



ACTUAL PROBLEMS OF MODERN SCIENCE, EDUCATION AND TRAINING

KHOREZMSCIENCE.UZ





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Section 1. MODERN PROBLEMS OF PEDAGOGY AND PSYCHOLOGY

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ANALYSIS OF EFFICIENCY INDICATORS OF ARTIFICIAL-INTELLIGENCE-BASED EDUCATIONAL SYSTEMS

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Annotatsiya. Mazkur maqolada sun'iy intellektga (SI) asoslangan ta'lim tizimlarining samaradorlik ko'rsatkichlari ilmiy-nazariy va analitik jihatdan tahlil qilinadi. Ta'lim jarayonida SI texnologiyalaridan foydalanishning afzalliklari, talabalar o'zlashtirish darajasiga ta'siri, shaxsiylashtirilgan (adaptiv) ta'lim imkoniyatlari hamda o'qitishni avtomatlashtirish samaradorligi mavjud xalqaro meta-tahlillar natijalari asosida yoritilgan. Tadqiqotda SI asosidagi platformalarning ta'lim sifati, o'zlashtirish dinamikasi va vaqt tejamkorligiga ta'siri statistik ko'rsatkichlar, qiyosiy jadvallar hamda diagrammalar yordamida ko'rib chiqilgan.

Kalit so'zlar: *sun'iy intellekt, ta'lim tizimi, mashinaviy o'qitish, adaptiv ta'lim, ta'lim samaradorligi, raqamli ta'lim, ta'lim analitikasi, effekt o'lchami.*

Аннотация. В данной статье анализируются показатели эффективности образовательных систем на основе искусственного интеллекта (ИИ). Рассмотрены преимущества использования технологий ИИ в учебном процессе, их влияние на уровень усвоения знаний студентами, возможности персонализированного (адаптивного) обучения, а также эффективность автоматизации преподавания на основе результатов международных мета-анализов. Влияние ИИ-платформ на качество образования и экономию времени представлено с помощью статистических показателей, сравнительных таблиц и диаграмм.

Ключевые слова: *искусственный интеллект, образовательная система, машинное обучение, адаптивное обучение, эффективность образования, цифровое образование, образовательная аналитика, размер эффекта.*

Abstract. This article provides a scientific-theoretical and analytical assessment of the efficiency indicators of artificial-intelligence (AI) based educational systems. The advantages of applying AI technologies in the learning process, their impact on students' achievement levels, the opportunities for personalized (adaptive) learning, and the efficiency of teaching automation are examined on the basis of existing international meta-analyses. The influence of AI-based platforms on educational quality, learning dynamics and time efficiency is reviewed through statistical indicators, comparative tables and diagrams. The results obtained indicate that AI tools yield medium-to-high positive effects compared with traditional instruction.

Keywords: *artificial intelligence, educational system, machine learning, adaptive learning, educational efficiency, digital education, learning analytics, effect size.*

Introduction

In recent years, artificial-intelligence (AI) technologies have become the principal driving force behind the digital transformation of the education sector. Solutions based on machine learning, natural language processing (NLP), big-data analytics and neural networks make it possible to personalize the learning process, automate assessment and predict learning outcomes. In education, AI manifests itself not merely as a technical instrument but as a factor that redesigns the pedagogical process itself [1, 2].

In the Republic of Uzbekistan, the development of the digital economy and digital education is regarded as one of the priority directions of state policy. Within the framework of the “Digital Uzbekistan 2030” strategy, the task of introducing modern information technologies-including AI tools-into educational institutions has been set [16]. For this reason, a scientific and analytical assessment of the real efficiency of AI-based educational systems is of pressing importance.

In practice, however, the impact of AI tools on educational quality is often assessed subjectively. Questions such as how much AI platforms increase students’ achievement, to what extent they ease the teacher’s workload, and in which pedagogical situations they deliver the highest results require systematic answers. The aim of this article is to carry out a comparative analysis of the efficiency indicators of AI-based educational systems on the basis of existing international empirical studies and meta-analyses, and to determine their quantitative expression.

Literature Review

Over the past decade, the scientific literature on the application of AI in education has grown rapidly. Chen and co-authors systematized the main directions of AI in education—intelligent tutoring systems, adaptive platforms, automated assessment and learning analytics—and showed that these technologies are a powerful means of individualizing instruction [1]. Zawacki-Richter and colleagues, in a systematic review of AI applications in higher education, noted that the bulk of the research focuses on adaptive systems and profiling, while the pedagogical foundations remain insufficiently studied [2]. Holmes, Bialik and Fadel, providing a comprehensive analysis of the prospects and limitations of introducing AI into education, argue that the technology delivers results only when it is integrated with pedagogy [3, 4].

The efficiency of intelligent tutoring systems (ITS) is the most extensively studied direction. The meta-analysis by Ma and co-authors, covering 107 effect sizes and more than 14,000 participants, showed that the use of ITS produces a higher result than traditional large-group instruction by an average of $g = 0.42$, and higher than computer-aided instruction by $g = 0.57$ [5]. VanLehn’s analysis established that human tutoring yields an effect of $d = 0.79$ and ITS yields a close $d = 0.71$ -that is, modern AI systems achieve results very near human supervision [6]. Kulik and Fletcher, in an analysis covering 50 studies, showed that in 92 % of the cases in which ITS was applied students outperformed those in the traditional classroom, with a median effect size of 0.66 [7]. The theoretical basis for these results is provided by Bloom’s well-known “two-sigma”

problem: individual (one-to-one) instruction raises the average learner to the top 2 % of the distribution, and AI seeks to reproduce precisely this individual approach at mass scale [8].

Recent studies have also turned their attention to generative AI and chatbots. Ayeni and colleagues, reviewing personalized learning technologies, note that adaptive systems significantly improve achievement by taking into account different learning styles and paces [9]. A meta-analysis covering 31 empirical studies confirms that AI-assisted personalized learning has a stable positive effect on student outcomes [10]. The analysis by Sommer and co-authors, covering the years 2010–2022, showed that adaptive learning systems consistently improve learner outcomes [13]. At the same time, some studies emphasize the context-dependence of the AI effect: in a meta-analysis of U.S. K-12 schools, Leite and colleagues found that ITS produces an overall positive but comparatively moderate effect ($g = 0.271$), and that this effect declines in rural schools [11]. Wu and Yu confirmed, through a meta-analysis, the positive impact of chatbots on achievement, motivation and self-confidence [12].

The literature review shows that AI-based educational tools yield a positive effect compared with traditional instruction in most cases; however, the strength of this effect depends on the type of technology, the educational level, the subject area and the conditions of implementation. Therefore, in assessing efficiency it is advisable to rely not on a single indicator but on a multidimensional approach.

Research Methodology

The study employed systematic-analytical and comparative approaches. In the first stage, meta-analyses and systematic reviews published in 2014-2025 that empirically assessed the impact of AI on learning outcomes were selected. The effect size (Cohen's d or Hedges' g) was adopted as the unit of analysis, since it allows the results of different studies to be compared in a standardized form. In interpreting the effect, Cohen's criterion was applied: 0.2 - small, 0.5 - medium, 0.8 and above - large effect.

In the second stage, the efficiency of AI-based educational systems was systematized according to six key indicators: learning achievement, student engagement (involvement), degree of personalization, coverage (scalability), feedback speed and student satisfaction. These indicators were comparatively assessed under traditional and AI-based learning conditions. The statistical data were generalized on the basis of the effect sizes obtained from the sources; the relative values of the indicators were presented as generalized estimates reflecting the trends reported in the literature. Diagrams and radar charts were used to visualize the data.

Analysis and Results

An AI-based educational system operates as a single architecture composed of interconnected functional modules. Figure 1 presents the generalized structural organization of this system. At the centre of the system lies the AI core, which combines machine-learning, NLP and analytics algorithms and processes student data and learning content. The core controls four main modules: personalized (adaptive) learning, automated assessment, learning analytics and real-time feedback. The

ultimate outcome of these modules is an increase in learning achievement and a saving of teacher time.

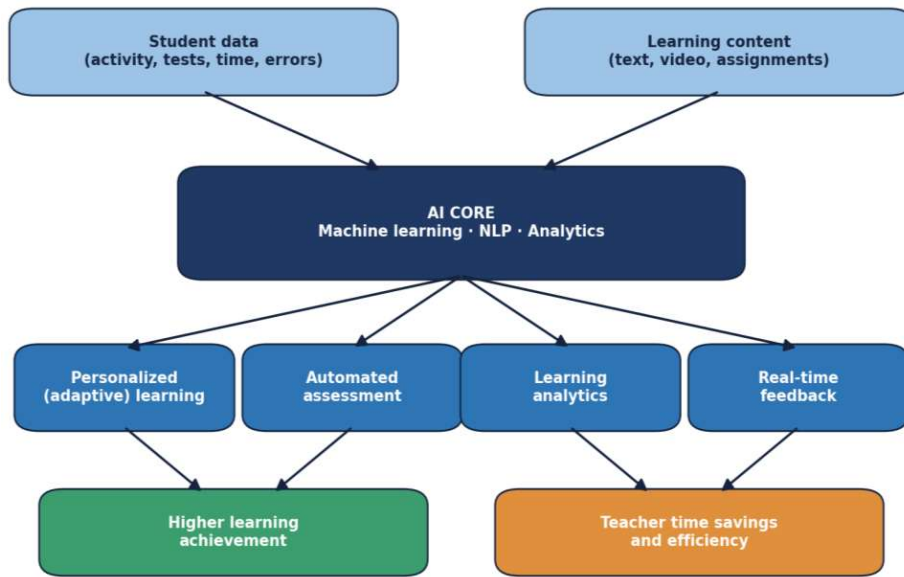


Figure 1. Architecture of an artificial-intelligence-based educational system.

To compare the strength of the impact of different AI technologies on learning outcomes, the effect sizes reported in international meta-analyses were generalized (Figure 2). The results of the analysis show that chatbots and generative-AI tools have the highest effect ($d \approx 1.02$), while the overall impact of AI in education reaches the level of a large effect ($d \approx 0.86$). Intelligent tutoring systems ($g \approx 0.50$) and AI integrated with blended learning ($g \approx 0.50$) produce a medium effect and approach human supervision ($d \approx 0.79$). The most moderate result is observed in the application of ITS at the K-12 level ($g \approx 0.27$), which confirms the dependence of the effect on the educational level.

Table 1 systematizes the main AI technologies, their effect sizes and their sources.

