the taxonomic composition of the pollen was determined, the dominant nectar-producing plants were identified, and the results of the palynological analysis were compared with the declared botanical origin of the product. It was found that in 88.9% of the samples examined, the declared floral composition corresponded to the actual pollen composition, whilst in 11.1% of cases, discrepancies were identified between the labelling and the results of the palynological analysis. The pollen most frequently identified in the samples was that of sunflower (*Helianthus annuus*), buckwheat (*Fagopyrum esculentum*), currant (*Ribes* spp.), angelica (*Angelica archangelica*), echinops (*Echinops* spp.), as well as a number of other nectar-producing plants characteristic of the flora of the East Kazakhstan Region. The data obtained indicate a significant diversity in the forage base of honey bees in the region under study and confirm the high informative value of palynological analysis in determining the botanical origin of honey. The practical value of this study lies in demonstrating the use of palynological analysis as an effective tool for the laboratory verification of the botanical origin of natural honey, for monitoring its authenticity, and for improving the reliability of labelling. The results

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obtained can be used in veterinary and sanitary inspections, the development of regional databases of pollen spectra, the improvement of the quality control system for beekeeping products, and the promotion of Kazakhstani honey on domestic and international markets

Keywords: honey; melissopalynology; honey authenticity; pollen profile; nectar-producing plants; honey authentication

Introduction

The quality and safety of honey depend directly on its botanical and geographical origin, the environmental conditions during honey collection, the bee breed, climatic characteristics and production methods. Therefore, verifying the authenticity of natural honey, confirming its botanical origin and identifying counterfeit products is one of the most important areas of scientific research in the fields of beekeeping and food safety. On the global market, there are increasingly frequent cases of natural honey being adulterated, various sugar syrups being added, and the product's origin being misrepresented. In this context, palynological analysis occupies a special place amongst the scientific methods used to determine the authenticity of honey. This method makes it possible to determine the plants from which the honey was collected and the geographical region of production by means of microscopic examination of the pollen grains contained in the honey. Furthermore, palynological analysis is recognised worldwide as one of the most reliable methods for determining the botanical origin of honey. A significant number of studies have been devoted to the issues of determining the botanical origin and authenticating honey. For example, C. Pita-Calvo & M. Vázquez (2018) demonstrated that the botanical and geographical origin of honey has a decisive influence on its chemical composition, organoleptic properties and commercial value, and that palynological analysis is one of the most informative methods for confirming these characteristics.

X. Wang *et al.* (2022) noted in a systematic review that the most reliable results in determining the origin of honey are achieved through the combined use of melissopalynological analysis, physico-chemical parameters and modern analytical methods, including metabolomics and chemometrics. According to O. Escuredo & M.C. Seijo (2022), determining the botanical origin of honey is of great importance not only for confirming its authenticity, but also for assessing the biological activity, quality and consumer value of the product. The authors emphasise that the pollen spectrum remains one of the main criteria for identifying monofloral and polyfloral honey varieties. A study by Z. Shakoori *et al.* (2023) showed that a combination of melissopalynological and physico-chemical analysis allows for an objective assessment of honey quality, confirmation of its botanical origin and the detection of possible cases of adulteration.

In the Republic of Kazakhstan, beekeeping is one of the most dynamically developing sectors of agriculture. The country's diverse natural and climatic zones provide favourable conditions for the growth of a wide variety of honey plants. The East Kazakhstan Region, in particular, is characterised by its floral diversity, ecological purity and the development of beekeeping. In this region, buckwheat, sunflowers, raspberries, hawthorn, rose hips, currants, lime trees, angelica, alfalfa and many other honey plants are widespread. As a result, the region produces high-quality varieties of polyfloral and monofloral honey. A study by G. Moldakhmetova *et al.* (2023), focusing on honey from various natural and climatic zones of Kazakhstan, found that the pollen composition of the samples reflects the regional characteristics of the honey-producing flora and can be used to determine the botanical and geographical origin of the product. The findings highlight the potential of melissopalynological analysis for assessing the quality of Kazakhstani honey. Determining the botanical composition of honey is important not only from a scientific perspective, but also from economic and veterinary-sanitary standpoints. Determining the actual origin of the product boosts consumer confidence, ensures compliance with international trade requirements and enhances export potential. Furthermore, the results of palynological analysis make it possible to assess the resources of honey plants in a specific region, locate beekeeping operations effectively and improve the honey quality control system.

Recent research confirms that melissopalynological analysis is one of the main methods for determining the botanical and geographical origin of honey. When combined with physico-chemical methods, it enables reliable product authentication, quality assessment and the detection of possible adulteration (Pita-Calvo & Vázquez, 2018; Xagoraris *et al.*, 2021; Escuredo & Seijo, 2022). According to J. Louveaux *et al.* (1978), the methodology of melissopalynological analysis was developed to determine the botanical origin of honey. Subsequently, W. Von der Ohe *et al.* (2004) refined the methodology, proposing harmonised approaches to the interpretation of results and its application in studies of honey authenticity. Recent studies confirm the relevance of this approach (Pita-Calvo & Vázquez, 2018; Wang *et al.*, 2022; Shakoori *et al.*, 2023). In Kazakhstan, the number of studies examining the palynological composition of honey has been increasing in recent years. According to G. Moldakhmetova *et al.* (2023), palynological analysis of honey samples from various natural and climatic zones of Kazakhstan revealed considerable diversity in pollen composition, reflecting the characteristics of the nectar-producing flora in different regions of the country. The results obtained confirmed the possibility of using the pollen spectrum to determine the botanical and geographical origin of honey.

The aim of the study was to determine the botanical origin of samples of natural honey produced in the East Kazakhstan Region of the Republic of Kazakhstan by analysing their palynological composition, followed by an assessment of the authenticity and quality of the product. Research objectives: (1) to determine the palynological composition of honey samples produced in the East Kazakhstan Region; (2) to investigate the species composition of pollen grains in honey using microscopic analysis; (3) to identify the botanical origin of the honey; (4) scientific assessment of the authenticity and quality of the honey based on the results of palynological analysis.

Literature Review

Honey is one of the most valuable products of beekeeping, the quality and biological value of which are determined by the botanical origin of the nectar, the geographical characteristics of the region, climatic conditions, the composition of the nectar-producing vegetation, and the production methods used (Machado De-Melo *et al.*, 2018). In recent decades, with the expansion of the global market for natural honey, the importance of methods for verifying its authenticity and its botanical and geographical origin has increased significantly. One of the most informative and widely recognised methods for identifying the origin of honey is palynological analysis (melissopalynology), which is based on the study of plant pollen grains contained in the honey samples under investigation (Von der Ohe *et al.*, 2004).

This method makes it possible to determine the composition of the nectar-producing flora, establish the botanical origin of the product, and confirm its geographical provenance, which is particularly important for the certification of honey and the detection of cases of adulteration (Persano Oddo & Piro, 2004). Pollen grains enter the honey during the collection of nectar by honeybees and retain the characteristic morphological features of the plants from which the nectar was collected. Thanks to the high stability of their outer shell (exine), pollen grains remain preserved for a long time, making them reliable subjects for study. The morphology of pollen from each plant species differs in terms of size, shape, number and structure of apertures, surface texture and other diagnostic features, which allow plant taxa to be identified down to the genus and, quite often, down to the species. It is for this reason that palynological analysis is regarded as a kind of "biological passport" indicating the origin of honey.

In international practice, melissopalynology is used not only to determine the botanical origin of honey, but also to address a wide range of scientific and applied problems. These include assessing the condition of the bees' forage resources, studying the biodiversity of vegetation, monitoring changes in flora under the influence of climatic factors, determining bee migration routes, quality control of beekeeping products, detecting adulteration, and environmental monitoring of areas disturbed by human activity (Barth, 2004). In many European countries, palynological analysis is a mandatory step in confirming the botanical origin of monofloral honey varieties. According to the recommendations of the International Commission on Apicultural Botany and the International Commission on Honey, the results of microscopic examination should be considered in conjunction with the physico-chemical parameters of the product, as different plant species are characterised by varying degrees of pollen representation in honey (Louveaux *et al.*, 1978; Bogdanov, 2009).

Recent research indicates that melissopalynology remains one of the most accessible and informative methods for honey quality control. Despite the rapid development of molecular genetic methods, including DNA metabarcoding, it is palynological analysis that remains the international benchmark for determining the botanical origin of honey (Hawkins *et al.*, 2015; Keller *et al.*, 2015; Bell *et al.*, 2016). For the Republic of Kazakhstan, palynological analysis is of particular importance due to the high diversity of natural and climatic zones and the abundance of honey-producing flora (Rib, 2013). The East Kazakhstan Region is considered the most valuable region for beekeeping, as it combines mountainous, forest, meadow and steppe ecosystems. This diversity ensures the formation of a unique pollen spectrum in honey, which can be used to confirm its regional origin and enhance the competitiveness of Kazakhstani products on the international market.

Palynology emerged as an independent scientific discipline in the early 20th century following the development of light microscopy techniques and the accumulation of knowledge regarding the morphological characteristics of pollen from various plant species (Traverse, 2007). Melissopalinology is currently undergoing rapid development thanks to the introduction of digital microscopy, automated image recognition and molecular biology techniques. However, despite the emergence of new analytical technologies, classical palynological analysis remains the primary method for determining the botanical origin of honey and is used in most European laboratories for product certification. Based on botanical origin, more than 150 different types of honey are distinguished, which differ from one another in terms of taste, colour, aroma, acidity, diastase activity, the ratio of glucose, sucrose and fructose, and the quantitative content of minerals.

Studies focusing on determining the botanical origin of honey have shown that its identification can be based on a combination of physico-chemical and palynological indicators. R. Fernández-Torres *et al*. (2005) established that the mineral composition of honey is closely linked to its botanical origin and can be used as an additional criterion for identifying different varieties. R.G. Kurmanov & A.R. Ishbirdin (2013) investigated the botanical and geographical origin of honey available on the Siberian market and demonstrated the possibility of determining the regional origin of the product based on its pollen spectrum. Subsequently, R.G. Kurmanov (2019) summarised data on the botanical and geographical origin of Russian honey, systematised the palynological characteristics of Bashkir honey, and presented an atlas of pollen from the main honey plants, used to determine its botanical origin. Thus, the literature confirms the high informative value of melissopalynological analysis for establishing the botanical origin of honey and justifies the need to conduct similar studies for various regions of Kazakhstan.

Materials and Methods

The study involved 18 samples of natural honey collected between May and August 2022 from apiaries in the East Kazakhstan Region of the Republic of Kazakhstan. Of these, 8 samples (44.4%) were declared by the producers as sunflower honey, 7 samples (38.9%) as polyfloral honey and 3 samples (16.7%) as buckwheat honey. The studies were carried out at the State Specialised Enterprise "Republican Veterinary Laboratory" of the Committee for Veterinary Control and Supervision under the Ministry of Agriculture of the Republic of Kazakhstan (Astana). Melissopalinological analysis is based on determining the qualitative and quantitative composition of pollen grains contained in honey, which makes it possible to establish its botanical and geographical origin.

Taxa were identified by comparing the morphological characteristics of pollen grains with atlases and identification guides for honey plant pollen (Louveaux *et al*., 1978; Sawyer, 1988; Agashe & Caulton, 2019). To prepare the micro-slides, 10.0 g of honey was dissolved in 20 ml of distilled water at a temperature not exceeding 40°C until completely dissolved. The resulting solution was centrifuged for 10 minutes at a speed of 2,500-3,000 rpm. After removing the supernatant, approximately 10 ml of distilled water was added to the pellet and the mixture was centrifuged again for 5 minutes. The supernatant was then removed, and the entire pellet was transferred to a microscope slide, spread evenly over its surface, dried at a temperature not exceeding 40°C, and mounted in glycerine-gelatine for subsequent microscopy.