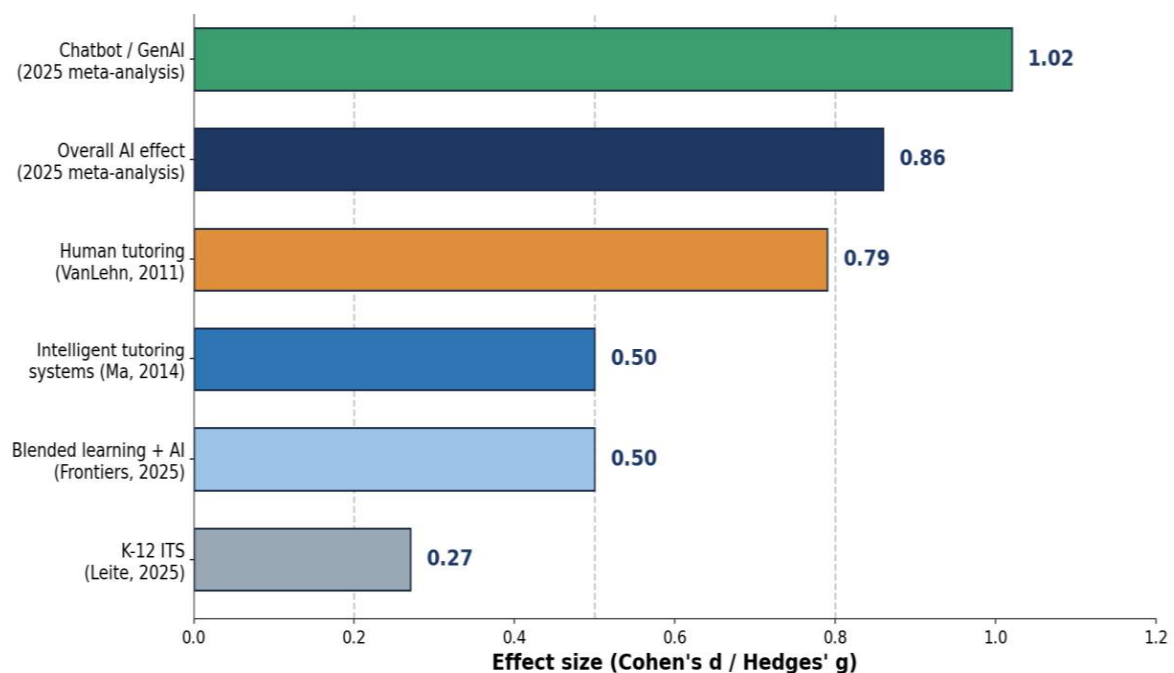


Figure 2. Effect of AI technologies on learning outcomes (based on meta-analyses).

Table 1. Efficiency of AI technologies (based on meta-analyses).

AI technology	Effect size (d / g)	Source
Chatbot / generative AI	≈ 1.02 (large)	2025 meta-analysis [12]
Overall AI effect	≈ 0.86 (large)	2025 meta-analysis [10]
Human tutoring (benchmark)	≈ 0.79 (large)	VanLehn, 2011 [6]
Intelligent tutoring systems (ITS)	≈ 0.50 (medium)	Ma et al., 2014 [5]
Blended learning + AI	≈ 0.50 (medium)	Frontiers, 2025 [14]
ITS (K-12 level)	≈ 0.27 (small–medium)	Leite et al., 2025 [11]

A comparison of the superiority of AI-based education over traditional education across four key indicators is presented in Figure 3. The analysis shows that learning achievement rises on average from 68 % to 84 %, student engagement from 64 % to 83 %, the degree of personalization from 30 % to 90 %, and student satisfaction from 72 % to 88 %. The largest change is observed in the degree of personalization—this confirms that the main advantage of AI lies in its ability to provide each learner with a flexible, individualized pathway.

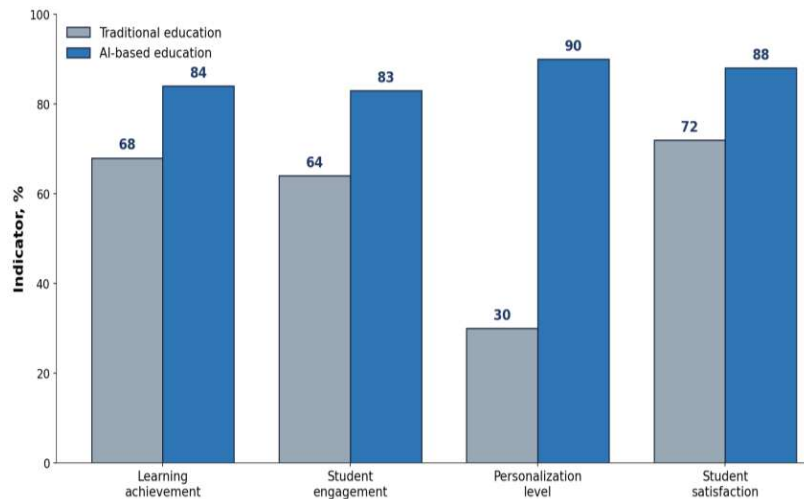


Figure 3. Comparison of traditional and AI-based education indicators.

For a multidimensional assessment of efficiency, a radar analysis was carried out across six indicators (Figure 4).

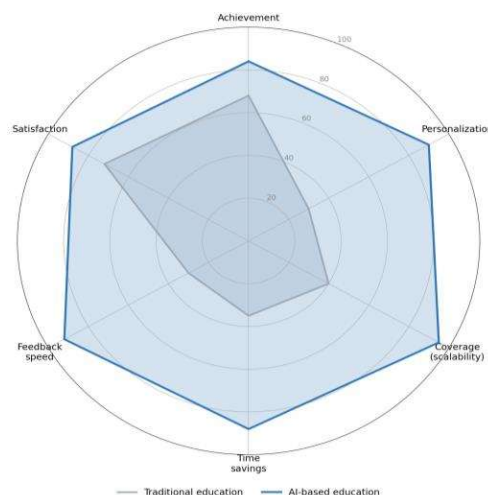


Figure 4. Comparative analysis across efficiency indicators.

The AI-based system surpasses traditional education on all dimensions, with a particularly pronounced difference in coverage (scalability), feedback speed and personalization. This is explained by the ability of AI systems to provide individual attention and rapid feedback to many learners simultaneously-a result that is practically unattainable in a traditional classroom setting.

Table 2 presents a quantitative comparison of the main efficiency indicators.

Table 2. Comparative efficiency indicators of traditional and AI-based education.

Efficiency indicator	Traditional	AI-based	Change
Learning achievement, %	68	84	+16
Student engagement, %	64	83	+19
Personalization level, %	30	90	+60
Student satisfaction, %	72	88	+16
Feedback speed (relative)	low	high	↑↑

According to Bloom's "two-sigma" theory, individual instruction shifts the average learner upward in the distribution [8]. The average effect observed in AI-based systems ($d \approx 0.8$) shifts the distribution of student achievement to the right by approximately 0.8 standard deviations (Figure 5). This means that a student who achieves an average result under traditional conditions moves to the upper part of the distribution under AI-assisted learning. Although this shift is smaller than the two sigmas identified by Bloom, it constitutes a substantial pedagogical gain under conditions of mass education.

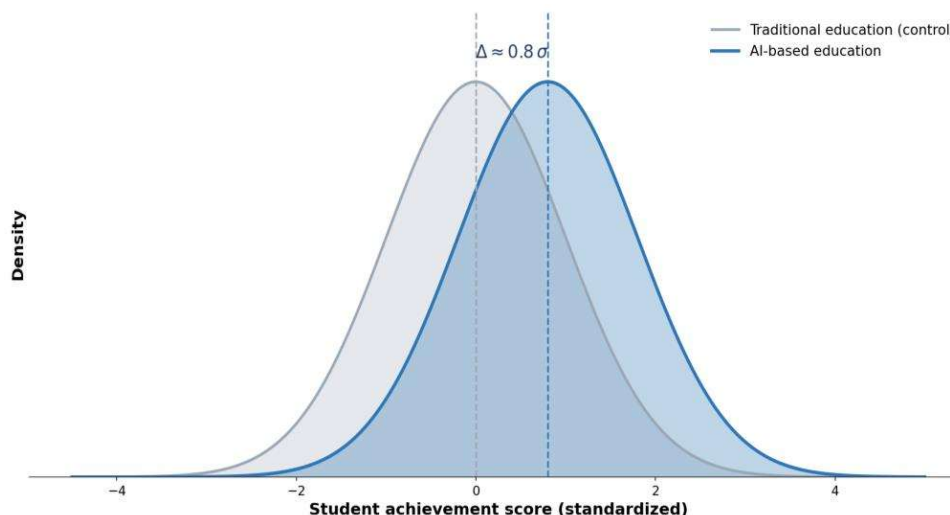


Figure 5. Shift of the student-achievement distribution in AI-based education.

The results obtained are consistent with the literature review and show that the efficiency of AI-based educational systems depends on the following factors. First, the type of technology: generative AI and chatbots yield the highest effect, while it has a stable medium result. Second, the educational level: the effect is higher in higher education and among adult learners, and more moderate in K-12. Third, the implementation model: AI delivers better results when it is applied as a complementary tool (a hybrid model) rather than as a complete replacement for traditional instruction. At the same time, the efficiency of AI is closely linked to pedagogical design, the role

of the teacher and the quality of the data; the technology in itself does not automatically guarantee a high result.

Conclusion

The results of the study showed that artificial-intelligence-based educational systems yield a positive effect ranging from medium to high compared with traditional instruction. The generalized effect size amounts to $d \approx 0.8$, which leads to a substantial shift in the distribution of student achievement. The main advantages of AI are the ability to personalize learning, automate assessment, provide rapid feedback and ensure individual attention on a large scale.

At the same time, the efficiency of AI tools is not universal: it depends on the type of technology, the educational level, the subject area and the implementation model. The highest result is achieved when AI is applied as a hybrid approach that complements traditional pedagogy.

On the basis of the above, the following recommendations are put forward:

- when introducing AI tools in educational institutions, their efficiency should be systematically monitored on the basis of effect size and multidimensional indicators;
- AI should be integrated as a tool that augments rather than replaces the teacher;
- adaptive platforms adapted to national conditions-including Uzbek-language educational content-should be developed;
- methodological training aimed at improving teachers' AI literacy should be strengthened.

In future research, the experimental assessment of the efficiency of AI tools within the educational system of Uzbekistan is regarded as a promising direction.

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DEVELOPING STUDENTS’ SENSE OF SOCIAL RESPONSIBILITY THROUGH A PEDAGOGICAL APPROACH: THE ROLE AND IMPORTANCE OF EXTRACURRICULAR ACTIVITIES IN EDUCATIONAL INSTITUTIONS

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Annotatsiya. Ushbu maqolada ta’lim tashkilotlarida talabalarda (o’quvchilarda) ijtimoiy mas’uliyat hissini rivojlantirishda sinfdan tashqari faoliyatning roli va ahamiyati asoslab berilgan. Unda turli madaniy-ma’rifiy, sport, ko’ngillilik va ijtimoiy loyihalarning talabalarning ijtimoiy faolligi, ma’naviy-axloqiy rivojlanishi, jamoaviy hamkorlik ko’nikmalari hamda fuqarolik mas’uliyatini shakllantirishga ta’siri tahlil qilingan. Tadqiqotda sinfdan tashqari faoliyatni ta’lim jarayoniga integratsiya qilish imkoniyatlari va samaradorligi o’rganilib, uning talabalarning shaxsiy va ijtimoiy rivojlanishini ta’minlashdagi pedagogik imkoniyatlari ochib berilgan.

Kalit so’zlar: talaba, metodologiya, pedagogik yondashuv, ta’lim jarayoni, shaxsga yo’naltirilgan ta’lim, ijtimoiy-madaniy muhit, sinfdan tashqari faoliyat, ijtimoiy faollik, jamoaviy hamkorlik, ta’lim tashkiloti.

Аннотация. В данной статье обосновываются роль и значение внеурочной деятельности в образовательных организациях в развитии чувства социальной ответственности у студентов. Рассматривается влияние

различных культурно-просветительских, спортивных, волонтерских и социальных проектов на формирование социальной активности студентов, их духовно-нравственное развитие, навыков коллективного сотрудничества и гражданской ответственности. В исследовании анализируются возможности и эффективность интеграции внеурочной деятельности в образовательный процесс, а также раскрывается её педагогический потенциал в обеспечении личностного и социального развития студентов.

Ключевые слова: студент, методология, педагогический подход, образовательный процесс, личностно-ориентированное образование, социокультурная среда, внеурочная деятельность, социальная активность, коллективное сотрудничество, образовательная организация.

Abstract. This article substantiates the role and importance of extracurricular activities within educational organizations in developing students' sense of social responsibility. It examines the impact of various cultural-educational, sports, volunteer, and social projects on the formation of students' social activity, spiritual and moral development, collective cooperation skills, and civic responsibility. The study analyzes the possibilities and effectiveness of integrating extracurricular activities into the educational process and reveals their pedagogical potential in fostering students' personal and social development.

Keywords: student, methodology, pedagogical approach, educational process, person-centered education, socio-cultural environment, extracurricular activities, social activity, collective cooperation, educational organization.

Introduction

At present, the education policy of the Republic of Uzbekistan is aimed at nurturing young people as intellectually and morally well-developed, socially active, and responsible citizens who are committed to serving their country and society. As the President of the Republic of Uzbekistan, Shavkat Mirziyoyev, has emphasized: *"Educating young people as comprehensively developed individuals and raising them to become responsible and conscientious citizens is the guarantee of our country's development"* [4]. This statement highlights the growing importance of systematically organizing extracurricular activities within educational institutions. While classroom instruction remains the primary means of imparting academic knowledge, it offers limited opportunities for fostering students' personal development and social responsibility. Consequently, extracurricular activities have become an essential component of the educational process, providing students with practical experiences that contribute to the development of socially responsible attitudes and behaviors.

Literature Review

The sustainable development of society and the future prosperity of the nation depend largely on the younger generation's ability to become socially active and responsible individuals. In the New Uzbekistan Development Strategy, improving the quality of education, strengthening students' civic consciousness, and fostering a sense of social responsibility have been identified as strategic priorities [5]. Accordingly, the

educational process should extend beyond formal classroom instruction to include well-organized extracurricular activities that support students' holistic development.

Extracurricular activities play a significant role in promoting students' personal growth, enriching their social experiences, and cultivating moral and ethical values. Participation in cultural and educational events, community service projects, sports activities, volunteer initiatives, student clubs, and various interest-based organizations enables students to strengthen their sense of social responsibility, develop teamwork and leadership skills, recognize their civic duties, and actively participate in community life [11]. Such activities create authentic learning environments in which students apply theoretical knowledge to real-life situations while developing interpersonal competencies and socially responsible behaviors. Therefore, investigating the role and significance of extracurricular activities in developing students' sense of social responsibility from both theoretical and practical perspectives represents one of the important challenges facing contemporary pedagogical research. The findings of such studies can contribute to improving educational and воспитательный (character-building) practices within educational institutions and identifying effective pedagogical approaches for fostering students' social responsibility.

The theory of socio-cultural activity provides a conceptual framework for understanding students' roles within society and for identifying the knowledge, competencies, and values that influence their professional and personal development. According to Anthony Giddens' theory of structuration, professional identity formation is closely associated with the process of self-identification, or the development of self-awareness, which consists of two interrelated dimensions:

According to Giddens, identity formation in professional development encompasses two interrelated dimensions:

- *Social identity* refers to an individual's awareness of the characteristics shared with others and their sense of belonging to a social group [1].
- *Personal identity* refers to the unique characteristics that distinguish an individual from other people [1].

Independent thinking and creative reasoning constitute an essential process of self-development. Through this process, individuals construct their understanding of themselves and their relationships with the surrounding social environment. Alongside the influence of socialization and the cultural and social context on identity formation, the ability to exercise autonomy and make informed choices represents a crucial factor in developing students' professional and creative potential.

To enhance the effectiveness of extracurricular activities, it is advisable to organize students into small groups consisting of four to seven members. Such group structures strengthen motivation and increase each participant's contribution to collective activities. Within small groups, students maintain mutual encouragement, communicate effectively, achieve success collaboratively, and subsequently transfer these positive experiences into the educational environment.

The extracurricular environment in higher education institutions represents an informal yet stimulating setting for acquiring collective professional experience. This environment requires active collaboration among participants through joint decision-

making, mutual assistance, regular meetings, and cooperation in the implementation of community-based and socially oriented projects. Accordingly, the pedagogical technology of extracurricular activities is grounded in diverse educational paradigms—including inquiry-based, traditional, and critical-situation approaches—and is specifically designed to foster students' sense of social responsibility. From a content-process perspective, this technology consists of a sequential framework comprising orientation within scientific, technological, and socio-cultural educational environments, motivational support, organization of activities, and systematic reflection. The process of modeling extracurricular activities involves identifying the object of the model (the extracurricular activity itself), its subject (pedagogical technology aimed at developing social responsibility), and the conditions required for its successful implementation. From a social perspective, the process of identity formation considers both the individual's sense of responsibility and personal uniqueness. Every action performed by a student during extracurricular activities should therefore be viewed not only as an expression of personal characteristics but also as the product of previous social experiences and interpersonal relationships.

Extracurricular activities create unique opportunities for students to acquire meaningful social experience. Such experiences strengthen individual identity, encourage active engagement with society, and prepare students for future professional responsibilities. The relationships between individual and collective social experiences acquired during extracurricular participation are complex and multidimensional. Consequently, the process of identity formation cannot be understood independently of its broader social context. The social conditions accompanying collective experiences and the relationships that sustain them play a decisive role in shaping students' social responsibility.

Literature Review

In examining the relationship between the individual and the social dimensions of human development, Jaan Valsiner places particular emphasis on the psychological characteristics of the individual [6]. From this perspective, modeling these personal qualities through extracurricular activities is essential for fostering students' sense of social responsibility.

According to the first interpretation, extracurricular activities strengthen the mechanisms through which students develop knowledge and practical competencies. In addition to supporting individual psychological development, these activities facilitate students' socialization as active members of society by enabling them to participate in specific spheres of social life [6]. As a result, a balanced and harmonious relationship is established between the individual and the surrounding social environment.

The second interpretation complements the first by emphasizing the necessity of integrating individual and social dimensions. Within this framework, the external (social) and internal (personal) realities of extracurricular activities become interconnected, creating a new shared reality that contributes to the development of students' social responsibility. This integration is not deliberately imposed but emerges naturally through participation in the educational process [6].

The third interpretation employs the metaphor of “social contagion.” In this perspective, social influences operating within extracurricular activities affect students through indirect mechanisms resembling the transmission of “social viruses” [6]. This metaphor illustrates that no individual living within society remains entirely isolated from social influences. Consequently, the principles of integration, interaction, and social cohesion should be understood not only as pedagogical objectives but also as broader social imperatives. These three interpretations-particularly the final metaphor of social contagion-constitute an important theoretical foundation for the proposed model of developing students’ social responsibility through extracurricular activities. The model encourages students to engage actively in collaborative interactions, personal development, and the establishment of social cohesion within educational communities.

Valsiner’s developmental model further argues that both students and society are active participants rather than passive observers in the process of social experience [6]. Through participation in meaningful activities, students acquire concrete social practices and competencies. Consequently, extracurricular activities become a natural environment for socialization, enabling students to integrate theoretical knowledge with authentic social engagement while cultivating responsible citizenship.

Vygotsky L.S. emphasized that interaction with other individuals plays a decisive role in personality development [7]. According to his sociocultural theory, the external and internal dimensions of human experience cannot be examined independently because they are inherently interconnected. This interdependence is fundamentally grounded in social experience, through which individuals internalize cultural values, social norms, and patterns of behavior. In Vygotsky’s theoretical framework, culture is regarded as the product of human social life and activity. Consequently, understanding the evolution of students’ individual development requires examining the processes of social interaction and direct communication that occur between two or more participants. Learning and development are therefore viewed as socially mediated processes in which knowledge and competencies are constructed through collaborative engagement [10].

The model for developing students’ sense of social responsibility proposed in this study is centered on students’ active participation in practical activities implemented in diverse contexts and settings. Such participation provides opportunities for meaningful engagement in social life while simultaneously contributing to students’ personal growth and professional preparation. Through these experiences, students acquire the competencies, values, and attitudes necessary for responsible citizenship and professional practice. In his research, Etienne Wenger argues that identity is shaped not only through the practices in which individuals participate but also through those from which they remain excluded [8]. From this perspective, identity is not a fixed or static characteristic; rather, it is a dynamic and continuously evolving construct formed through psychological reflection and participation in communities of practice [9].

Students’ attitudes toward social practice, including their perceptions of belonging or non-belonging to particular communities and activities, significantly influence their behavior, values, and worldview. These experiences ultimately contribute to the development of professional identity. A student can therefore be

understood as the product of the accumulated social experiences within the community to which they belong [8]. These experiences, including those shaped by social stratification and broader societal conditions, influence students' social position, interests, aspirations, sources of motivation or exclusion, and the aspects of their identities that receive recognition or remain marginalized.

Taken together, the theoretical perspectives of Jaan Valsiner, Vygotsky L.S., and Etienne Wenger demonstrate the importance of organizing extracurricular activities in ways that enable students to develop self-awareness, strengthen social relationships, and enhance their professional competencies [6-8]. Active participation in diverse contexts of socialization provides students with authentic opportunities to cultivate a sense of social responsibility, develop collaborative and reflective skills, and integrate personal growth with civic engagement. Consequently, extracurricular activities should be regarded as an essential pedagogical mechanism for preparing socially responsible, professionally competent, and civically engaged graduates capable of contributing to sustainable social development

In contemporary higher education, preparing students for specific areas of professional knowledge is achieved not only through formal classroom instruction but also through well-organized extracurricular activities. These activities encompass a wide range of social and professional practices, engaging students in interactive collaboration with their peers as well as with members of the wider community, including non-governmental organizations, public institutions, and diverse social groups. Within this process, communication occupies a central position as a key factor in fostering students' sense of social responsibility. The development of communication culture through extracurricular activities is therefore an essential prerequisite for enhancing students' social competence. By participating in meaningful dialogue, collaborative problem-solving, and community engagement, students acquire the interpersonal skills necessary for responsible participation in both academic and professional environments. The acts of making commitments and expressing well-founded opinions during communication create ethical obligations. Such interactions occur within specific institutional contexts in which both the responsibility to act and the promotion of shared moral values emerge. Consequently, individuals who express particular viewpoints assume responsibility for ensuring that their subsequent actions are consistent with the commitments embodied in their statements. In this way, communication extends beyond the exchange of information to become a mechanism for cultivating ethical responsibility and accountability.