Microscopic examination was carried out using Leica DM500 and Mikromed-3 light microscopes at a magnification of ×1,000. During the analysis, pollen grains were identified by displaying the image on a computer screen for recording and subsequent processing of the results. For each sample, at least 500 pollen grains were counted, after which the percentage of each taxon in the total pollen spectrum was determined. Honey was classified as monofloral if the dominant pollen type accounted for at least 45% of the total number of pollen grains counted. The results obtained were used to determine the botanical origin of the honey, assess its authenticity and verify its compliance with regulatory requirements. The process of microscopic examination and identification of pollen grains in honey samples is illustrated in Figure 1.

Figure 1. Palynological analysis of honey using a light microscope
Source: authors' photo

Figure 1 illustrates the methodology for conducting a palynological analysis of honey using a light microscope. This method is based on the detection and identification of pollen grains present in the honey, which makes it possible to determine its botanical and geographical origin. During the study, prepared slides were examined under a microscope, with the images displayed on a computer screen for subsequent recording and processing of the results. Analysis of the pollen spectrum made it possible to determine the species composition of the honey plants that contributed to the formation of the product under investigation. Based on these data, an assessment of the honey's authenticity was carried out, and conclusions were drawn regarding its quality and compliance with regulatory requirements.

Results and Discussion

To characterise the material under investigation, Table 1 presents details of the sampling locations and the declared botanical origin of the honey. The study included 18 samples collected from apiaries in seven districts of the East Kazakhstan Region. The largest proportion consisted of samples declared as sunflower honey (n = 8; 44.4%), whilst polyfloral (n = 7; 38.9%) and buckwheat (n = 3; 16.7%) honey were represented in smaller numbers. This distribution allows for a comparison of the declared botanical origin with the results of the melissopalinological analysis.

Table 1. Characteristics of the honey samples studied (sampling area and declared botanical origin)

Sample No.	District	Declared floor area
1	2	3
1	Altai District	Polyfloral
2		Buckwheat
3		Sunflower
4	Glubokovsky District	Polyfloral
5		Sunflower
6	Kurchumsky District	Polyfloral
7		Sunflower
8		Sunflower
9	Katon-Karagay District	Polyfloral
10		Buckwheat
11		Sunflower
12	Ridder District	Polyfloral
13		Buckwheat
14		Sunflower
15	Urjar District	Polyfloral
16		Sunflower
17	Shemonoikhinsky District	Polyfloral
18		Sunflower

Source: compiled by the authors

As can be seen from the data in Table 1, the samples were collected in areas characterised by a variety of natural and climatic conditions and nectar-producing vegetation. This made it possible to assess the correspondence between the declared floral composition and the actual pollen composition of the honey, and to carry out a comparative analysis of the botanical origin of samples from various districts of the East Kazakhstan Region. The data obtained during the study of the floral composition of the honey are summarised in Table 2.

Table 2. Results of the melissopalynological analysis of the honey samples studied

No.	Botanical composition	Declared floor area	Result
1	Common buckwheat (*Fagopyrum esculentum* Moench.) – 89.9%; Medicinal angelica (*Angelica officinalis*) – 3.6%; Daurian rhododendron (*Rhododendron dauricum* L.) – 2.6%; Spiked currant (*Ribes spicatum* Robson.) – 3.9%.	Buckwheat	Buckwheat
2	Annual sunflower (*Helianthus annuus* L.) – 15.8%; Common groundsel (*Aegopódium podagrária*) – 10.2%; Field buckwheat (*Fagopyrum esculentum* Moench.) – 18.6%; Berry apple (*Malus baccata* Borkh.) – 11.3%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 12.6%; Sweet clover (*Melilotus officinalis* (L.) Lam) – 13.3%; Blackcurrant (*Ribes nigrum* L.) – 18.2%.	Polyfloral	Polyfloral
3	Annual sunflower (*Helianthus annuus* L.) – 88.6%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 6.3%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 3.6%; (*Scabiosa comosa* Fisch.) – 0.9%; Raspberry (*Rubus idaeus* L.) – 0.3%; Tansy-leaved cinquefoil (*Potentilla tanacetifolia* Willd.) – 0.3%.	Sunflower	Sunflower
4	Common buckwheat (*Fagopyrum esculentum* Moench.) – 91.3%; Blackcurrant (*Ribes nigrum* L.) – 3.9%; Berry apple (*Malus baccata* (L.) Borkh.) – 2.9%; Blood-red hawthorn (*Crataegus sanguinea* Pallas.) – 0.9%; Tansy-leaved phacelia (*Phacelia tanacetifolia* Benth.) – 0.5%; Annual sunflower (*Helianthus annuus* L.) – 0.3%; Narrow-leaved fireweed (*Chamerion angustifolium* (L.) Holub.) – 0.2%.	Polyfloral	Buckwheat
5	Annual sunflower (*Helianthus annuus* L.) – 88.3%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 5.2%; Narrow-leaved fireweed (*Chamerion angustifolium* (L.) Holub.) – 3.3%; Blackcurrant (*Ribes nigrum* L.) – 1.9%; Apple tree (*Malus baccata* (L.) Borkh.) – 0.9%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 0.2%; Blood-red hawthorn (*Crataegus sanguinea* Pallas.) – 0.1%; Medium spirea (*Spiraea media* Fr. Schmidt.) – 0.1%.	Sunflower	Sunflower
6	Medicinal angelica (*Angelica officinalis*) – 33.3%; Annual sunflower (*Helianthus annuus* L.) – 36.1%; Spiked currant (*Ribes spicatum* Robson.) – 22.6%; Blood-red hawthorn (*Crataegus sanguinea* Pallas.) – 8%.	Polyfloral	Polyfloral

Table 2. Continued

No.	Botanical composition	Declared floor area	Result
7	Annual sunflower (*Helianthus annuus* L.) – 86.9%; Medicinal sweet clover (*Melilotus officinalis* (L.) Lam.) – 9.1%; Two-spined currant (*Ribes diacantha* Pallas.) – 2%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 1.5%; Norway maple (*Acer platanoides*) – 0.5%.	Sunflower	Sunflower
8	Annual sunflower (*Helianthus annuus* L.) – 90.1%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 4.1%; Spiked currant (*Ribes spicatum* Robson.) – 2.6%; Narrow-leaved fireweed (*Chamerion angustifolium* (L.) Holub.) – 1.6%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 1.6%.	Sunflower	Sunflower
9	Annual sunflower (*Helianthus annuus* L.) – 33.3%; Spiked currant (*Ribes spicatum* Robson.) – 36.6%; Scabious (*Scabiosa comosa* Fisch.) – 30.1%.	Polyfloral	Polyfloral
10	Common buckwheat (*Fagopyrum esculentum* Moench.) – 89.1%; Annual sunflower (*Helianthus annuus* L.) – 9.1%; Blood-red hawthorn (*Crataegus sanguinea* Pallas.) – 0.6%; Medicinal sweet clover (*Melilotus officinalis* (L.) Lam.) – 1.2%.	Buckwheat	Buckwheat
11	Annual sunflower (*Helianthus annuus* L.) – 90.1%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 4.1%; Spiked currant (*Ribes spicatum* Robson.) – 2.6%; Narrow-leaved fireweed (*Chamerion angustifolium* (L.) Holub.) – 1.6%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 1.6%.	Sunflower	Sunflower
12	Medium spirea (*Spiraea media* Fr. Schmidt.) – 33.3%; Medicinal sweet clover (*Melilotus officinalis* (L.) Lam.) – 29.1%; Common groundsel (*Aegopódium podagraria*) – 31.3%; Medicinal angelica (*Angelica officinalis*); Common buckwheat (*Fagopyrum esculentum* Moench.) – 3.1%; Thyme (*Thymus dahuricus* L.) – 3.2%.	Polyfloral	Polyfloral
13	Common buckwheat (*Fagopyrum esculentum* Moench.) – 89.9%; Medicinal angelica (*Angelica officinalis*) – 3.6%; Daurian rhododendron (*Rhododendron dauricum* L.) – 2.6%; Spiked currant (*Ribes spicatum* Robson.) – 3.9%.	Buckwheat	Buckwheat
14	Annual sunflower (*Helianthus annuus* L.) – 86.6%; Berry apple (*Malus baccata* (L.) Borkh.) – 6.7%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 3.3%; Dandelion (*Taraxacum* sp.) – 2.1%; Field mint (*Mentha arvensis*) – 1.3%.	Sunflower	Sunflower
15	Annual sunflowers (*Helianthus annuus* L.) – 80.6%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 10.3%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 3.6%; Dandelion (*Taraxacum* sp.) – 3.1%; Field mint (*Mentha arvensis*) – 2.4%.	Sunflower	Sunflower
16	Blackcurrant (*Ribes nigrum* L.) – 25.6%; Dandelion (*Taraxacum* sp.) – 15.1%; Broad-leaved Echinops (*Echinops latifolius* Tausch.) – 14.3%; Daurian rhododendron (*Rhododendron dauricum* L.) – 11.3%; Buckwheat (*Fagopyrum esculentum* Moench.) – 8.8%; Annual sunflower (*Helianthus annuus* L.) – 6.5%; Apple tree (*Malus baccata* (L.) Borkh.) – 5.9%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 5.4%,	Polyfloral	Polyfloral
17	Annual sunflower (*Helianthus annuus* L.) – 87.1%; Common buckwheat (*Fagopyrum esculentum* Moench.) – 3.1%; Spiked currant (*Ribes spicatum* Robson.) – 5.3%; Thyme (*Thymus dahuricus* L.) – 3.2%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 1.3%.	Polyfloral	Sunflower
18	Annual sunflower (*Helianthus annuus* L.) – 81.6%; Berry apple (*Malus baccata* (L.) Borkh.) – 5.7%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 4.3%; Narrow-leaved fireweed (*Chamerion angustifolium* (L.) Holub.) – 2.6%; Broad-leaved echinops (*Echinops latifolius* Tausch.) – 2.6%; Field mint (*Mentha arvensis*) – 3.2%.	Sunflower	Sunflower

Source: compiled by the authors

The results of the palynological analysis showed that 16 out of the 18 samples examined (88.9%) corresponded to their declared botanical origin, whilst 2 samples (11.1%) did not correspond to the information provided by the manufacturers. In particular, sample No. 4, declared as polyfloral, was found to contain 91.3% *Fagopyrum esculentum* Moench. pollen and was classified as buckwheat honey. Sample No. 17, declared as polyfloral, contained 87.1% *Helianthus annuus* L. pollen, which allowed it to be classified as sunflower honey.

The results obtained are consistent with data from numerous studies, according to which melissopalinological analysis is one of the most informative methods for determining the botanical origin of honey and verifying the accuracy of its labelling (Louveaux *et al.*, 1978; Sawyer, 1988; Kurmanov, 2019). Studies carried out in various regions of Russia and Kazakhstan also show that identifying the dominant pollen type makes it possible to distinguish between monofloral and polyfloral honey varieties with a high degree of certainty (Kurmanov & Ishbirdin, 2013; Kurmanov, 2019; Moldakhmetova *et al.*, 2023). The discrepancies identified may be due to several reasons. The most likely causes are the mixing of batches of honey during extraction or storage, errors in product labelling, and variations in honey collection during different flowering periods. In some cases, the cause may be the deliberate labelling of a product category that is more appealing to consumers, as multifloral honey is often perceived as more valuable due to the diversity of its botanical origins. Another possible cause may be the bees' selectivity when collecting nectar: during the mass flowering of a single nectar-producing plant, the bees predominantly visit that species, leading to a predominance of pollen from a single taxon in the final product, even when other flowering plants are present in the honey-harvesting area.