The German philosopher and social theorist Jürgen Habermas argues that achieving mutual understanding among social actors requires the development of universal communicative competencies [2]. According to his *Theory of Communicative Action*, communication serves as the most effective means of reaching rational consensus. Habermas identifies several essential conditions for successful communicative action [3]:

- statements should be truthful and factually valid;
- speakers should sincerely believe in the arguments they present;
- viewpoints expressed through language should remain open to rational discussion and mutual acceptance within the communicative process.

Accordingly, communicative discourse and public statements must possess an ethical dimension because they establish the foundations of trust, mutual respect, and cooperation within social relationships. Communication is therefore not merely a linguistic activity but also a moral practice that supports responsible civic participation. Within extracurricular activities, it is essential to encourage students to analyze issues of communication and cooperation from multiple perspectives while adhering to a coherent system of ethical principles. Establishing clear standards of respectful, responsible, and constructive communication should serve as the starting point for organizing extracurricular interactions. Such standards promote an inclusive educational environment in which students learn to express their views responsibly, appreciate diverse perspectives, resolve conflicts through dialogue, and develop the communicative competencies necessary for socially responsible professional practice. These standards serve several important pedagogical functions. They expand students' understanding of professional conduct, provide benchmarks for educational and character-development activities, and establish a common language between students and prospective employers. However, communication standards alone cannot comprehensively define a highly qualified professional; rather, they represent only one dimension of the broader process of developing professional competence. Within extracurricular activities, communication and collaboration occupy a central position in fostering students' sense of social responsibility. As Jürgen Habermas argues, the achievement of consensus through ethical communication is fundamental not only to professional competence but also to students' personal development [2]. Respectful dialogue, shared decision-making, and adherence to ethical principles enable students to develop responsibility, accountability, and mutual trust while strengthening their capacity for constructive social interaction.

Analysis and Results

One of the core components of the proposed model for developing students' sense of social responsibility is the *value domain*. This domain is closely associated with the ability to distinguish right from wrong, understand and adhere to ethical norms, and consciously accept moral responsibility for one's actions. The following principles constitute the foundation of this value system:

- the ability to master appropriate processes and methods;
- responsibility and accountability;
- honesty and integrity;
- objectivity and impartiality.

The proposed model expects students to uphold values such as safety, social and environmental sustainability, respect for human dignity, compliance with legal and institutional regulations, cooperation, and mutual support. Through participation in extracurricular activities, these values are internalized through practical experience, enabling students to acquire socially meaningful knowledge and develop responsible patterns of behavior. Another fundamental dimension of the model is the promotion of *justice and solidarity*. These values encourage students to empathize with others, respect their rights, and ensure fairness in interpersonal relationships [14]. Within



social practice, a fair approach involves creating equal opportunities for all participants, treating individuals with respect, and fostering inclusive collaboration.

Extracurricular activities constitute a pedagogical process that extends beyond formal classroom instruction and encompasses spiritual and educational programs, community engagement, sports and cultural events, volunteer initiatives, and scientific and innovative activities [13]. Their principal components include:

Spiritual and educational activities, including literary evenings, commemorative events dedicated to historical figures, moral education sessions, and roundtable discussions on national, cultural, and religious values [14];

Community engagement activities, such as environmental campaigns, participation in neighborhood development, charitable initiatives, and student-led social projects [12];

Sports and cultural activities, including athletic competitions, arts festivals, and educational visits to museums, theaters, and cultural institutions;

Volunteer service, involving support for orphanages, nursing homes, and other social welfare institutions [12];

Scientific and innovative activities, including student conferences, start-up projects, research clubs, and debate societies [15].

These activities not only broaden students' knowledge but also contribute significantly to their social development by cultivating socially responsible attitudes, civic awareness, and ethical behavior. The principal pedagogical and psychological functions of extracurricular activities include:

Developing responsibility, enabling students to recognize and accept responsibility for their decisions and actions [11];

Strengthening teamwork, by cultivating collaboration, collective decision-making and shared responsibility [15];

Fostering civic engagement, through active participation in community life and a deeper awareness of civic duties and national responsibility [12];

Promoting value-based education, by encouraging the practical application of national and universal human values [14];

Enhancing psychological resilience and leadership, by strengthening students' self-confidence, initiative, adaptability, and leadership capacities [15].

Psychological research indicates that students who actively participate in extracurricular activities demonstrate higher levels of intrinsic motivation and a stronger commitment to socially beneficial behavior [11]. These outcomes contribute directly to the natural development of social responsibility and civic consciousness.

In recent years, Uzbekistan's higher education system has significantly expanded extracurricular opportunities. Within the framework of the "Youth - Our Future" program, students have been actively involved in social projects and entrepreneurial start-up initiatives. The *Centers for Spirituality and Enlightenment* regularly organize educational and moral development programs [14], while university-based clubs and societies-including debate clubs, theater groups, innovation centers, and research associations-promote students' social participation and leadership [15]. Likewise, sports and cultural festivals encourage healthy lifestyles while strengthening responsibility toward peers and the wider community. Environmental initiatives,

including tree-planting campaigns and recycling projects, foster students' awareness of environmental stewardship and sustainable development. These experiences demonstrate that extracurricular activities contribute not only to students' academic development but also to the formation of socially responsible individuals. Within Uzbekistan's educational system, extracurricular activities have become an effective mechanism for strengthening both personal and collective responsibility, reinforcing civic identity, promoting national and universal human values, and preparing students to recognize and fulfill their responsibilities toward society. Consequently, extracurricular activities should be regarded as an indispensable component of higher education, serving as an effective pedagogical instrument for developing socially responsible, ethically conscious, and professionally competent graduates.

Conclusion

In conclusion, extracurricular activities within Uzbekistan's education system serve as an important pedagogical instrument for fostering students' social development and strengthening their sense of social responsibility. While classroom instruction primarily focuses on the acquisition of theoretical knowledge, extracurricular activities provide opportunities to apply that knowledge in authentic social contexts, thereby enabling students to develop civic awareness, social engagement, and a stronger sense of responsibility toward society.

Through participation in extracurricular activities, students:

- develop both personal and collective responsibility;
- cultivate respect for national and universal human values;
- become more actively integrated into the social environment;
- strengthen their civic consciousness and increase their willingness to participate actively in community life.

In particular, spiritual and educational programs, community-based initiatives, sports and cultural activities, and volunteer projects not only enhance students' sense of responsibility but also contribute to their holistic personal development. Consequently, extracurricular activities should be systematically expanded and continuously improved through evidence-based pedagogical approaches within higher education institutions. Their integration into educational practice represents an essential strategy for preparing socially responsible, ethically aware, and professionally competent graduates capable of contributing to the sustainable development of society.

To further strengthen the development of students' social responsibility through extracurricular activities, the following recommendations are proposed:

- A specialized methodological framework should be developed for planning and implementing extracurricular activities explicitly aimed at fostering students' social responsibility.
- Student participation in volunteer and community service activities should be institutionalized and systematically expanded within higher education institutions.
- Each educational institution should introduce a *Student Social Engagement Index* to assess students' levels of social participation, civic responsibility, and community involvement.



- The evaluation of extracurricular activities should extend beyond measuring participation rates and instead incorporate indicators of social impact, community benefit, and students' personal and civic development.

Implementing these recommendations will contribute to enhancing the educational value of extracurricular activities and strengthening their role as an integral component of student development. By promoting active citizenship, ethical responsibility, and social engagement, higher education institutions can better prepare graduates to address contemporary societal challenges and contribute meaningfully to national and global sustainable development goals.

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Section 2. MODERN PROBLEMS OF TECHNICAL SCIENCES

UDC: 681.5, 519.7

DEVELOPMENT OF INTELLIGENT DECISION-MAKING MODELS BASED ON FORMAL LANGUAGES AND PETRI NETS FOR COMPLEX SYSTEM ASSESSMENT AND OPTIMIZATION

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Annotatsiya. Ushbu maqolada formal tillar va Petri tarmoqlari yordamida boshqariladigan tizimlar uchun matematik modellar, algoritmlar hamda dasturiy platforma taqdim etilgan. Taklif etilgan yondashuv formal tillar nazariyasi, Petri tarmoqlariga asoslangan boshqaruv mexanizmlari va parallel bajarilish strategiyalarini birlashtirib, formal tizimlarning generativ va hisoblash xususiyatlarini tahlil qilish imkonini beradi. Ko'p to'plamlar (multiset) algebrasi va belgilangan (labeled) Petri tarmoqlari asosida matematik modellar ishlab chiqilgan bo'lib, ular qadamli (step), ko'p qadamli (multistep) va maksimal qadamli (maximal-step) bajarilish rejimlarini qo'llab-quvvatlaydi. Tajriba natijalari shuni ko'rsatadiki, maksimal parallel ishga tushirish strategiyasi hosila daraxtining (derivation tree) o'rtacha chuqurligini taxminan 34 % ga kamaytiradi va shu orqali holatlar fazosini o'rganish hamda formal tahlil samaradorligini oshiradi. Birgalikda foydalaniladigan resurslarga parallel murojaat qilish natijasida yuzaga keladigan bloklanish (deadlock) holatlarini bartaraf etish uchun konfliktlarni hal qilish mexanizmi taklif etilgan. Olingan natijalar ushbu yondashuvning parallel hisoblash jarayonlarini modellashtirish va formal tillar oilalarining ifodalash quvvatini tahlil qilishda samarali ekanligini tasdiqlaydi.

Kalit so'zlar: *Petri tarmoqlari, formal tillar, Petri tarmoqlari bilan boshqariladigan grammatikalar, parallel hisoblashlar, parallel va taqsimlangan tizimlar, multito'plamlar algebrasi, hosila daraxtlari, tillar ierarxiyasi, boshqariladigan qayta yozish tizimlari, dasturiy platforma, matematik modellashtirish.*

Аннотация. В данной статье представлены математические модели, алгоритмы и программная платформа для формальных языков и систем, управляемых сетями Петри. Предложенный подход объединяет теорию формальных языков, механизмы управления на основе сетей Петри и стратегии параллельного выполнения для анализа порождающих и вычислительных свойств формальных систем. Разработаны математические модели на основе алгебры мультимножеств и маркированных сетей Петри, поддерживающие режимы пошагового (step), многократного пошагового (multistep) и максимально-параллельного (maximal-step) выполнения.

Экспериментальные результаты показывают, что стратегия максимально-параллельного срабатывания переходов уменьшает среднюю глубину дерева вывода примерно на 34 %, что повышает эффективность исследования пространства состояний и формального анализа. Для устранения ситуаций взаимной блокировки (deadlock), возникающих при одновременном доступе к общим ресурсам, предложен механизм разрешения конфликтов. Полученные результаты подтверждают эффективность предложенного подхода для моделирования параллельных вычислительных процессов и анализа выразительной мощности семейств формальных языков.

Ключевые слова: *Сети Петри, формальные языки, грамматики, управляемые сетями Петри, параллельные вычисления, параллельные и распределённые системы, алгебра мультимножеств, деревья вывода, иерархия языков, регулируемые системы переписывания, программная платформа, математическое моделирование.*

Abstract. This paper presents mathematical models, algorithms, and a software framework for formal languages and systems controlled by Petri nets. The proposed approach integrates formal language theory, Petri-net-based control mechanisms, and parallel execution strategies to analyze the generative and computational properties of formal systems. Mathematical models based on multiset algebra and labeled Petri nets are developed to support step, multistep, and maximal-step execution modes. Experimental results demonstrate that the maximal parallel firing strategy reduces the average derivation-tree depth by approximately 34%, thereby improving the efficiency of state-space exploration and formal analysis. A conflict-resolution mechanism is introduced to eliminate deadlock situations arising from concurrent access to shared resources. The obtained results confirm the effectiveness of the proposed approach in modeling concurrent computational processes and analyzing the expressive power of formal language families.

Keywords: *Petri nets, formal languages, Petri-net-controlled grammars, parallel computation, concurrent systems, multiset algebra, derivation trees, language hierarchy, regulated rewriting systems, software framework, mathematical modeling.*

Introduction

The rapid development of parallel and distributed computing systems has led to a significant increase in the complexity of modern computational environments. Under such conditions, the formal and mathematically precise description of concurrent processes, the efficient management of their states, and the in-depth analysis of parallel execution mechanisms have become among the most pressing scientific problems. Therefore, the importance of formal methods based on rigorous mathematical approaches for modeling complex systems is steadily increasing.

Although Petri nets are widely used as a powerful mathematical tool for the formal representation of parallel and asynchronous systems, there is a growing need to develop new types of generative models through their integration with formal language theory.

In particular, grammar-controlled Petri systems for parallel generation of formal languages have not yet been fully explored and require further in-depth investigation.

In recent years, the theoretical study of formal language processing has attracted considerable attention worldwide. Petri nets provide a powerful graphical and mathematical formalism for modeling the states of parallel and distributed systems, including resource allocation and synchronization mechanisms. In particular, Petri-net-based models allow formal grammars to be combined with sophisticated control strategies through the execution of parallel production rules. Such an approach facilitates the formal analysis of complex systems, including parallel computing environments, workflow management systems, communication protocols, and multicore architectures.

Within this framework, mathematical models of formal languages and systems governed by Petri nets have been developed, and their generative and computational properties under parallel execution have been investigated. Special attention has been given to the effects of step, multistep, maximal-step, and maximal-multistep execution modes on language generation. In addition, new approaches for constructing hierarchies of formal language families have been proposed.

The relevance of this research is also supported by the Decree of the President of the Republic of Uzbekistan dated October 21, 2019, No. PF–5850 “On measures to radically increase the prestige and status of the Uzbek language as a state language,” which sets the task of ensuring the proper representation of the state language in information and communication technologies, particularly on the global internet, as well as the creation of software products in the Uzbek language. This dissertation contributes, to a certain extent, to the implementation of the objectives outlined in this legal and regulatory document.

Furthermore, the Action Strategy for the Further Development of the Republic of Uzbekistan for 2017–2021 defines tasks such as the development of national content, the creation and promotion of modern information resources and multimedia products in the state language that meet the needs of education, science, and youth, as well as the widespread implementation of information and communication technologies.

Currently, the rapid development of information and communication technologies, artificial intelligence, cloud computing, and parallel and distributed systems has significantly increased the demand for formal modeling of complex computational processes. Modern computing systems exhibit parallel, concurrent, and asynchronous characteristics, which makes them difficult to fully describe using classical mathematical models. Therefore, the creation of new mathematical frameworks that formally represent distributed systems and concurrent computation processes remains one of the most important scientific challenges.

The following state documents determine the relevance of the topic: The Resolution No. PQ-358 of the President of the Republic of Uzbekistan, dated October 14, 2024, entitled “On the Approval of the Strategy for the Development of Artificial Intelligence Technologies until 2030,” sets forth priority goals and objectives aimed at creating favorable conditions for the implementation of artificial intelligence technologies in industry, engineering, and economic sectors, ensuring the country’s integration among the world’s leading nations utilizing AI technologies, as well as

further increasing and improving the volume of software products and provided services [1, 2].

Petri nets have emerged as a powerful formalism in the theory of formal language processing, providing both a rigorous theoretical foundation and an effective framework for modeling the states of parallel and distributed systems. They enable the graphical and mathematical representation of resource allocation, synchronization, and exchange among system components. In particular, Petri nets facilitate the integration of formal grammars with advanced control mechanisms by supporting the execution of parallel rules and concurrent processes. This capability allows for the formal analysis of complex computational systems, including parallel computing environments, workflow management systems, communication protocols, and multicore processing architectures.

Within this context, mathematical models of formal languages and systems governed by Petri nets have been developed, and their generative and computational capabilities under parallel execution have been investigated. Special attention has been devoted to examining the influence of step, multistep, maximal-step, and maximal-multistep execution modes on formal language generation. Furthermore, novel approaches have been proposed for establishing and analyzing the hierarchy of formal language families generated by Petri-net-controlled systems, thereby contributing to a deeper understanding of their expressive power and computational characteristics [2, 3].

The main objective of this research is to develop mathematical models, interpretation algorithms, and a set of software tools based on formal language and automata theory [3, 4] for analyzing and adequately assessing students' textual responses and knowledge levels in natural and programming languages within modern artificial intelligence-based e-learning platforms.

The solution of this problem requires constructing a mathematical model, discretizing it using numerical methods, and implementing it in the form of software systems. According to the form of production rules, grammars are divided into two main classes: context-free grammars (where only one nonterminal is replaced) and context-sensitive grammars (where substrings containing at least one nonterminal are replaced). Context-free grammars possess elegant mathematical properties and are widely applied in practical problems, including the classification of programming languages, compiler construction, and the structural description of markup languages such as HTML and XML.

Literature Review

The fundamental foundations of formal language theory and Petri net theory can be traced to the pioneering works of Noam Chomsky, Stephen Kleene, and Carl Adam Petri. Their contributions established the theoretical basis for the study of formal languages, automata, and concurrent systems. Subsequently, extensive research on Petri-net-controlled grammars and regulated rewriting systems has been conducted by researchers such as Jürgen Dassow, Shukhrat Turaev, Manfred Kudlek, Manfred Jantzen, Rüdiger Stiebe, Georg Zetsche, and many others, significantly advancing the theoretical framework of language generation and computational models.

In Uzbekistan, a number of studies on the development of mathematical models and algorithms have been carried out by researchers including Malik Aripov, A. Po‘latov, M. Musayev, N. Ravshanov, B.B. Elov, J.X. Djumanov, and O‘. Bekbayev. Their work has focused on the development and enhancement of computational models, the theoretical and practical aspects of language models (including statistical and neural approaches), as well as addressing key challenges in computer-based modeling through systematic scientific investigations [2, 5].

Within the theory of Petri net languages, substantial attention has been devoted to labeled Petri nets, firing sequences, and the concept of generative hierarchies. Furthermore, the effects of step and multistep transition strategies on formal language generation have been extensively investigated, providing important insights into the expressive and computational capabilities of Petri-net-based language models. These research directions necessitate the systematic development of computer-oriented mathematical models within the field of computational linguistics, as well as further studies on the processing of formal language rules. In addition, they require the identification and refinement of grammatical and linguistic rules in formal-language texts and the construction of linguistic databases necessary for software tools developed on the basis of linguistic-mathematical models and algorithms [3, 7].

An analysis of existing scientific research indicates that the development of models, algorithms, and software systems for parallel and concurrent grammatical processing in formal languages based on Petri-net firing sequence models is aimed precisely at addressing this research gap. Such studies contribute to advancing the theoretical foundations and practical applications of Petri-net-controlled formal language systems.

Research Methodology

In the AI-based description of natural languages, concepts such as formal definitions, mathematical models, grammar algorithms, and software tools are introduced. The simulation parameters of the labeled-step Petri net are summarized. During the execution of concurrent transitions, token flows were dynamically calculated, allowing the state evolution and resource distribution processes within the system to be analyzed quantitatively. The classical architecture is formally defined using multiset algebra together with an initial marking. To ensure parallelism during the derivation process, several operational execution modes have been defined and mathematically modeled [2, 7].

$$PN = (P, T, F, W, \mu_0)$$
$$\mu_{k+1} = \mu_k + C \cdot \vec{u}_k$$

Step mode (s). Multiple transitions may be enabled and fired simultaneously, provided that their total resource consumption does not exceed the available marking. Formally, the following condition must hold:

$$\sum_{t \in U} W(p, t) \leq \mu(p).$$

Multistep mode (m). A transition rule may be applied multiple times within a single derivation step, allowing a multiset of transitions to be executed concurrently.

Maximal Step mode (n). A maximal set of enabled transitions is fired simultaneously. In this mode, no additional transition can be included in the firing set without violating the enabling conditions imposed by the current marking. These execution modes provide different levels of concurrency and resource utilization, enabling a comprehensive analysis of the generative and computational behavior of Petri-net-controlled formal systems. Experimental evaluations demonstrated that the maximal parallel firing strategy decreased the average derivation-tree depth by 34%, thereby substantially improving the efficiency of state-space exploration and formal analysis in parallel computational systems.

In addition, the proposed conflict-resolution mechanism, addressing concurrent access of asynchronous processes to shared resources, effectively eliminated deadlock situations, yielding a deadlock probability of zero under the considered execution model. By integrating experimental evidence with established theoretical results, a comprehensive hierarchy of language families generated by sequential and concurrent Petri-net-controlled grammars was constructed. The resulting hierarchy formalizes the inclusion relationships among these language classes and provides a unified representation of their generative capabilities.

Within the graphical representation of the hierarchy, upward-oriented links denote strict or non-strict inclusion relations between language families, represented by $\subset$ and $\subseteq$, respectively.

Mathematical and functional characterization of the hierarchical chain.

1. *Classical foundation and base layer.* At the lowest level of the hierarchy lie the classes of finite languages (FIN) and context-free languages (CF). Experimental results indicate that when context-free grammars are embedded into either sequential or Petri-net-controlled computational frameworks, their computational power preserves at least the expressive capacity of the classical CF class. Thus, the context-free language family serves as the fundamental basis of the proposed hierarchy.

2. *Concurrent control branch (sCF, mCF, nCF).* When context-free grammars operate under concurrent execution semantics, including step (s), multistep (m), and maximal-step (n) modes, their generative capacities become mutually equivalent, forming a unified language family:

$$PN = sCF = mCF = CF$$

Moreover, this family is strictly more expressive than the classical context-free language class.

$$CF \subset sCF$$

Since, the concurrent execution of production rules enables the generation of non-linear and highly parallel structures that cannot be represented within the conventional sequential derivation framework.

3. *Equivalence of integrated petri nets and regulated grammars (rgCF).* One of the central theoretical contributions of the hierarchy is the proof that the class of languages generated by concurrently controlled grammars, denoted by rgCF, is computationally equivalent to several well-established classes of regulated rewriting systems, including matrix grammars, regularly controlled grammars, and vector (or valence) grammars:

$$rgCF = PN - CF = MAT = rC = pV$$

This equivalence constitutes a fundamental convergence point between sequential and concurrent control mechanisms, demonstrating that distinct control paradigms ultimately possess the same generative power despite differences in their operational semantics.