The proportion of samples with labelling discrepancies in this study was 11.1%, which is comparable to the results of international studies, in which the frequency of discrepancies between the declared and actual botanical origin of honey is typically 5-20%, depending on the region, the honey varieties studied and the control methods used (Fernández-Torres *et al.*, 2005; Wang *et al.*, 2022; Escuredo & Seijo, 2022). The data obtained indicate a fairly high degree of accuracy in the labelling of the honey samples studied from the East Kazakhstan Region; however, they confirm the need for mandatory palynological verification of the botanical origin of the product during veterinary and sanitary inspections and quality assessments.

Conclusions

The melissopalynological analysis carried out on 18 honey samples collected from apiaries in the East Kazakhstan Region confirmed the effectiveness of the palynological method for determining botanical origin and verifying the accuracy of product labelling. It was found that 16 out of 18 samples (88.9%) corresponded to their declared botanical origin. In two samples (11.1%), discrepancies were identified between the declared and actual floral composition: sample No. 4, labelled as polyfloral, was classified as buckwheat honey according to the analysis results, whilst sample No. 17 was classified as sunflower honey. The pollen of annual sunflower (*Helianthus annuus* L.) and common buckwheat (*Fagopyrum esculentum* Moench.) was the most frequently encountered in the samples studied, indicating their predominant role in determining the botanical origin of honey from the East Kazakhstan Region. Pollen from currants (*Ribes* spp.), globe thistle (*Echinops latifolius* Tausch.), angelica (*Archangelica officinalis*), fireweed (*Chamerion angustifolium* (L.) Holub.) and other honey plants was also regularly detected in the polyfloral samples. The results obtained can be used in veterinary and sanitary inspections, in confirming the botanical origin of honey, in improving the certification system for beekeeping products in the Republic of Kazakhstan, and in export quality control and authenticity checks for honey. Prospects for further research include extending the geographical scope of sampling to other regions of Kazakhstan, increasing the sample size, conducting seasonal monitoring of pollen composition, and carrying out a comprehensive comparison of the results of melissopalynological analysis with the physico-chemical quality indicators of honey.

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Conflict of Interest

None.

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Кыргыз Республикасынын Чыгыш Казакстан облусунда өндүрүлгөн балдын палинологиялык анализи

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Аннотация. Табигый аары балынын ботаникалык келип чыгышын верификациялоо аарычылык продукциясынын сапатын заманбап контролдоонун негизги багыттарынын бири болуп саналат, анткени гүлдүк келип чыгышы жөнүндө ишенимдүү маалымат анын керектөөчүлүк баалуулугун аныктап, продукциянын аныктыгын тастыктап жана жасалмалоонун алдын алууга мүмкүндүк берет. Бул маселе өзгөчө өсүмдүктөрдүн түрдүк ар түрдүүлүгү жогору болгон Казакстан Республикасынын Чыгыш Казакстан облусу үчүн актуалдуу болуп саналат, анткени аймактын табигый шарттары ар кандай ботаникалык келип чыгыштагы балды өндүрүүгө ыңгайлуу шарттарды түзөт. Изилдөөнүн максаты палинологиялык анализдин негизинде табигый аары балынын үлгүлөрүнүн чыныгы ботаникалык келип чыгышын аныктоо жана алынган жыйынтыктардын өндүрүүчүлөр көрсөткөн гүлдүк келип чыгышына шайкештигин баалоо болду. Изилдөөнүн объектиси катары Чыгыш Казакстан облусунун ар түрдүү райондорунан алынган жана өндүрүүчүлөр тарабынан көп гүлдүү, гречиха жана күн карама балы катары белгиленген 18 үлгү колдонулду. Изилдөө жарык микроскопиясынын жардамы менен жүргүзүлүп, чаңча бүртүкчөлөрү морфологиялык белгилеринин негизинде идентификацияланды. Ар бир үлгү боюнча чаңчанын таксономиялык курамы аныкталып, басымдуу нектар берүүчү өсүмдүктөр белгиленип, палинологиялык анализдин жыйынтыктары өндүрүүчүлөр көрсөткөн ботаникалык келип чыгыш менен салыштырылды. Изилденген үлгүлөрдүн 88,9 %ында көрсөтүлгөн гүлдүк келип чыгышы чыныгы чаңча курамына туура келгени аныкталса, 11,1 %ында маркировка менен палинологиялык изилдөөнүн жыйынтыктарынын ортосунда айырмачылыктар табылды. Үлгүлөрдө эң көп күн караманын (*Helianthus annuus*), гречиханын (*Fagopyrum esculentum*), карагаттын (*Ribes* spp.), дягилдин (*Angelica archangelica*), мордовниктин (*Echinops* spp.) жана Чыгыш Казакстан облусуна мүнөздүү башка нектар берүүчү өсүмдүктөрдүн чаңчалары аныкталды. Алынган маалыматтар изилденген аймакта бал аарыларынын азыктык базасынын жогорку ар түрдүүлүгүн көрсөтүп, балдын ботаникалык келип чыгышын аныктоодо палинологиялык анализдин жогорку маалыматтуулугун тастыктайт. Изилдөөнүн практикалык мааниси палинологиялык анализди табигый балдын ботаникалык келип чыгышын жана аныктыгын лабораториялык верификациялоонун, маркировканын ишенимдүүлүгүн жогорулатуунун натыйжалуу куралы катары негиздөөгө байланыштуу. Алынган жыйынтыктар ветеринардык-санитардык экспертиза жүргүзүүдө, чаңча спектрлеринин аймактык маалымат базаларын түзүүдө, аарычылык продукциясынын сапатын контролдоо системасын өркүндөтүүдө жана Казакстандын балын ички жана эл аралык рыноктордо илгерилетүүдө колдонулушу мүмкүн

Негизги сөздөр: аары балы; мелиссопалинология; балдын аныктыгы; чаңча профили; бал берүүчү өсүмдүктөр; балды аутентификациялоо

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Аннотация. Верификация ботанического происхождения натурального пчелиного меда является одной из ключевых задач современного контроля качества продукции пчеловодства, поскольку достоверность информации о флористическом происхождении определяет ее потребительскую ценность, подтверждает подлинность и способствует предупреждению фальсификации. Особую актуальность данная проблема приобретает для регионов с высоким флористическим разнообразием, к которым относится Восточно-Казахстанская область Республики Казахстан, где природные условия формируют широкий спектр медоносной растительности и создают благоприятные предпосылки для производства меда различного ботанического происхождения. Цель исследования заключалась в установлении фактического ботанического происхождения образцов натурального пчелиного меда на основе палинологического анализа их пыльцевого состава, а также в оценке соответствия полученных результатов заявленной производителями флорности. Объектом исследования послужили 18 образцов натурального пчелиного меда, полученных из различных районов Восточно-Казахстанской области и маркированных производителями как полифлорные, гречишные и подсолнечниковые. Исследование выполняли методом световой микроскопии с последующей идентификацией пыльцевых зерен по комплексу морфологических признаков. Для каждого образца определяли таксономический состав пыльцы, выделяли доминирующие медоносные растения и сопоставляли результаты палинологического анализа с заявленным ботаническим происхождением продукции. Установлено, что в 88,9 % исследованных образцов заявленная флорность соответствовала фактическому пыльцевому составу, тогда как в 11,1 % случаев выявлены расхождения между маркировкой и результатами палинологического исследования. Наиболее часто в образцах была идентифицирована пыльца подсолнечника (*Helianthus annuus*), гречихи (*Fagopyrum esculentum*), смородины (*Ribes* spp.), дудника (*Angelica archangelica*), мордовника (*Echinops* spp.), а также ряда других медоносных растений, характерных для флоры Восточно-Казахстанской области. Полученные данные свидетельствуют о значительном разнообразии кормовой базы медоносных пчел в исследуемом регионе и подтверждают высокую информативность палинологического анализа при определении ботанического происхождения меда. Практическая ценность исследования заключается в обосновании применения палинологического анализа в качестве эффективного инструмента лабораторной верификации ботанического происхождения натурального меда, контроля его подлинности и повышения достоверности маркировки. Полученные результаты могут быть использованы при проведении ветеринарно-санитарной экспертизы, разработке региональных баз данных пыльцевых спектров, совершенствовании системы контроля качества продукции пчеловодства и продвижении казахстанского меда на внутреннем и международном рынках

Ключевые слова: пчелиный мед; мелиссопалинология; подлинность меда; пыльцевой профиль; медоносные растения; аутентификация меда

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Issues of management accounting implementation in the agrarian sector of the Kyrgyz Republic

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Abstract. The relevance of this research is driven by the necessity to transition the agricultural sector of the Kyrgyz Republic from extensive farming practices to a modern management model based on accurate cost data. Establishing a reliable information base is a prerequisite for the effective development of the national agribusiness sector, positioning the modernization of accounting systems as a priority for the industry's economic growth. The study aimed to identify institutional, methodological, and human resource barriers hindering the development of management accounting in the country's agriculture and to substantiate practical mechanisms for overcoming them. The methodological framework was based on a comprehensive analysis of agricultural entities in the Chüy, Issyk-Kul, and Osh regions, employing systemic and comparative analysis methods. The research findings demonstrated that the existing obstacles are multifaceted. It was established that the widespread use of the "single-pool" (lump-sum) accounting method deprives management of necessary product-specific analytics and leads to significant distortions in profitability indicators. Particular attention was given to the gap between the requirements of IFRS (IAS) 41 and operational reality: due to the lack of active regional markets, measuring biological assets at fair value remains practically unfeasible. The study proved that the forced implementation of international standards amidst the current shortage of qualified personnel and specialised software results in a formalistic approach to accounting that fails to reflect actual financial flows. The paper proposed a phased adaptation algorithm for management accounting systems, which includes the development of industry-specific methodological guidelines and the creation of standard frameworks for peasant (private) farms. The practical significance of the research lies in the potential application of "direct costing" and "standard costing" tools to optimise accounting policies within agribusiness enterprises and to modernise educational curricula in agricultural universities

Keywords: strategic cost control; costing methods; internal control system; regulatory framework; accounting policy; financial information; production efficiency

Introduction

Agriculture is a strategic driver of the long-term development of the national economy and the achievement of food security. The specific characteristics of agricultural production at the current stage of market transformation require a fundamental modernisation of the internal information environment of economic

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entities. There is a need for a consistent shift away from extensive approaches to resource management towards scientifically grounded models based on continuous monitoring, control and analysis of production costs. Improving the economic resilience of the agro-industrial complex under conditions of price volatility is impossible without the implementation of practical tools for strategic and operational management accounting. Scientific research has established a substantial theoretical and methodological foundation in the field of agricultural accounting; however, many applied aspects remain the subject of ongoing debate. The conceptual foundations for distinguishing between financial and management accounting, as well as the role of management accounting in strategic decision-making, were examined in detail by M.A. Vakhrushina & N.V. Malinovskaya (2014), who demonstrated a direct relationship between business performance and the quality of internal reporting. The sector-specific characteristics of cost formation, shaped by seasonality and the diversity of agricultural products, are examined in detail in the work of N. Beishenaly & F. Dufays (2023), which provides a regulatory and methodological framework for cost allocation in the agro-industrial complex (AIC).

The specific characteristics of the development of accounting systems under the particular conditions of the agricultural sector of the Kyrgyz Republic in recent years have been reflected in a number of publications. In particular, A.A. Baimuratov *et al.* (2023) identified a critical problem concerning the blurring of boundaries between analytical accounting and management accounting in Kyrgyzstan, which results in the underutilisation of analytical tools by management. E. Belek uulu *et al.* (2024b) provided a detailed analysis of the organisational barriers to establishing accounting systems across various subsectors of the agricultural sector, emphasising that the small-scale nature of production hinders the implementation of standardised automation systems. The institutional aspects and barriers to the adaptation of international standards in the Republic were examined in the study by A. Bekmuratov *et al.* (2025), which identified an objective mismatch between IFRS requirements and the actual capabilities of small business entities. Similarly, W. Crewett (2015) demonstrated that the accounting policies of most agricultural enterprises in the Kyrgyz Republic are largely formal in nature and are not used to optimise expenditure. The specific features of cost calculation in livestock farming are reflected in the works of A. Dörre (2015), while the methodology of flexible cost management based on direct costing in crop production was investigated by A. Dzhumagulov & I. Mistriukova (2025). Practical recommendations for organising accounting in peasant (farmer) farms based on IFRS were proposed in the article by A. Kadyraliev *et al.* (2024).