4. *Lambda rules and turing completeness (RE)*. Allowing Petri-net transitions to employ lambda productions (λ -rules) substantially increases the expressive power of the system. Under this extension, the language families

$$PN_{\lambda} - CF(yoki\ MAT_{\lambda}, rC_{\lambda})$$

are obtained, exhibiting significantly enhanced computational capabilities.

At the top of the hierarchy resides the class of recursively enumerable languages (RE), which corresponds to the full computational power of Turing machines. Consequently, these language families achieve Turing completeness, representing the highest level of expressive and computational capability within the hierarchy.

Implications of the Language Hierarchy. The resulting Hierarchy of Language Families demonstrates that the inherently concurrent nature of Petri nets provides substantial computational advantages over purely sequential grammatical mechanisms, particularly in terms of reducing derivation-tree depth and improving the efficiency of language generation and state-space exploration.

However, despite these operational advantages, the hierarchy reveals that concurrent and sequential control paradigms converge to equivalent mathematical language classes at higher levels of expressiveness, such as MAT and rC. This result confirms that the proposed software framework and its parallel algorithms are capable of processing and generating complex sequential language structures within a parallel execution environment without any loss of information or expressive power (see Figure 1).

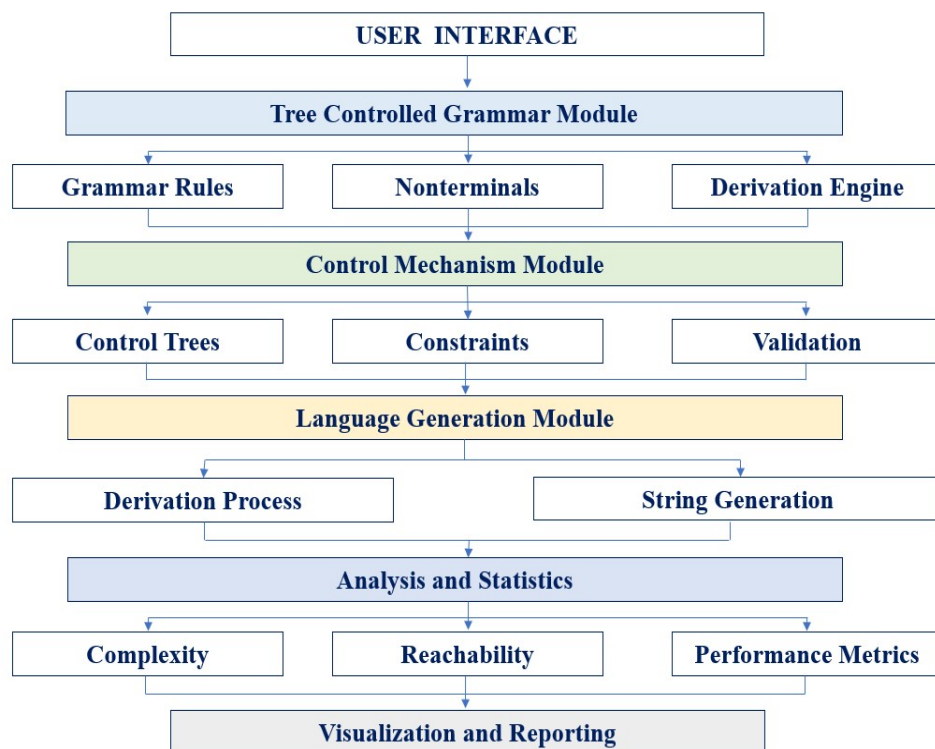


Figure 1. Architecture of the software package for modeling and analysis of tree controlled grammars.

The core component of the software package is the Tree Controlled Grammar Module, which provides data structures for representing grammar symbols, production rules, derivation trees, and control mechanisms. This module implements the formal definitions introduced in previous chapters and serves as the computational kernel of the system (see Figure 2).

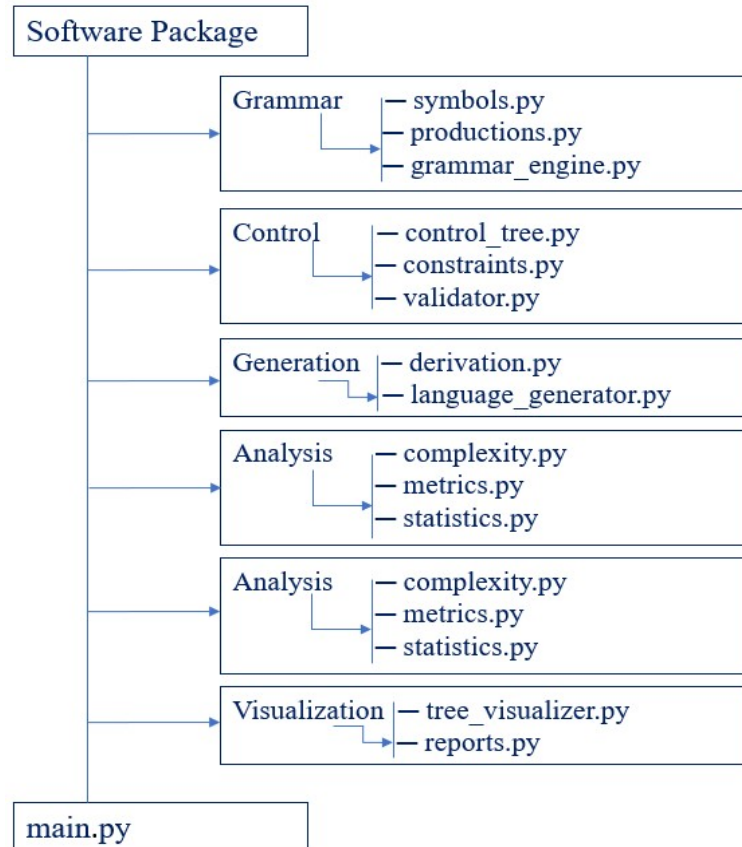


Figure 2. Internal modular structure of the Python-Based Software System.

Analysis and Results

An improved mathematical model for the description and analysis of formal language systems controlled by Petri nets through an integrated framework has been developed. A mathematical model and computational algorithms for generating formal languages with respect to reachability and stability properties have been proposed and developed. Improved algorithms have been designed to enhance and evaluate the accuracy, efficiency, and reliability of computational processes.

The operating principles, functional architecture, and system requirements of an object-oriented software package based on a modular architecture have been developed. Based on the above definitions, several research problems are addressed. These include constructing mathematical models and production-rule systems based on formal languages and context-free grammars for modeling students' textual concepts and error dynamics in intelligent learning environments. Numerical-logical algorithms based on deterministic and nondeterministic finite automata (DFA/NFA) are designed for scanning open-ended textual and programming responses, constructing parse trees, and minimizing syntactic errors.

Furthermore, software architectures are developed using object-oriented and functional programming paradigms to implement hybrid environments integrating Large Language Models with formal parsing technologies. Computational experiments are carried out to evaluate time complexity, memory efficiency, and assessment accuracy using real educational datasets.

Conclusion

The scientific novelty of the research is characterized by several conceptual and algorithmic contributions. A new mathematical model has been proposed for evaluating student responses not through simple keyword matching but through semantic interpretation using context-free formal grammars. An adaptive recommendation algorithm has been developed to identify the causes of syntactic and logical errors in textual responses and source code using finite automata and regular expressions.

Additionally, a generative mechanism has been proposed for dynamically constructing formal rule sets and assessment criteria based on the subject content or examination tasks defined by instructors. A hybrid software architecture integrating large language models and deterministic formal language theory has also been developed to analyze open-text semantics with high precision while filtering hallucinations generated by neural networks. As a result, a formal mathematical model based on the hierarchy of context-free languages, together with the functional and structural architecture of the developed software system, has been proposed for objective semantic analysis in student knowledge assessment systems. Experimental results confirmed the adequacy, computational efficiency, and practical applicability of the proposed approach.

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UDC: 661, 661.5, 628.5

ECOLOGICAL RESOURCE-SAVING TECHNOLOGY FOR PROCESSING AMMONIUM PHOSPHATE SEDIMENT SLUDGE

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Annotatsiya. Maqolada monoammoniyfosfat ishlab chiqarish jarayonida ekstraksiya fosfor kislotasini ammiak bilan neytrallaganda hosil bo'ladigan ammoniyfosfatli cho'kindi shlam tarkibidagi P_2O_5 ni natriy karbonat yoki natriy gidroksidi ta'sirida ajratib olish hamda sanoat ahamiyatiga ega texnik natriy tripolifosfat ($Na_5P_3O_{10}$) mahsulotini olish jarayoni tadqiq etilgan. Tadqiqot ob'ekti sifatida tarkibida 25,47% P_2O_5 , 8,55% CaO, 3,23% MgO, 1,42% Fe_2O_3 , 1,46% Al_2O_3 tutgan fosfatli cho'kindi shlam olingan. Jarayonga ta'sir etuvchi texnologik ko'rsatkichlar ta'siri aniqlangan: jarayon harorati – 85-95°C, t – 60-75 daqiqa, pH = 6,5-6,7, Q:S nisbati 1:4÷5 da P_2O_5 ning ajralish darajasi 71,51-72,95% gacha yetishi va ajratib olingan eritmadan standart talablariga javob beradigan natriy tripolifosfat olish mumkinligi aniqlandi. Taklif etilayotgan texnologiya P_2O_5 yo'qotishlarini mavjud usulga nisbatan kamaytirish, fosfat shlamining atrof-muhitga ta'sirini kamaytirish, ishlab chiqarishning amalda chiqindisiz, resurstejamkor texnologiyasini ishlab chiqarish imkonini beradi.

Kalit so'zlar: monoammoniyfosfat, fosfatli cho'kindi shlam, P_2O_5 ning ajralish darajasi, resurstejamkor texnologiya.

Аннотация. В статье исследован процесс извлечения P_2O_5 , содержащегося в аммонийфосфатном осадочном шламе, который образуется при нейтрализации экстракционной фосфорной кислоты аммиаком в процессе производства моноаммонийфосфата, под действием карбоната натрия или гидроксида натрия, а также процесс получения имеющего промышленное значение технического триполифосфата натрия ($Na_5P_3O_{10}$). В качестве объекта исследования был взят фосфатный осадочный шлам, содержащий 25,47% P_2O_5 , 8,55% CaO, 3,23% MgO, 1,42% Fe_2O_3 и 1,46% Al_2O_3 . Определено влияние технологических показателей на процесс: при температуре процесса 85-95°C, t = 60-75 мин, pH = 6,5-6,7 и соотношении Т:Ж 1:4÷5 степень извлечения P_2O_5 достигает 71,51-72,95%, и установлено,

что из выделенного раствора можно получить триполифосфат натрия, отвечающий требованиям стандарта. Предлагаемая технология позволяет снизить потери P_2O_5 по сравнению с существующим способом, уменьшить воздействие фосфатного шлама на окружающую среду и разработать практически безотходную, ресурсосберегающую технологию производства.

Ключевые слова: моноаммонийфосфат, фосфатный осадочный шлам, степень извлечения P_2O_5 , ресурсосберегающая технология.

Abstract. This article studies the process of recovering the P_2O_5 contained in ammonium phosphate sediment sludge - formed when extraction phosphoric acid is neutralized with ammonia during the production of monoammonium phosphate - by means of sodium carbonate or sodium hydroxide, and of obtaining the industrially significant product technical sodium tripolyphosphate ($Na_5P_3O_{10}$). Phosphate sediment sludge containing 25.47% P_2O_5 , 8.55% CaO, 3.23% MgO, 1.42% Fe_2O_3 and 1.46% Al_2O_3 was used as the research object. The influence of the technological parameters affecting the process was determined: at a process temperature of 85-95°C, $t = 60-75$ min, $pH = 6.5-6.7$ and an S:L ratio of 1:4÷5, the degree of P_2O_5 recovery reaches 71.51-72.95%, and it was established that sodium tripolyphosphate meeting standard requirements can be obtained from the recovered solution. The proposed technology makes it possible to reduce P_2O_5 losses compared with the existing method, to reduce the environmental impact of the phosphate sludge, and to develop a practically waste-free, resource-saving production technology.

Keywords: monoammonium phosphate, phosphate sediment sludge, degree of P_2O_5 recovery, resource-saving technology.

Introduction

On an industrial scale, the rational use of raw-material resources and the processing of technogenic waste is a problem of not only technological but also ecological importance. In the production of monoammonium phosphate, when extraction phosphoric acid (EPA) is neutralized with ammonia, a sludge precipitate is formed together with the unreacted monoammoniumphosphate; it consists of $MgNH_4PO_4$, $CaHPO_4$, $AlPO_4$, $FePO_4$ and other sparingly soluble compounds. In these sludge precipitates, 30-40% of the P_2O_5 present in the raw material is lost; besides causing environmental pollution and economic damage, the high content of magnesium, sodium, iron, aluminium and a number of other elements makes it impossible to use them as a mineral fertilizer or for other intended purposes [1-3].

Although a number of works have been carried out worldwide on the processing of phosphate sludge, they are distinguished by the complexity of the processing and by the limited possibilities for using the products obtained [4-6]. The production of alkali-metal phosphates is usually based on the use of extraction or thermal phosphoric acid; however, thermal acid is a very expensive product owing to its energy consumption and is not produced in practice in our Republic. The use of EPA, in turn, requires additional purification processes, since the presence of iron, aluminium, calcium, magnesium and insoluble residues leads both to a decrease in the quality of the finished

product and to a deterioration in the production capacity of the process because of the difficulty of separating the impurities [7-10].

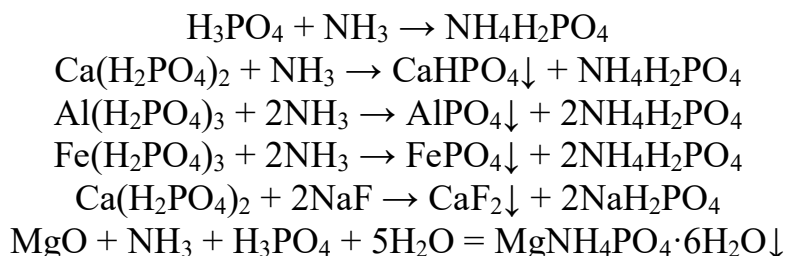
The authors have reported the results of research on the production of trisodium phosphate from ammophos (a commercial product with a P_2O_5 content of at least 46%) in the presence of soda ash and caustic soda [11]. Data are given on the optimal conditions for producing trisodium phosphate from ammonium phosphate, as well as on the ratios of the reagents (soda ash, caustic soda and ammonium phosphate). It was shown that the trisodium phosphate obtained from ammonium phosphate with a P_2O_5 content of at least 18.5% has a high degree of purity, while the mass fraction of water-insoluble particles does not exceed 0.003%. Data are also provided on the possibility of processing gaseous and solid waste into target products (a liquid NPCa fertilizer).

In current industrial practice, the EPA used for the production of monoammonium phosphate requires a complex, multi-stage purification process: the acid is first purified of fluorine, trivalent-metal impurities, calcium and insoluble residues. During purification, up to 30-40% of the P_2O_5 may be lost. In addition, large volumes of recirculating liquids arise in the technological cycle, and their disposal creates certain problems. Therefore, a need has arisen to develop a technologically simple and flexible process that makes it possible to produce alkali-metal phosphates, including phosphate salts.

The aim of this research is to scientifically substantiate the processing of the phosphate sludge - formed during the separation of a MAP solution obtained by neutralizing defluorinated and desulfated EPA with ammonia - into technical sodium tripolyphosphate salt in the presence of sodium carbonate, and to determine the influence of the technological parameters (temperature, time, pH, reagent ratio) on the process efficiency.

Research Methodology

The research object was the sediment sludge used as an intermediate raw material. It is formed during the production of monoammonium phosphate, when partially defluorinated and desulfated EPA is neutralized with ammonia; together with the unreacted monoammonium phosphate it consists of $MgNH_4PO_4$, $CaHPO_4$, $AlPO_4$, $FePO_4$ and other sparingly soluble compounds. The separation of the monoammonium phosphate solution by ammoniation of partially defluorinated and desulfated EPA proceeds according to the following chemical reactions:



After the ammoniation process, the phosphate sludge separated by filtration consists of the phosphate precipitates of calcium, aluminium and iron and of the unreacted monoammonium phosphate. The chemical composition of the two

phosphate sediment-sludge samples taken for the experiments, wt.%: P_2O_5 - 25.47; CaO - 8.55; MgO - 3.23; Fe_2O_3 - 1.42; Al_2O_3 - 1.46; N - 3.54; SO_4 - 0.29; F - 1.17.

In the ammonium phosphate sediment-sludge sample, the P_2O_5 content is 25.47%, which shows that a large part of the phosphate raw material has accumulated in the sediment sludge. The calcium oxide content is 8.55%, magnesium oxide 3.23%, and the iron and aluminium oxides 1.42% and 1.46% respectively; the nitrogen content of 3.54% confirms the presence of partially unreacted monoammonium phosphate in the sediment sludge. The sulfate-ion content is relatively low (0.29%), while fluorine amounts to 1.17%. Because of the large amount of accompanying impurities in this sludge, there are certain limitations to its direct use as a fertilizer; on the other hand, this proves the economic expediency of processing the phosphate sediment sludge.

The phosphate sediment sludge was processed in the presence of sodium carbonate at 85-95°C; this includes the subsequent filtration of the resulting mixture and the processing of the separated sodium phosphate solution into the commercial product sodium tripolyphosphate. The mixture of the sodium carbonate solution at 85-90 °C and the phosphate sludge selected as the research object was maintained at pH = 8.1-8.5.

Analysis and Results

In the experimental work, the influence of the process time, temperature and S:L ratio on the degree of recovery of the phosphorus component of the sludge into the solution was studied.

In the treatment of the phosphate sludge with a sodium carbonate solution, the influence of the process time on the degree of P_2O_5 recovery into the solution was studied over the range from 45 to 110 minutes. The degree of P_2O_5 recovery into the solution was 60.81% at 45 min, 72.95% at 60 min, 74.49% at 75 min, 75.12% at 90 min and 75.36% at 110 min. The data show that at 60-75 min the P_2O_5 recovery reaches 73-75%. With a further increase in time it changed only very slightly (Figure 1).

In the treatment of the phosphate sludge with a sodium carbonate solution, the influence of the process temperature on the degree of P_2O_5 recovery into the solution was studied over the range from 75 to 95°C.

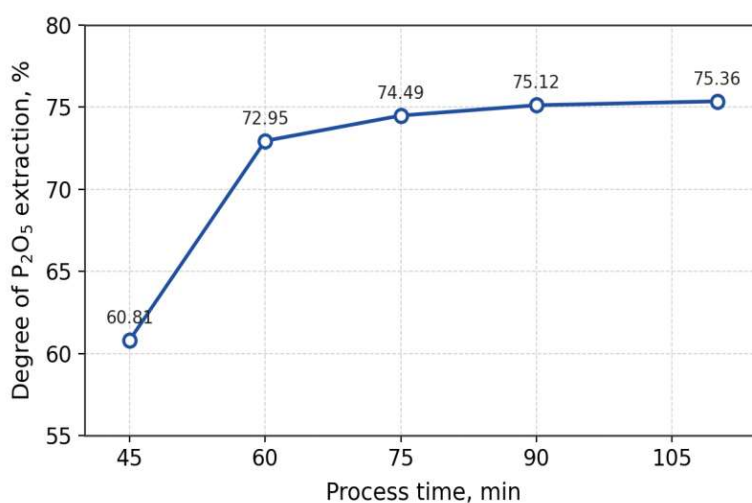


Figure 1. Influence of the process time on the degree of recovery of P_2O_5 from the phosphate sludge into the solution.

The degree of P_2O_5 recovery into the solution was 54.0% at 75°C, 62.23% at 80°C, 69.19% at 85°C, 72.48% at 90°C and 72.95% at 95°C. The data show that the P_2O_5 recovery increases over the temperature range of 75-95°C (Figure 2).

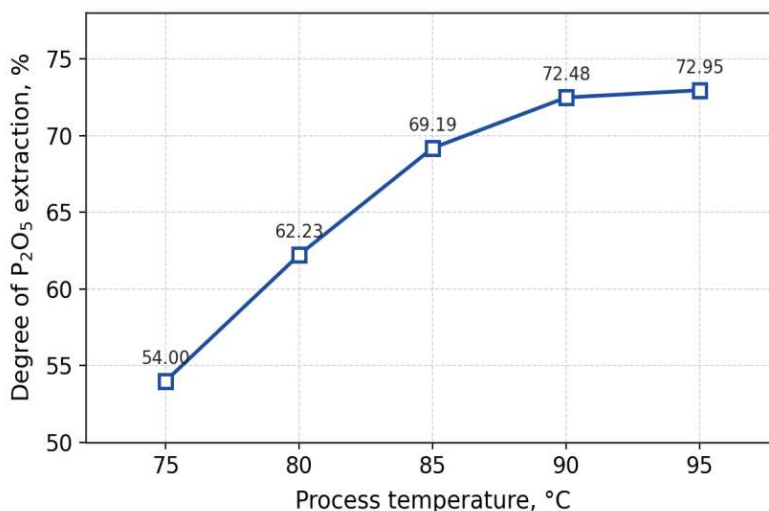


Figure 2. Influence of the process temperature on the degree of recovery of P_2O_5 from the phosphate sludge into the solution.

In the experiments carried out, the S:L ratio was varied from 1:2 to 1:8, and in each case the degree of P_2O_5 recovery (%) and the filtration rate ($kg/m^2 \cdot h$) were determined (Table 1).

Table 1. Influence of the S:L ratio (sediment sludge : Na_2CO_3 solution) on the degree of P_2O_5 recovery and the filtration rate.