Despite the abundance of existing studies, the problem of developing a comprehensive and cost-effective algorithm for establishing accounting systems for small-scale agricultural enterprises in the Kyrgyz Republic remains unresolved. The aim of this study was to identify the specific institutional, methodological and human-resource barriers that hinder the implementation of management accounting in agricultural enterprises of the Kyrgyz Republic, and to develop realistic, step-by-step measures to overcome these barriers without fundamentally restructuring the existing accounting systems.

Materials and Methods

The methodological foundation of the study was based on a systems approach, within which management accounting is viewed as an integrated information framework embedded in the overall strategic management system of an agricultural enterprise. Interaction with the study participants was conducted in strict accordance with the principles of professional ethics set out by the National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research (1979) and All European Academies (ALLEA) (2023). During the semi-structured interviews conducted with managers and chief accountants of 74 agricultural enterprises, the requirements of informed consent and complete anonymity were strictly observed. All respondents were informed about the objectives of the study and their right to withdraw their data. The internal accounting documentation obtained during the interviews was subjected to a de-identification procedure to ensure the confidentiality of commercially sensitive information, thereby preventing the disclosure of respondents' identities or the names of specific agricultural enterprises.

The search and selection of scientific literature, regulatory and legal acts, and statistical materials were conducted for the period from 2018 to 2026 in the Scopus and Web of Science databases using the following key search queries: "management accounting in the agro-industrial complex of the Kyrgyz Republic", "cost calculation in agriculture", "IAS 41 Kyrgyzstan", and "cost of a peasant (farmer) farm". Several foundational studies from earlier periods were included as key theoretical sources that established the methodological basis of the research topic and remain relevant (Osmonkulova, 2006; Rakhmatullaev *et al.*, 2010; Crewett, 2015). The method of comparative analysis was applied to compare the regulatory framework of the Kyrgyz Republic with the systems of the countries of the Eurasian Economic Union (EAEU). The classification and grouping method was used to differentiate agricultural enterprises according to the maturity levels of their accounting systems, based on the completeness of the data collected. The analytical and monographic methods were applied in processing the statistical compilations by U. Mirlanbek *et al.* (2023) and the reports by I. Mukambaeva *et al.* (2024) to identify macroeconomic trends.

The empirical basis of the study comprised survey data from 74 entities, including large agricultural co-operatives and peasant (farmer) farms in the Chüy, Issyk-Kul and Osh regions. Data were collected through semi-structured interviews with managers and chief accountants, as well as through a qualitative audit of internal accounting documentation and accounting policy provisions. To assess overall sectoral dynamics for 2019-2023, official statistical indicators (the share of the agricultural sector in GDP, employment, the number of peasant (farmer) farms, and production output) were additionally used, making it possible to compare the extensive growth of the sector as a whole with the qualitative findings from the survey of 74 agricultural enterprises.

Results and Discussion

Overall state of management accounting in the agricultural sector of the republic

According to the National Statistical Committee of the Kyrgyz Republic (2024), the share of the agricultural sector in the country's gross domestic product ranges between 11% and 14%, while the sector provides employment for approximately one-quarter of the rural population. The dynamics of these indicators are presented in Table 1.

Table 1. Key indicators of the agricultural sector of the Kyrgyz Republic, 2019-2023

Indicator	2019	2020	2021	2022	2023
Share of the agricultural sector in GDP, %	10.4	12.2	12.4	11.0	9.5
Employment in agriculture, % of total employment	10.9	12.2	18.3	17.8	17.1
Number of peasant (farmer) farms, thousand units	452	462	468	473	488
Agricultural production, billion KGS	220	249	324	358	382

Source: compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (2024)

The analysis shows that the agricultural sector is characterised by an extensive development trajectory: the increase in production volumes in monetary terms is associated with a rise in the number of small-scale farms (reaching 488,000 by 2023) and inflation, rather than with improvements in management efficiency. The qualitative survey made it possible to classify agricultural enterprises according to the maturity levels of their accounting systems (Table 2). The survey showed that fully developed management accounting systems (Level III) operate in isolation, whereas the small-scale agricultural sector (Level I) lacks analytical tools. This supports the argument put forward by G.O. Osmonkulova (2006) regarding the detrimental impact of an information deficit on the financial sustainability of agricultural businesses.

Table 2. Differentiation of the surveyed agricultural enterprises in the Kyrgyz Republic by the level of management accounting development

Level of accounting development	Organisational structure	Characteristics of the environment	Impact on decision-making
I. Basic	Small-scale farms	Accounting for tax purposes only	Ad hoc pricing
II. Fragmented	Medium-sized farms	Accounting for direct costs	Post-production costing
III. Systematic	Agricultural holdings	Automation and budgeting	Marginal analysis

Source: compiled by the authors based on the results of the study

Institutional and regulatory barriers

The functioning of management accounting systems in the agricultural sector of the Kyrgyz Republic is constrained by rigid institutional frameworks. The principal legislative act, Law of the Kyrgyz Republic No. 76 (2002), is focused exclusively on financial reporting requirements, while disregarding the needs of internal management planning (Rakhmatullaev *et al*., 2010). Special tax regimes for agricultural producers (Tax Code of the Kyrgyz Republic, 2022) create counterproductive incentives: the exemption from maintaining primary cost accounting has effectively legitimised the abandonment of analytical accounting in small businesses. Researchers M. Akzholova & A. Osmonova (2019) emphasise that the existing regulatory framework is not adapted to the scale of farming operations, while the accounting policies of most entities are formal and declarative in nature, failing to reflect actual production processes. Ignoring fair value results in a systematic understatement of return on sales by 12-19%, while the gap between actual costs and the market valuation of biological assets averages 24.5%.

Quantitative assessment of efficiency and IFRS compliance. An empirical survey of 74 entities revealed a critical gap between regulatory requirements and actual practice. Only 18 agricultural enterprises (24%) implement IAS 41 "Agriculture" (International Accounting Standards Board, 2023). This limits agricultural enterprises' access to long-term bank financing (National Statistical Committee of the Kyrgyz Republic, 2024). Illustrative Cases of the Transition to the Proposed Accounting Methods. To test the hypothesis of a direct relationship between the quality of management accounting and business performance, two cases involving the implementation of the proposed accounting tools were analysed.

Case 1: Modernisation of a livestock complex (Chüy region). The farm, with a herd of 150 cattle, previously used the historical cost method, which did not account for live-weight gains during the interim reporting period. Following the implementation of the fair value measurement model proposed in this study, using current market quotations, the reported profit for the period increased by 15%. The improved asset structure enabled the enterprise to restructure its loan portfolio and obtain an investment loan from a commercial bank at an interest rate reduced by 2.5 percentage points, as a direct result of greater accounting transparency.

Case 2: Optimisation of accounting in crop production (Issyk-Kul region). The agricultural enterprise, with 500 hectares of cultivated land, used a traditional pooled cost accounting method, whereby indirect costs were allocated in proportion to revenue. After switching to the proposed direct costing algorithm, it was found that the production cost of grain crops had been overstated by 12%, while the actual contribution margin from vegetable crops was 8% higher than previously calculated. The findings enabled management to discontinue less efficient activities, freeing up 15% of working capital for investment in the high-return segment, which had previously been impossible due to the "blurred" cost calculation. To assess the specific features of the institutional environment and identify differences in approaches to cost accounting organisation across Central Asian countries, a comparative analysis of the key conditions for implementing management accounting was conducted (Table 3).

Table 3. Comparative analysis of the institutional conditions for implementing management accounting

Criterion	Kyrgyz Republic	Republic of Kazakhstan	Republic of Uzbekistan
Sector-specific guidelines	Absent	Approved	National Accounting Standards (NAS)
Tax incentives	Counterproductive	Incentivising	Moderate
IT support	Absent	Subsidised	Government programmes

Source: compiled by the authors based on regulatory acts (Law of the Kyrgyz Republic No. 76, 2002; Tax Code of the Kyrgyz Republic, 2022) and research (Akzholova & Osmonova, 2019)

Analysis of institutional barriers. The data presented indicate that the lack of methodological continuity in the Kyrgyz Republic has become a key factor contributing to the "accounting vacuum". In contrast to the Republic of Uzbekistan, where the mandatory transition to value added tax (VAT) compelled enterprises to establish transparent cost-accounting systems, tax legislation in the Kyrgyz Republic has pursued maximum simplification, resulting in the erosion of the management function of accounting. In Kazakhstan, by contrast, the institutional environment has been transformed through targeted government subsidies for the acquisition of software, whereas in the Kyrgyz Republic the financial burden of automation has been placed entirely on the limited resources of agricultural enterprises themselves. This conclusion is consistent with the observations of U. Mirlanbek *et al.* (2023) regarding systemic problems in state support for the agricultural sector in Kyrgyzstan, as well as with the findings of I. Mukambaeva *et al.* (2024), which demonstrated the limited impact of the state investment budget on the structural indicators of the sector. Thus, the formal adherence to "simplified" tax regimes without obligations to maintain cost-accounting records restricts the opportunities for strategic planning, making agricultural enterprises highly vulnerable to market fluctuations in agricultural commodity prices.

Methodological problems in cost calculation

Cost calculation in agricultural production is recognised as one of the most complex aspects of accounting. The theoretical foundations of sector-specific costing (Belek uulu *et al.*, 2024b) confirm that the multi-sectoral and seasonal nature of agriculture inherently complicates accounting processes. At present, the pooled cost accounting method predominates among enterprises in the Kyrgyz Republic, characterised by a lack of differentiation between primary and joint costs (Belek uulu *et al.*, 2024a). The problems associated with this deterioration of accounting processes are also confirmed by Belek uulu *et al.* (2024c). Notably, modern management accounting cost-management tools, including elements of activity-based costing (ABC costing) and standard costing**,** are already being successfully applied in certain sectors of the Kyrgyz economy outside agriculture (Toichiev, 2025). This makes it particularly relevant to examine the applicability of similar approaches to agricultural production.

Analysis of methodological vulnerability and quantitative indicators. The study of 74 agricultural enterprises showed that 76% of the entities use a simplified pooled cost accounting method, disregarding the requirements of IAS 41 (International Accounting Standards Board, 2023). This results in distortions in financial performance: the lack of cost differentiation understates the profitability of individual crops by 12-19%, while the gap between actual costs and the fair value of biological assets reaches 24.5% (National Statistical Committee of the Kyrgyz Republic, 2024). To determine the advantages of different approaches to cost calculation in agricultural production, the main cost accounting methods were compared according to the following criteria: analytical capability, managerial value, implementation complexity, and prevalence among agricultural enterprises in the Kyrgyz Republic (Table 4).

Table 4. Comparative characteristics of cost accounting methods in agricultural production

Criterion	Pooled cost accounting	Direct costing	Standard costing
Analytical capability	Low	High	High
Managerial value	Limited	High (contribution margin)	High (planning)
Implementation complexity	Low	Medium	High
Prevalence in the Kyrgyz Republic	76% of enterprises	20% of enterprises	4% of enterprises

Source: compiled by the authors based on the article by E. Belek uulu *et al.* (2024b)

To gain a deeper understanding of the nature of the distortions arising from the use of the traditional approach, a cost calculation model was developed for typical agricultural crops. Table 5 presents the initial indicators reflecting the transformation of the cost structure and contribution margin when moving from the pooled cost accounting method to direct costing. Table 5 clearly demonstrates that under the pooled cost accounting method, the contribution margin is substantially understated (10 units for both crops), which may mislead management. By contrast, the application of direct costing makes it possible to identify the actual contribution margin, as illustrated in Figure 1.

Table 5. Comparative model of cost structure and contribution margin per unit of output

Cost category	Pooled cost accounting (grain crops)	Direct costing (grain crops)	Pooled cost accounting (vegetable crops)	Direct costing (vegetable crops)
Variable costs	60	60	60	85
Allocated indirect costs	30	5	30	5
Total cost	90	65	90	90
Contribution margin	10	35	10	10

Note: the data are presented in conventional units per unit of output; the difference of 25 units (indirect costs) when switching to direct costing is transferred from production cost to expenses of the reporting period
Source: compiled by the authors

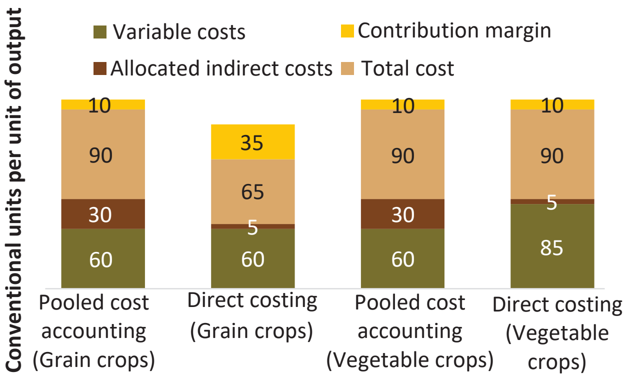

Figure 1. Comparison of the impact of cost accounting methods on cost structure and contribution margin
Source: compiled by the authors

The data presented clearly illustrate the methodological trap faced by entities using the pooled cost accounting method. Under the traditional approach (grain crops – 90 units; vegetable crops – 90 units), the cost of the crops appears identical, which may lead managers to make erroneous strategic decisions based on fiscal rather than economic indicators. The transition to direct costing, as demonstrated by the grain crop example, reveals "hidden" reserves: production cost decreases to 65 units, while the contribution margin increases 3.5-fold, from 10 to 35 units. In the case of vegetable crops, the method makes it possible to clearly identify the cost structure required for decisions on expanding or reducing cultivated areas. Thus, the implementation of management accounting does not merely "complicate" the paperwork; rather, it becomes a practical tool for increasing the profitability of production.

Practical aspects of transitioning to the proposed methods

Case 1: The effect of transitioning to direct costing (Issyk-Kul region). The enterprise introduced a distinction between fixed and variable costs. Previously, pooled cost accounting indicated that the vegetable segment was generally loss-making. Following the transition to the proposed algorithm, it was found that the contribution margin for key crops was 8% higher. Eliminating inefficient crops increased overall profitability by 6% within a single operating cycle.

Case 2: Eliminating distortions in the valuation of biological assets (Chüy region). The enterprise switched to fair value measurement. Before the implementation of the method, the discrepancy between the accounting data and the market valuation of the livestock amounted to 24.5%. Regular revaluation, as demonstrated by the analysis of 2026 data, enabled the increase in value to be reflected objectively, raising reported profit by 15% and strengthening creditors' confidence. Analytical Summary. The data indicate that the pooled cost accounting method creates a "hidden loss phenomenon". High-input crops, such as sugar beet, are artificially overvalued due to the allocation of costs across total production, whereas grain crops are undervalued, thereby masking managerial inefficiencies. The proposed transition to direct costing and the application of IAS 41 make it possible to eliminate this discrepancy and ensure greater transparency of contribution margins.

Accounting for biological assets: IAS 41 requirements, application practices and assessment of distortions. The adoption of IAS 41 "Agriculture" represents a paradigm shift in accounting, moving from the historical cost principle towards fair value measurement (International Accounting Standards Board, 2023). Researchers A. Bekmuratov *et al.* (2025) appropriately identify a key barrier: the limited availability of active markets for most biological assets in the regions of the Kyrgyz Republic. A study of 74 agricultural enterprises showed that only 18 entities (24%) have implemented IAS 41, whereas 56 enterprises (76%) fully disregard IFRS requirements and continue to use the historical cost model. It was established that this approach results in an understatement of return on sales by 12-19%. The average gap between the actual cost of biological asset production and their fair market value amounts to 24.5%. This makes financial reporting less informative for creditors, as the value of collateral is reflected in the balance sheet at a level significantly below its market value (National Statistical Committee of the Kyrgyz Republic, 2024). To systematise the identified differences between the requirements of IAS 41 and the actual accounting practices for biological assets among agricultural enterprises in the Kyrgyz Republic, a comparative analysis of the key accounting aspects was conducted (Table 6).

Table 6. Comparison of IAS 41 requirements and the practice of accounting for biological assets in the Kyrgyz Republic

Accounting aspect	IAS 41 requirements	Practice of enterprises in the Kyrgyz Republic	Methodological gap
Valuation of biological assets	Fair value	Historical cost	Understatement of assets in the balance sheet
Recognition of agricultural produce	At fair value	At actual cost	Distortion of financial performance
Information disclosure	Detailed (including changes over time)	Not provided	Lack of investment transparency
Changes in value	Recognised in the reporting period	Not recognised until sale	Failure to account for market factors

Source: compiled by the authors based on International Accounting Standards Board (2023)

Practical transition cases

Case 1: Valuation of a breeding herd (Chüy region). The farm switched from accounting for the herd at historical production cost to measuring it at fair value. Following the revaluation of the biological assets, the carrying amount of assets increased by 26%, enabling the enterprise to increase its bank lending limit. The actual gain arising from changes in the value of the assets amounted to 15%, according to the authors' 2026 research data.

Case 2: Accounting for grain crops at the point of harvest (Issyk-Kul region). The enterprise introduced the recognition of harvested crops at fair value at the point of separation from the biological asset. Previously, profit was effectively "locked in" until the point of sale. The proposed method enabled the financial result to be recognised promptly, revealing that the contribution margin from grain crops was 8% higher than previously estimated. This provided management with a practical tool for making informed decisions during the harvesting period.

The analysis of Table 6 reveals a systemic gap. The main contributing factor is the absence of official price quotations in regional markets (the "mal bazaar"). Mechanically replicating IFRS requirements without taking into account the lack of transparent market indicators increases the workload associated with accounting while generating little or no managerial benefit. Nevertheless, as demonstrated by the cases presented, even a partial transition to market-based valuation can eliminate investment opacity and substantially improve an enterprise's financial profile.

Staff shortages and organisational constraints

A review of the literature reveals systemic problems hindering the development of management accounting. Researchers point to a shortage of specialists capable of adapting management accounting tools to the specific characteristics of agriculture (W. Crewett, 2015), fragmented information systems (Dzhumagulov & Mistriukova, 2025), and a general lack of internal regulations governing management accounting. The survey of 74 agricultural enterprises revealed that in 68 cases (92%), accounting functions are performed either by the managers themselves or by specialists with secondary vocational education who are unfamiliar with contribution margin analysis. The findings indicate that the lack of qualified personnel is correlated with the disregard of IAS 41 (International Accounting Standards Board, 2023). In enterprises where accounting is handled by a full-time specialist with a higher degree in economics, the likelihood of implementing elements of direct costing is 3.5 times higher than in the other groups.

Practical case: overcoming the staff shortage. Implementation of remote management consulting (Chüy region). The enterprise did not have the resources to hire a qualified economist. The introduction of a remote monthly consulting system based on the proposed algorithms enabled the existing accountant to acquire fundamental knowledge of direct costing within six months**.** Result: Cost transparency increased, product costs were calculated with an accuracy of up to 95%, and operating expenses decreased by 11% due to the identification of inefficient expenditure items. Analysis of Organisational Constraints. A comparison of the data confirms the conclusion of M.A. Vakhrushina & N.V. Malinovskaya (2014) regarding the dependence of accounting efficiency on human resource capacity. Basic software infrastructure is available to most entities, but it is primarily used as an "electronic typewriter" for preparing primary accounting documents.

The key obstacle remains the psychological barrier: the managers of peasant (farmer) enterprises (PFEs) fear that detailed internal accounting may trigger greater fiscal scrutiny. Conversely, overcoming the staff shortage requires the implementation of systematic management consulting and remote staff training models. Only the integration of external analytical expertise into existing accounting processes will enable accounting records to be transformed from a purely fiscal instrument into a comprehensive system supporting strategic decision-making.

Conclusions

The study of 74 agricultural enterprises in the Kyrgyz Republic demonstrated that the institutional and methodological weaknesses of management accounting are systemic in nature. The current Law of the Kyrgyz Republic "On Accounting", together with simplified tax regimes, undermines incentives for maintaining analytical accounting. The empirical findings confirm that 76% of the surveyed entities rely on the simplified pooled cost accounting method, focusing exclusively on fiscal purposes, thereby depriving management of timely information on actual production costs. The main finding of the study is the quantitative confirmation of the detrimental impact of current accounting practices. It was established that the use of the pooled cost accounting method distorts financial performance: the lack of cost differentiation understates the profitability of individual crops by 12-19%, thereby masking actual losses. With regard to the accounting for biological assets, a critical gap was identified between actual costs and fair value, averaging 24.5%. This systematically understates the carrying amount of assets, thereby hindering access to long-term bank financing. Only 24% of the surveyed agricultural enterprises have partially implemented IAS 41, although the lack of transparent market quotations in the regions limits the effectiveness of this process. A comparative analysis of the experience of EAEU countries (Kazakhstan and Uzbekistan) demonstrated that, without government support – such as methodological guidelines and IT subsidies – the agricultural sector of the Kyrgyz Republic remains isolated. The authors' recommendations are based on a phased differentiation approach. At the first stage, sector-specific direct costing models should be developed and adapted to small-scale farms, where 92% of accounting functions are performed by non-specialist personnel. As demonstrated by the case studies presented, the implementation of these methods can increase reported profit by 15% and raise the contribution margin of key crops by 8%.

Despite the findings obtained, this study has several limitations. First, the conclusions are based on data from agricultural entities in the Chüy, Issyk-Kul, and Osh regions, which does not allow the results to be automatically extrapolated to high-mountainous regions with different climatic and institutional conditions. Second, the high proportion of small-scale farms in the sample creates practical difficulties in implementing comprehensive accounting systems due to the high level of administrative costs relative to the scale of production. Third, the fair value measurement of biological assets under IAS 41 at the current stage relies to a considerable extent on expert judgement due to the absence of active market quotations, which calls for caution when interpreting financial indicators. These limitations highlight the need for further development of regional methodological guidelines that take into account the specific characteristics of small-scale agricultural enterprises. Future research should focus on the experimental implementation of specialised direct costing registers within pilot agricultural cooperatives. In particular, adapting the proposed approaches to the mountain livestock farming and intensive horticulture sectors could help bridge the gap between universal accounting methodologies and the actual production-specific conditions of the Kyrgyz Republic.

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Кыргыз Республикасынын агрардык ишканаларында башкаруу эсебин уюштуруунун көйгөйлөрү

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Аннотация. Изилдөөнүн актуалдуулугу Кыргыз Республикасынын агрардык секторун экстенсивдүү чарба жүргүзүү ыкмаларынан продукциянын өздүк наркы жөнүндө так маалыматтарга негизделген башкаруунун заманбап моделине өткөрүү зарылчылыгы менен шартталган. Ишенимдүү маалыматтык базаны түзүү республиканын агроөнөр жай комплексинин натыйжалуу өнүгүшүн камсыз кылуунун милдеттүү шарты болуп саналат, бул эсепке алуу системаларын модернизациялоо маселелерин тармактын экономикалык өсүшү үчүн артыкчылыктуу милдеттердин катарына чыгарат. Иштин максаты – өлкөнүн айыл чарбасында башкаруу эсебинин өнүгүшүнө тоскоол болгон институционалдык, методологиялык жана кадрдык барьерлерди аныктоо, ошондой эле аларды жоюунун практикалык механизмдерин негиздөө болуп саналат. Изилдөөнүн методологиялык негизин Чүй, Ысык-Көл жана Ош облустарынын агроструктураларынын ишмердүүлүгүнө тутумдук жана салыштырмалуу талдоо методдорун колдонуу менен жүргүзүлгөн комплекстүү анализ түздү. Аймактык практиканы изилдөөнүн жыйынтыктары учурдагы тоскоолдуктар комплекстүү мүнөзгө ээ экендигин көрсөттү. Эсепке алуунун «казандык» методун бардык жерде колдонуу менеджментти продукциянын түрлөрү боюнча зарыл аналитикадан ажыратары жана рентабелдүүлүк көрсөткүчтөрүн олуттуу бурмалоого алып келери аныкталды. Иштин жүрүшүндө ФОЭК (IAS) 41 талаптары менен реалдуу практиканын ортосундагы ажырымга өзгөчө көңүл бурулду: өлкөнүн аймактарында активдүү рыноктордун жоктугунан улам биологиялык активдерди адилет наркы боюнча баалоо иш жүзүндө аткарылгыс милдет бойдон калууда. Эл аралык стандарттарды азыркы учурдагы квалификациялуу кадрлардын жана адистештирилген программалык камсыздоонун жетишсиздиги шартында мажбурлап киргизүү реалдуу каржылык агымдарды чагылдырбаган формалдуу эсепке алууга гана алып келери далилденди. Макалада башкаруу эсебинин системаларын этап-этабы менен адаптациялоонун алгоритми сунушталды, ал тармактык методикалык сунуштамаларды иштеп чыгууну жана дыйкан чарбалары үчүн типтүү моделдерди түзүүнү камтыйт. Изилдөөнүн практикалык маанилүүлүгү агроөнөр жай комплексинин АӨК ишканаларынын эсептик саясатын оптималдаштыруу жана айыл чарба жогорку окуу жайларындагы билим берүү программаларын модернизациялоо үчүн «директ-костинг» жана «стандарт-кост» системаларынын элементтерин колдонуу мүмкүнчүлүгүндө турат

Негизги сөздөр: стратегиялык чыгымдарды көзөмөлдөө; калькуляциялоо ыкмалары; ички контролдоо системасы; ченемдик-укуктук жөнгө салуу; эсеп саясаты; финансылык маалымат; өндүрүштүн натыйжалуулугу

Проблемы организации управленческого учета в аграрных предприятиях Кыргызской Республики

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Аннотация. Актуальность исследования обусловлена необходимостью перехода аграрного сектора Кыргызской Республики от экстенсивных методов хозяйствования к современной модели управления, базирующейся на точных данных о себестоимости продукции. Создание надежной информационной базы является обязательным условием для обеспечения эффективного развития агропромышленного комплекса республики, что делает вопросы модернизации учетных систем одной из приоритетных задач для экономического роста отрасли. Цель работы заключалась в выявлении институциональных, методологических и кадровых барьеров, препятствующих развитию управленческого учета в сельском хозяйстве страны, а также в обосновании практических механизмов их преодоления. Методологическую основу исследования составил комплексный анализ деятельности агроформирований Чуйской, Иссык-Кульской и Ошской областей с использованием методов системного и сравнительного анализа. Результаты изучения региональной практики показали, что существующие препятствия носят комплексный характер. Установлено, что повсеместное применение «котлового» метода учета лишает менеджмент необходимой аналитики в разрезе видов продукции и приводит к существенным искажениям показателей рентабельности. Особое внимание в работе уделено выявленному разрыву между теоретическими требованиями МСФО (IAS) 41 и реальностью: в условиях отсутствия активных рынков в регионах страны оценка биологических активов по справедливой стоимости остается практически труднореализуемой задачей. Доказано, что форсированное внедрение международных стандартов при текущем дефиците квалифицированных кадров и специализированного программного обеспечения приводит лишь к формальному ведению учета, не отражающемуф реальные финансовые потоки. В статье предложен алгоритм поэтапной адаптации систем управленческого учета, включающий разработку отраслевых методических рекомендаций и создание типовых моделей для крестьянских хозяйств. Практическая значимость исследования заключается в возможности использования предложенных инструментов, включая элементы систем «директ-костинг» и «стандарт-кост», для оптимизации учетной политики предприятий агропромышленный комплекс (АПК) и модернизации образовательных программ в сельскохозяйственных вузах

Ключевые слова: стратегический контроль затрат; методы калькулирования; система внутреннего контроля; нормативно-правовое регулирование; учетная политика; финансовая информация; производственная эффективность

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Effects of social hierarchy-related stress on hormonal reactivity and milk production in dairy cows at a commercial dairy complex

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Abstract. Regrouping disrupts established social relationships among dairy cows. Temporary overstocking additionally increases competition for feed, water, and lying space. The aim of this study was to evaluate the hormonal and production responses of cows with different stress-resistance types to social hierarchy-related stress at a commercial dairy complex. Cortisol and adrenaline concentrations were measured in 86 lactating cows before and 12 hours after 36 additional cows were introduced into a 540 m^2 pen; the cows were classified by stress-resistance type from basal cortisol, and daily milk yield, milk fat, and milk protein were assessed. Low, unstable, and high stress resistance was identified in 13 cows (15.12%), 55 cows (63.95%), and 18 cows (20.93%), respectively. Cortisol increased from 129.86 to 138.23 nmol/L in low-resistance cows, decreased from 72.33 to 68.89 nmol/L in unstable cows, and remained almost unchanged in high-resistance cows, at 47.21 and 48.03 nmol/L. At 12 hours, adrenaline was lower than baseline by 35.13%, 41.00%, and 14.12%, respectively. Daily milk yield decreased by 4.18 kg, or 14.88%, in low-resistance cows and by 1.28 kg, or 4.62%, in unstable cows, whereas it increased by 0.39 kg, or 1.30%, in high-resistance cows. Milk fat decreased by 2.96%, 6.63%, and 0.46%, respectively, whereas

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milk protein changed by -0.46%, -2.26%, and +3.13%. Correlations between post-challenge cortisol and milk yield were 0.33, 0.18, and 0.45, respectively; all 95% confidence intervals included zero and all p values exceeded 0.05. Low-resistance cows had the greatest risk of production loss and should be managed using low-disruption regrouping procedures and reduced competition for essential resources

Keywords: herd regrouping; social competition; basal cortisol; adrenaline; daily milk yield; stocking density; individual reactivity

Introduction

The intensification of dairy farming is accompanied by larger management groups, regular movement of animals between pens, and greater competition for feed-bunk space, drinking points, and lying areas. For a herd animal, these changes involve not only physical relocation but also the need to re-establish dominance and subordinate relationships. During the first hours after unfamiliar cows are mixed, displacements become more frequent, feeding behaviour and resting patterns change, and the physiological cost of adaptation depends on individual reactivity.

A recent review showed that social mixing most consistently alters activity, resting time, and the frequency of agonistic interactions, whereas evidence regarding hormonal and production consequences remains heterogeneous (Hubbard *et al.*, 2021). Prolonged social instability can also interact with nutritional and technological stressors and contribute to impaired health and production (Proudfoot & Habing, 2015). Social hierarchy is not a fixed linear attribute of an individual cow. Rank depends on context, resource availability, group composition, and the method used to calculate it. M.F. Bouissou *et al.* (2001) showed that dominance relationships in cattle depend on age, body size, experience, and the context in which animals compete. J. Krahn *et al.* (2024) subsequently demonstrated that group size affects the number and distribution of agonistic interactions among dairy cows. Thus, when resources are limited, an observed competitive advantage may reflect not only stable social rank but also the animal's current motivation. In this study, the term "social hierarchy-related stress" therefore refers to stress induced by regrouping and temporary overstocking, rather than to a previously measured rank for each cow.

Individual variation in the response has practical importance for dairy production. Sociability, fearfulness, and coping style determine how an animal modifies its behaviour when encountering competitors (Nogues *et al.*, 2020). Under restricted feed access, individual differences may become more pronounced because competition changes feeding behaviour and access to the ration (DeVries, 2019). Physiological status and production level can also modify cortisol concentrations and their relationship with milk production (Tallo-Parra *et al.*, 2018). These factors can modify the response to regrouping and should be considered when hormonal and production outcomes are interpreted. At commercial dairy complexes, both the average herd response and within-herd heterogeneity are important. Cows in the same management group may differ substantially in basal hormonal activity, behaviour, and their ability to maintain milk yield during a combined social and management challenge. Preliminary classification based on basal cortisol can help identify categories of animals at increased risk of production loss. The objective of the study was to evaluate changes in cortisol and adrenaline concentrations, daily milk yield, and major milk components in cows of different stress-resistance types after regrouping and temporary overstocking within a single commercial cohort.

Literature Review

The social organisation of cattle combines dominance relationships with selective affiliative bonds. Familiar animals may provide social support during relocation or regrouping. J.L. Rault (2012) concluded that the presence of familiar conspecifics can reduce behavioural and physiological responses to adverse events. This supports moving cows in small, familiar subgroups whenever farm organisation permits. Parity and previous social experience also affect the response to mixing. C.J.C. Phillips & M.I. Rind (2001) compared mixed and unmixed groups of primiparous and multiparous cows. Milk yield in mixed cows was 3% lower during the first week and remained approximately 1% lower during the following six weeks. Mixed cows spent less time grazing and more time standing, indicating that changes in feeding behaviour can contribute to production losses.

Regrouping causes the most pronounced changes immediately after animals are introduced into a new pen. J. Denham & A. Adams Progar (2023) observed changes in salivary cortisol and behaviour in both newly introduced and resident Holstein heifers after regrouping. A review by A.J. Hubbard *et al.* (2021) confirmed the consistency of behavioural responses but noted heterogeneous evidence for endocrine, immune, and production consequences. Competition for feed-bunk space intensifies social pressure. Reduced feed-bunk allowance increases the frequency of displacements and can restrict feeding opportunities, especially for subordinate cows (DeVries, 2019). J. Lyu *et al.* (2023) likewise found that group size and regrouping affected physiological stress indicators and behaviour in dairy calves. These mechanisms are important for interpreting an experiment in which both group composition and space allowance per cow changed simultaneously.

The physiological response to social competition does not always correspond to overt aggression. Cortisol is a widely used indicator of hypothalamic-pituitary-adrenal axis activity, but it should be interpreted according to stressor duration, circadian rhythm, physiological status, and the sampling procedure (Möstl & Palme, 2002; Mormède *et al.*, 2007). Repeated venipuncture can itself influence plasma cortisol concentrations (Hopster *et al.*, 1999). C.E. Hernández *et al.* (2014) demonstrated that peak salivary cortisol occurs later than peak plasma cortisol after a stressful procedure in dairy cattle. N.J. Cook (2012) therefore recommended standardising sampling time, animal handling, sample medium, and laboratory processing. The relationship between social contacts and production is also inconsistent. Some cows maintain milk production despite changes in behaviour, whereas others experience a marked short-term decline. Overall, the literature indicates that hierarchy-related stress should be assessed by jointly considering the nature of the challenge, hormonal markers, and individual production dynamics rather than inferring stress from a single behavioural or endocrine measure.

Materials and Methods

Experimental animals and housing conditions. The study was conducted in 2023 at the Pobeda LLP breeding farm in the Pavlodar Region, Republic of Kazakhstan. The field phase was carried out from August to November 2023. The experiment included 86 clinically healthy lactating cows from a single commercial herd. The cohort comprised 27 Holstein, 31 Red Steppe, and 28 Simmental cows. Animals were matched for stage of lactation, live weight, and production status. According to the selection characteristics of the production groups, the cows were approximately 3-6 years old, with a mean age of 4.3 years. They were in their second to fourth lactations, at approximately 90-210 days in milk, with a mean of 148 days. Live weight ranged from approximately 520 to 650 kg and averaged 575 kg. Production status corresponded to an average baseline daily milk yield of 28.29 kg per cow. Cows showing clinical signs of udder, limb, or reproductive disease were excluded.

Cows were loose-housed in pens at a commercial dairy farm. The production sections normally contained 70-90 cows and were formed according to lactation stage and productivity. Each section had automatic drinking points, a feed bunk, and individual lying places with rubber flooring and straw bedding renewed daily. Automatic scrapers removed manure at approximately 20-minute intervals, and three industrial fans were installed above each section. Before the experiment, the animals were placed in a stable management group and maintained with an unchanged composition for one month to allow adaptation to the facility and stabilisation of social relationships. The experimental pen had a total area of 540 m^2, equivalent to approximately 6.2 m^2 per cow. During the experimental period, indoor air temperature ranged from approximately 14 to 22°C, relative humidity from 50 to 68%, and air velocity from 0.2 to 0.4 m/s. These conditions were within the thermoneutral range for adult dairy cows and reduced the likelihood that heat stress substantially affected the regrouping response. Animals had free access to drinking water and a total mixed ration. The approximate daily ration per cow consisted of 24.0 kg of maize silage, 12.0 kg of haylage, 3.0 kg of mixed-grass hay, 3.0 kg of barley grain, 1.5 kg of maize grain, 2.0 kg of rapeseed meal, 1.5 kg of sunflower meal, and 0.2 kg of vitamin–mineral premix. The ration supplied approximately 23 kg of dry matter per cow per day and contained about 15.5% crude protein, 33% neutral detergent fibre, and 10.6 MJ of metabolisable energy per kilogram of dry matter. Milking was performed twice daily at 05:00 and 17:00 in a herringbone milking parlour. The 24-place milking installation was manufactured by Westfalia, Germany.

Experimental procedures and statistical analysis. Social hierarchy-related stress was induced by combining regrouping with temporary overstocking. In the evening, 36 cows from another management group were introduced into the pen containing the adapted experimental animals. The total number of cows in the pen increased to 122, and the space allowance declined to 4.4 square metres per cow. The 36 introduced cows created the experimental challenge but were not included in the statistical analysis of the original 86-cow cohort. The challenge lasted 12 hours. Baseline measurements were obtained under resting conditions before regrouping. Repeat blood sampling and a test milking were performed the following morning after the 12-hour challenge. Individual daily milk yields for the 15 days before and 15 days after regrouping were also extracted from the farm database to assess short-term recovery of production.

Blood was collected from the coccygeal vein 30 minutes after morning milking within the same time window for all cows. Serum-separator tubes were used for hormone measurements. Samples were transported in an insulated container at no more than 4 degrees Celsius and delivered to the laboratory within two hours of collection. Cortisol and adrenaline concentrations were determined using a solid-phase enzyme-linked immunosorbent assay on a Tecan Infinite F50 microplate reader, with optical density measured at 450 and 620 nanometres. The analyser was manufactured by Tecan Austria GmbH, Grödig, Austria. Bovine Cortisol ELISA and Bovine Epinephrine/Adrenaline EPI ELISA kits manufactured by Shanghai BlueGene Biotech Co., Ltd., Shanghai, China, were used, and hormone concentrations were calculated from the corresponding calibration curves. Milk fat and protein percentages were measured using a Laktan 700 infrared analyser. The analyser was manufactured by Sibagropribor LLC, Krasnoobsk, Novosibirsk Region, Russian Federation. All baseline and post-challenge samples were analysed using the same protocol. Stress-resistance type was determined from basal cortisol concentration using a uniform classification algorithm. The number of frequency intervals was estimated with Sturges' rule, after which the mean and standard error were calculated. Values above M + 3m were classified as low stress resistance, values below M – 3m as high stress resistance, and intermediate values as unstable stress resistance. The approach is protected by Utility Model Patent No. 9336 of the Republic of Kazakhstan (Patent for Utility Model No. 9336, 2024). Cows were then assigned to one of the three stress-resistance types.

For each stress-resistance type, means were weighted by sample size and variances reconstructed from residual and between-mean components. Type proportions are reported with 95% Wilson confidence intervals and means with 95% t-distribution confidence intervals. Changes were expressed in absolute units, percentages, and relative to the baseline standard deviation (Δ/SD_0); absolute values below 0.20 were considered negligible, 0.20-0.49 small, 0.50-0.79 moderate, and 0.80 or greater large. Overall correlation coefficients were estimated on Fisher's z scale using n – 3 weights, with 95% confidence intervals and two-sided p values. Because individual paired observations were unavailable, confidence intervals and p values for pre–post differences were not reconstructed. Confirmatory analysis should use an individual-level linear mixed-effects model with fixed effects of time, stress-resistance type, and their interaction, adjustment for parity and stage of lactation, and a random intercept for cow. The study complied with the European Convention for the Protection of Animals Kept for Farming Purposes (1976), the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986), and Law of the Republic of Kazakhstan No. 97-VII (2021). Trained personnel performed all procedures and minimised restraint time.

Results and Discussion

Of the 86 cows, 55 (63.95%) were classified as unstable, 13 as low-resistance, and 18 as high-resistance; Wilson intervals were wider for the smaller low-resistance type (Table 1).

Table 1. Distribution of cows by stress-resistance type

Stress-resistance type	n	%	95% CI for proportion, %
Low	13	15.12	9.05-24.16
Unstable	55	63.95	53.41-73.30
High	18	20.93	13.67-30.68

Note: 95% confidence intervals for proportions were calculated using the Wilson method (n = 86)
Source: authors' calculations based on the study data

During the first hours after the new animals were introduced, sniffing, displacements, physical confrontations, increased movement at the feed bunk, restricted access to water, and insufficient lying space were recorded. Some animals remained in the passages because all lying places were occupied. These observations were descriptive and were not analysed using a formal ethogram. In the full cohort, the most consistent increase in cortisol occurred in low-resistance cows: the mean concentration increased by 8.37 nmol/L, or 6.45%. The standardised change was 0.25 baseline standard deviations and represented a small effect. In the unstable type, mean cortisol decreased by 4.77%, with a small standardised effect of -0.36; the wide post-challenge interval reflected pronounced heterogeneity in individual responses. In the high-resistance type, the change was negligible at 1.73%, or 0.07 baseline standard deviations (Table 2, Fig. 1).

Table 2. Changes in cortisol concentration by stress-resistance type

Type	n	Baseline, nmol/L, mean ± SE [95% CI]	Post-challenge, nmol/L, mean ± SE [95% CI]	Change, %	Δ/SD_0
Low	13	129.86 ± 9.45 [109.27-150.45]	138.23 ± 7.57 [121.74-154.72]	+6.45	+0.25
Unstable	55	72.33 ± 1.29 [69.74-74.92]	68.89 ± 3.56 [61.76-76.02]	-4.77	-0.36
High	18	47.21 ± 2.64 [41.64-52.78]	48.03 ± 1.90 [44.02-52.04]	+1.73	+0.07

Note: SE – standard error; CI – confidence interval; Δ/SD_0, – change standardised to the baseline standard deviation
Source: authors' calculations based on the study data

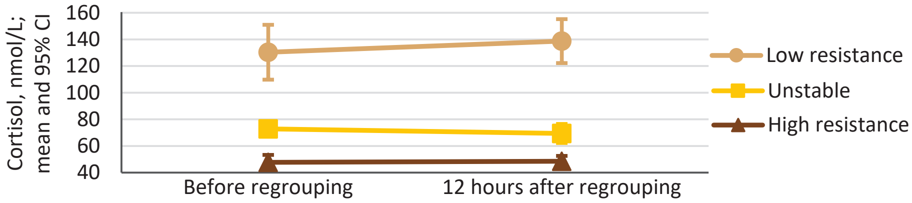

Figure 1. Changes in cortisol concentration after regrouping in the full study sample
Source: authors' calculations based on the study data

Adrenaline concentration 12 hours after regrouping was lower than baseline in all stress-resistance types. The decrease was 35.13% in the low-resistance type, 41.00% in the unstable type, and 14.12% in the high-resistance type. The standardised effect was moderate in low-resistance cows and small in unstable and high-resistance cows. This finding should not be interpreted as an absence of an acute stress response: the catecholamine response develops rapidly, and sampling at 12 hours probably captured a recovery phase. The remaining high variability supports the inclusion of several early sampling time points in future studies (Table 3).

Table 3. Changes in adrenaline concentration by stress-resistance type

Type	n	Baseline, pg/mL, mean ± SE [95% CI]	Post-challenge, pg/mL, mean ± SE [95% CI]	Change, %	Δ/SD_0
Low	13	70.68 ± 12.06 [44.41-96.95]	45.85 ± 7.60 [29.29-62.40]	-35.13	-0.57
Unstable	55	65.13 ± 7.22 [50.64-79.61]	38.43 ± 1.99 [34.44-42.42]	-41.00	-0.50
High	18	55.30 ± 5.97 [42.69-67.90]	47.49 ± 7.80 [31.03-63.95]	-14.12	-0.31

Note: change estimates are descriptive; paired covariance was unavailable in the summary report
Source: authors' calculations based on the study data

Analysis of the full cohort revealed a gradient in production stability. In low-resistance cows, daily milk yield decreased from 28.08 to 23.90 kg, a reduction of 4.18 kg or 14.88%. The standardised change of −0.66 represented a moderate negative effect. In the unstable type, the decrease was 1.28 kg or 4.62%, with a negligible standardised effect of −0.18. High-resistance cows largely maintained their average milk yield, which was 0.39 kg or 1.30% above baseline; the standardised change of 0.06 was negligible (Table 4, Fig. 2).

Table 4. Changes in adrenaline concentration by stress-resistance type

Type	n	Baseline, kg, mean ± SE [95% CI]	Post-challenge, kg, mean ± SE [95% CI]	Change, kg	Change, %	Δ/SD_0
Low	13	28.08 ± 1.75 [24.26-31.90]	23.90 ± 1.86 [19.84-27.96]	-4.18	-14.88	-0.66
Unstable	55	27.66 ± 0.94 [25.77-29.54]	26.38 ± 1.00 [24.38-28.38]	-1.28	-4.62	-0.18
High	18	30.35 ± 1.47 [27.25-33.45]	30.74 ± 1.28 [28.05-33.44]	+0.39	+1.30	+0.06

Source: authors' calculations based on the study data

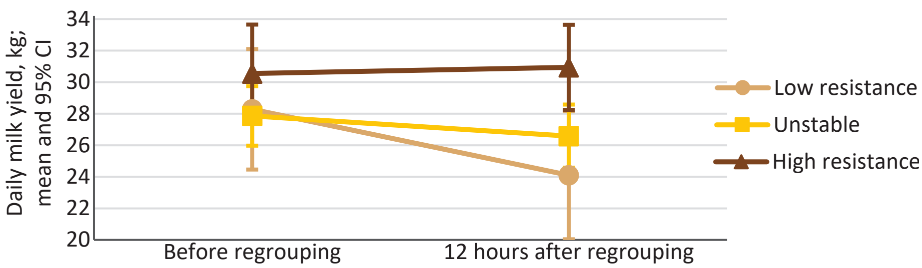

Figure 2. Changes in daily milk yield after regrouping in the full study sample
Source: authors' calculations based on the study data

Changes in milk composition were less pronounced than changes in yield. Milk fat decreased most markedly in the unstable type, by 6.63%; the standardised effect of -0.47 was small and approached a moderate magnitude. Milk fat decreased by 2.96% in the low-resistance type and by 0.46% in the high-resistance type. Milk protein was nearly unchanged in the low-resistance type, decreased by 2.26% in the unstable type, and increased by 3.13% in the high-resistance type. The latter represented a moderate descriptive effect but should be interpreted cautiously because individual paired covariance was unavailable (Table 5).

Table 5. Changes in milk fat and protein percentages by stress-resistance type

Type	n	Baseline milk fat, %	Post-challenge milk fat, %	Change in milk fat, %	Baseline milk protein, %	Post-challenge milk protein, %	Change in milk protein, %
Low	13	4.93 ± 0.19	4.78 ± 0.18	-2.96	2.82 ± 0.02	2.80 ± 0.04	-0.46
Unstable	55	4.90 ± 0.09	4.58 ± 0.08	-6.63	2.82 ± 0.03	2.76 ± 0.02	-2.26
High	18	4.71 ± 0.18	4.69 ± 0.15	-0.46	2.77 ± 0.04	2.86 ± 0.01	+3.13

Note: percentage changes were calculated from unrounded pooled values; minor differences arising from the rounded means are due to rounding
Source: authors' calculations based on the study data

Correlations between post-challenge cortisol and daily milk yield were positive but statistically inconclusive. The overall coefficient was 0.33 for the low-resistance type (95% confidence interval, -0.56 to 0.87; $p = 0.496$), 0.18 for the unstable type (-0.10 to 0.44; $p = 0.213$), and 0.45 for the high-resistance type (-0.16 to 0.82; $p = 0.141$). All confidence intervals included zero; therefore, the data do not support a consistent linear association between cortisol and milk yield within stress-resistance type. Cortisol should be regarded as one component of a multidimensional stress response rather than as a stand-alone universal predictor of production (Table 6).

Table 6. Correlation between post-challenge cortisol and daily milk yield by stress-resistance type

Type	n	r	95% CI	p
Low	10	0.33	-0.56-0.87	0.496
Unstable	55	0.18	-0.10-0.44	0.213
High	18	0.45	-0.16-0.82	0.141

Note: n is the number of cows with source data available for correlation analysis; the correlation coefficient was not reported for three low-resistance cows in the source report. Overall coefficients were calculated on Fisher's z scale using n − 3 weights; p is the two-sided value for testing a null correlation. The p values are exploratory and were not adjusted for multiple comparisons
Source: authors' calculations based on the study data

Findings for the full commercial cohort are consistent with evidence that the consequences of regrouping depend not only on the mean herd response but also on individual coping strategy. Vulnerability in the low-resistance type was expressed as both increased cortisol and a moderate decline in milk yield. The high-resistance type showed minimal changes in both outcomes. The unstable type had an intermediate production response but pronounced heterogeneity in its hormonal response. J.L. Marumo *et al.* (2024) studied 52 lactating cows moved in familiar groups of three to five animals into established pens of approximately 100 cows. Primiparous cows produced 3.80 ± 2.42 kg, or 12.2%, less milk on the first day after regrouping, whereas multiparous cows did not show a comparable decline. The 14.88% reduction in low-resistance cows in the present study was similar in magnitude, although the current classification was based on basal cortisol rather than parity. J.L. Marumo *et al.* (2024) also reported a decrease in milk fat of approximately 0.2 percentage points in both parity groups, while the present study found the largest relative reduction in milk fat in unstable cows, at 6.63%.

J. Brouček *et al.* (2015) examined 41 Holstein cows transferred to unfamiliar housing and a new milking system. Mean daily milk yield declined from 30.97 ± 7.26 to 23.76 ± 7.21 kg on the first day and recovered to 32.16 ± 8.87 kg by day 14. Their initial decline was greater than the pooled reduction in the present study, probably because their cows were exposed simultaneously to unfamiliar housing, relocation, and a different milking system. Both studies nevertheless indicate that the greatest production losses occur immediately after disruption. D.J.S. Jung *et al.* (2024) found that regrouping increased cortisol in dairy heifers on the first day. Regrouped heifers experienced 9.42 displacements per day compared with 2.64 in non-regrouped animals, while the difference had largely disappeared by day 7. These results correspond with the increased displacements and competition observed during the first hours of the present experiment. In contrast to the uniform group response reported by D.J.S. Jung *et al.* (2024) cortisol responses in the present study differed among stress-resistance types.

M. Soonberg *et al.* (2021) reported that motion index, step count, and lying-bout frequency changed more strongly in heifers than in experienced cows after group transitions. Cows initiated 7.04 ± 1.19 aggressive acts per hour compared with 3.66 ± 1.05 among heifers, whereas heifers received more aggressive interactions. These findings suggest that parity and previous regrouping experience may explain part of the individual variation observed in the present cohort. Regrouping was accompanied by a reduction in space allowance per cow; consequently, the observed effect reflects the combined influence of social instability and resource competition. In practice, low-resistance cows should be moved in familiar subgroups, provided with adequate feed-bunk, drinking, and lying space, and not transferred into an already overstocked pen. Use of the full commercial cohort produced more stable descriptive estimates for the three stress-resistance types but did not replace analysis of individual-level data. The summary report did not contain the covariance of paired measurements, so formal p values for change over time could not be reconstructed. In addition, the experiment was conducted on one farm and included a single regrouping event, while sampling at 12 hours did not capture the early adrenaline peak. External validation is required in independent herds using repeated regrouping events, multiple sampling time points, direct recording of agonistic interactions, and a linear mixed-effects model at the individual-cow level.

Conclusions

Within the full cohort, the unstable stress-resistance type accounted for 63.95% of cows, the low-resistance type for 15.12%, and the high-resistance type for 20.93%. Wilson intervals quantified uncertainty around these proportions, while inclusion of data from all 86 cows reduced the risk of overinterpreting the smaller low-resistance type. The most adverse combined response occurred in low-resistance cows: cortisol increased by 6.45%, whereas daily milk yield decreased by 4.18 kg or 14.88%; the standardised decline in yield was moderate. In the unstable type, milk yield decreased by 4.62% amid pronounced heterogeneity in the hormonal response. The high-resistance type largely maintained baseline cortisol and milk production.

Milk fat decreased in all three types, with the largest relative reduction occurring in unstable cows, at 6.63%, compared with 2.96% in low-resistance cows and 0.46% in high-resistance cows. Milk protein decreased by 0.46% in low-resistance cows and by 2.26% in unstable cows but increased by 3.13% in high-resistance cows. These changes in milk composition are descriptive and require confirmation using individual paired observations. Overall correlations between post-challenge cortisol and milk yield were statistically inconclusive: their confidence intervals included zero and all two-sided p values exceeded 0.05. Basal cortisol should therefore be used only as an additional marker of vulnerability and supplemented with assessments of behaviour, resource availability, and milk-yield dynamics. Confirmation of these findings requires individual-level analysis using a linear mixed-effects model that accounts for repeated measurements, parity, stage of lactation, and the interaction between time and stress-resistance type, together with external validation in independent dairy herds.

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Conflict of Interest

None.

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Социалдык иерархияга байланышкан стресстин коммерциялык сүт комплексиндеги уйлардын гормондук реактивдүүлүгүнө жана сүт өндүрүмдүүлүгүнө тийгизген таасири

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Аннотация. Уйларды кайра топтоштуруу алардын ортосунда калыптанган социалдык мамилелерди бузат. Убактылуу жыш жайгаштыруу тоют, суу жана эс алуучу жайлар үчүн атаандаштыкты кошумча күчөтөт. Изилдөөнүн максаты стресске туруктуулугунун типтери ар башка болгон уйлардын социалдык иерархияга байланышкан стресске карата гормондук жана өндүрүмдүүлүк реакцияларын коммерциялык сүт комплексинин шарттарында баалоо болгон. Аянты 540 м^2 болгон секцияга кошумча 36 уй киргизилгенге чейин жана андан 12 саат өткөндөн кийин 86 саан уйда кортизол менен адреналиндин концентрациялары өлчөнүп, уйлар базалдык кортизол боюнча классификацияланган жана суткалык сүт саап алуу, сүттөгү май менен белок бааланган. Стресске туруктуулугу төмөн, туруксуз жана жогору типтерге тиешелүүлүгүнө жараша 13 уй (15,12 %), 55 уй (63,95 %) жана 18 уй (20,93 %) кирген. Стресске туруктуулугу төмөн уйларда кортизол 129,86-дан 138,23 нмоль/л-ге чейин жогорулаган, туруксуз типте 72,33төн 68,89 нмоль/л-ге чейин төмөндөгөн, ал эми жогорку туруктуулуктагы уйларда дээрлик өзгөргөн эмес – 47,21 жана 48,03 нмоль/л. Он эки сааттан кийин адреналин баштапкы деңгээлден 35,13 %, 41,00 % жана 14,12 % төмөн болгон. Суткалык сүт саап алуу төмөн туруктуулуктагы уйларда 4,18 кг-га, же 14,88 %-га, туруксуз типте 1,28 кг-га, же 4,62 %-га азайган, ал эми жогорку туруктуулуктагы уйларда 0,39 кг-га, же 1,30%-га көбөйгөн. Сүттөгү май тиешелүүлүгүнө жараша 2,96 %, 6,63 % жана 0,46 % азайган, ал эми белок -0,46 %, -2,26 % жана +3,13 % өзгөргөн. Таасирден кийинки кортизол менен сүт саап алуунун корреляция коэффициенттери 0,33, 0,18 жана 0,45 болгон; бардык 95 % ишеним интервалдары нөлдү камтып, p маанилери 0,05тен жогору болгон. Өндүрүмдүүлүктүн төмөндөө коркунучу стресске туруктуулугу төмөн уйларда эң жогору болгондуктан, аларды багууда минималдуу тынчсыздануу жараткан кайра топтоштуруу ыкмаларын колдонуу жана негизги ресурстар үчүн атаандаштыкты азайтуу зарыл

Негизги сөздөр: үйүрдү кайра топтоштуруу; социалдык атаандаштык; кортизолдун базалдык концентрациясы; адреналин; суткалык сүт саап алуу; жайгаштыруу жыштыгы; жекече реактивдүүлүк

Влияние стресса, связанного с социальной иерархией, на гормональную реактивность и молочную продуктивность коров в условиях промышленного молочного комплекса

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Аннотация. Перегруппировка нарушает сложившиеся социальные взаимоотношения между молочными коровами. Временное увеличение плотности размещения дополнительно усиливает конкуренцию за корм, воду и места для отдыха. Целью исследования являлась оценка гормональных и продуктивных реакций коров с различными типами стрессоустойчивости на стресс, связанный с социальной иерархией, в условиях промышленного молочного комплекса. У 86 лактирующих коров до введения в секцию площадью 540 м^2 дополнительных 36 животных и через 12 часов после него определяли концентрации кортизола и адреналина, классифицировали коров по базальной концентрации кортизола и оценивали среднесуточный удой, содержание жира и белка в молоке. Низкая, нестабильная и высокая стрессоустойчивость установлена соответственно у 13 коров (15,12 %), 55 коров (63,95 %) и 18 коров (20,93 %). У коров с низкой стрессоустойчивостью концентрация кортизола увеличилась со 129,86 до 138,23 нмоль/л, у животных нестабильного типа снизилась с 72,33 до 68,89 нмоль/л, а у высокоустойчивых коров практически не изменилась – 47,21 и 48,03 нмоль/л. Через 12 часов концентрация адреналина была ниже исходной на 35,13 %, 41,00 % и 14,12 % соответственно. Среднесуточный удой у низкоустойчивых коров снизился на 4,18 кг, или 14, 88 %, у коров нестабильного типа – на 1,28 кг, или 4,62 %, а у высокоустойчивых коров увеличился на 0,39 кг, или 1,30 %. Содержание жира снизилось соответственно на 2,96 %, 6,63 % и 0,46 %, а содержание белка изменилось на -0,46 %, -2,26 % и +3,13 %. Коэффициенты корреляции между концентрацией кортизола после воздействия и удоем составили 0,33, 0,18 и 0,45; все 95 % доверительные интервалы включали нулевое значение, а значения p превышали 0,05. Наибольший риск снижения продуктивности установлен у коров с низкой стрессоустойчивостью, поэтому при работе с ними следует применять малотравматичные способы перегруппировки и минимизировать конкуренцию за основные ресурсы

Ключевые слова: органические удобрения; навоз; озимая рожь; плодородие почвы; устойчивое земледелие

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