№	S:L ratio	Degree of P_2O_5 extraction, %	Filtration rate, $kg/m^2 \cdot h$
1	1:2	55.04	167
2	1:3	66.51	654
3	1:4	71.79	984
4	1:5	72.92	1009
5	1:8	73.20	1123

As the S:L ratio (sludge : Na_2CO_3 solution) changed from 1:2 to 1:8, the degree of P_2O_5 recovery was observed to increase from 55.04% to 73.20%, while the filtration rate was very low at S:L = 1:2 and increased from 654 $kg/m^2 \cdot h$ to 1123 $kg/m^2 \cdot h$ at S:L = 1:3÷8, respectively. From both a technological and an economic standpoint, the optimal values proved to be S:L = 1:4 and 1:5.

The sodium phosphate suspension was maintained at 90-95°C for 90 minutes. By filtration, the insoluble impurities were separated from the suspension; the solution was then evaporated to a thick state and thermally treated at 360°C.

In the product obtained, the P_2O_5 content is 56.5-56.7%, which corresponds to the technical sodium tripolyphosphate standard (minimum 56%), while the Na_2O content is 41.40-41.43%, corresponding to the stoichiometric ratio (the theoretical value for $Na_5P_3O_{10}$ is 41.84%). The content of the remaining compounds is minimal. The degree of transfer of P_2O_5 from the phosphate sludge into this product is 71.51-72.95%. At the

same time, the mass fraction of sodium tripolyphosphate is 96.8%, and the pH of a 1% solution of sodium tripolyphosphate is 9.5-9.6.

Conclusion

When the ammonium phosphate sediment sludge is treated with Na_2CO_3 , the fact that the P_2O_5 recovery does not reach its maximum value can be explained by the limited degree of dissolution owing to the stable phosphorus compounds of Ca and Mg in the precipitate. The optimal technological parameters affecting the process were determined: at a process temperature of 85-95°C, $t = 60-75$ min, $\text{pH} = 8.1-8.5$ and an S:L ratio of 1:4÷5, the degree of P_2O_5 recovery reaches 71.51-72.95%, and it was established that $\text{Na}_5\text{P}_3\text{O}_{10}$ meeting standard requirements can be obtained from the recovered solution. The proposed technology makes it possible to relatively reduce the P_2O_5 losses in the ammonium phosphate sediment sludge formed during the separation of the monoammonium phosphate solution and to develop an ecologically waste-free, resource-saving production technology.

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UDC: 621.9, 669.1

PARAMETRIC STUDY OF CUTTING SPEED, FEED RATE, AND DEPTH OF CUT ON MATERIAL REMOVAL RATE IN MILD STEEL TURNING OPERATIONS

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Annotatsiya. Metalni kesib ishlov berish, ishlab chiqarish sanoatida muhim rol o'ynaydi. Ishlab chiqarilgan, loyihalangan va tayyorlangan mahsulotlar sifatining barqaror o'sishini ta'minlash uchun kesib ishlov berish parametrlari to'liq optimallashtirilishi kerak. Ushbu maqolaning maqsadi — silindrsimon kam uglerodli po'lat materialiga mexanik ishlov berishda kesish tezligi, kesish chuqurligi va uzatish tezligining metall olib tashlash tezligiga ta'sirini tegishli standart usul yordamida baholashdir. Tadqiqot natijasida o'rtacha qiymat 4,26 va standart og'ish 2,31 ekanligi aniqlandi. Olingan ma'lumotlar shuni ko'rsatadiki, metall olib tashlash tezligi kesish parametrlarining ta'siri natijasida keskin o'zgarishlarni namoyon etdi. Surish tezligi metall olib tashlash tezligiga eng katta ta'sir ko'rsatdi — surish tezligi oshgan sari olib tashlash tezligi ham sezilarli va izchil ravishda oshdi. Biroq, kesish asbobining eskirishi bilan bog'liq bo'lgan pasayish ham kuzatildi.

Kalit so'zlar: kam uglerodli po'lat metal, mexanik ishlov berish, metall olib tashlash tezligi, kesish tezligi, kesish chuqurligi.

Аннотация. Резка металла играет важную роль в обрабатывающей промышленности. Для обеспечения устойчивого роста качества производимых, проектируемых и изготавливаемых изделий необходимо полное освоение параметров резания. Цель данной статьи — оценить влияние скорости резания, глубины резания и скорости подачи на скорость удаления металла при механической обработке цилиндрического прутка из мягкой стали с использованием соответствующего стандартного метода. В ходе исследования было получено среднее значение 4,26 и стандартное отклонение 2,31. Полученные данные показывают, что скорость удаления металла претерпевала резкие изменения под влиянием параметров резания. Скорость подачи оказала наибольшее влияние на скорость удаления металла — по мере увеличения скорости подачи скорость удаления значительно и последовательно возрастала. Однако было замечено снижение показателей, обусловленное износом режущего инструмента.

Ключевые слова: прутки из мягкой стали, механическая обработка, скорость съёма металла, скорость резания, глубина резания.

Abstract. Metal cutting constitutes a cornerstone of modern manufacturing, and the systematic optimisation of cutting parameters is essential to ensure continuous advancement in the quality of engineered and fabricated products. The present work seeks to quantify the effects of key machining parameters — namely cutting speed, depth of cut, and feed rate — on the metal removal rate in mild steel cylindrical turning. Statistical analysis of the experimental data produced a mean value of 4.26 and a standard deviation of 2.31. The experimental data demonstrated that the metal removal rate exhibited considerable variability, directly attributable to the combined influence of the applied cutting parameters. The most significant variation in metal removal rate was induced by feed rate, which drove a steady and marked increase in material removal as its magnitude was progressively raised. A notable decline in MRR was subsequently observed, directly linked to the deterioration of the cutting tool edge during machining.

Keywords: *mild steel bar, machining, metal removal rate, cutting speed, depth of cut.*

Introduction

A competitive manufacturing economy is fundamentally sustained by the continuous pursuit of producing high-quality, cost-effective goods through the progressive enhancement of manufacturing processes (Gopalakannan and Senthilvelan, 2014). As nearly one third of engineered products and manufactured goods are attributed to the manufacturing industry, the processes governing their production demand heightened focus, particularly given their classification among the foremost technologies deployed across industrial sectors. Despite notable advancements, the generation of components exhibiting inadequate surface quality remains a persistent and critical challenge confronting modern manufacturing processes (Kant and Sangwan, 2015).

Among the most extensively utilised manufacturing processes, machining — broadly defined as a material removal operation encompassing turning, drilling, grinding, and milling — has played an instrumental role in driving global economic development (Sada, 2018).

The rapid proliferation of technology-driven machining processes has correspondingly intensified the demand for dimensional accuracy, compelling manufacturers to identify and implement optimal cutting parameters that yield the most significant improvements in process performance (Onifade et al., 2017).

Achieving certified standard products necessitates the careful identification and application of appropriate machining parameters alongside their optimised operational values. Given the multiplicity of variables that can be systematically manipulated to influence process output, machining is inherently classified as a multi-input, multi-output system. Gupta and Kumar (2015) advocate the utilisation of an Ishikawa cause-effect diagram for the systematic identification of parameters influencing turned part quality, highlighting that cutting parameters, tool characteristics, environmental factors, and workpiece material constitute the primary determinants of machining output quality.

Ojolo and Ogunkomaiya (2014) contend that a comprehensive understanding of machining processes necessitates a thorough investigation into the influence of input parameters on machining output. Accordingly, the present study aims to quantify the effects of cutting speed, depth of cut, and feed rate on the metal removal rate during the cylindrical turning of mild steel bar stock.

Research Methodology

A lathe machine fitted with a High Speed Steel (HSS) tool of 25° rake angle was employed for the execution of all machining experiments. The workpieces comprised mild steel bars with a diameter of 50 mm and a length of 200 mm. For cylindrical turning, the lathe was appropriately configured, with the HSS tool clamped securely to the tool post and the mild steel specimen held in position by means of a three-jaw chuck. The ranges of cutting parameters adopted in this investigation were established in accordance with experimentally validated values reported in the existing literature (Sada, 2020). Three cutting parameters were systematically varied within the following ranges: spindle speed (120–220 m/min), feed rate (0.10–0.24 mm/rev), and depth of cut (1–2.5 mm). The experimental trials were carried out in the presence of a soluble oil-based cutting fluid comprising 20% water concentration and 80% mineral oil.

Conversion of cutting speed to RPM. For each machining trial, the prescribed cutting speeds were converted into RPM prior to input, given that the lathe spindle speed selector is calibrated in RPM. This conversion was performed in accordance with Equation (1).

$$N = (1000 \times V) / (\pi \times D) \quad \dots (1)$$

where N is the spindle speed (RPM), V is the cutting speed (m/min), and D is the diameter of the workpiece (m).

Metal removal rate (MRR). Metal removal rate is defined as the rate of material extraction from the workpiece throughout the duration of the cutting operation, conventionally expressed in cm³/min and evaluated in accordance with Equation (2).

$$MRR = (Wb - Wa) / (\rho \times t) \quad \dots (2)$$

where Wb is the weight of the workpiece before machining, Wa is the weight after machining, t is the machining time, and ρ is the density of the work material (kg/m³).

Analysis and Results

Table 1 consolidates the results and analyses derived from the workshop machining experiments, documenting the measured values of cutting speed (m/min), feed rate (mm/rev), depth of cut (mm), and metal removal rate (cm³/min) across all experimental runs.

The plotted relationships between each cutting parameter and the response variable demonstrated measurable variations across the investigated ranges. Among the three parameters, feed rate exerted the most dominant influence, followed by cutting speed, whilst depth of cut contributed the least significant effect on the metal removal rate.

As evidenced by the feed rate versus MRR plot, the rate of material removal exhibits an upward trend with increasing depth of cut, yet undergoes a subsequent

decline attributable to the progressive deterioration of the cutting tool (Sada, 2018). A marked and progressive enhancement in metal removal rate was observed as the feed rate was systematically increased across the range of 0.2 mm/rev to 0.4 mm/rev.

Table 1. Results of machining experiment using selected cutting parameters.

Run	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	MRR (cm ³ /min)
1	1150	0.3	2.0	5.41
2	900	0.2	0.4	4.31
3	900	0.4	1.6	3.34
4	750	0.3	1.0	3.31
5	1150	0.3	1.0	4.34
6	1400	0.3	1.0	4.36
7	900	0.4	1.6	5.21
8	1150	0.2	1.0	4.29
9	900	0.2	1.6	3.31
10	1150	0.3	1.0	3.31
11	1400	0.2	0.4	4.32
12	1150	0.3	1.0	3.31
13	1400	0.3	1.0	5.32
14	1150	0.3	1.0	4.33
15	1150	0.4	1.0	4.32
16	900	0.4	0.4	5.31
17	1150	0.3	1.6	3.32
18	1150	0.3	1.0	4.32
19	1400	0.4	0.4	4.32
20	1400	0.2	1.6	5.21
Mean				4.264
SD				0.75

This trend corroborates previously reported findings in the literature, further confirming the predominant influence of feed rate relative to the other cutting parameters investigated. The observed behaviour is in close agreement with results documented in the existing literature, reinforcing the established dominance of feed rate as the most influential parameter among those examined in this study. A mean MRR of 4.264 cm³/min with a corresponding standard deviation of 0.75 was obtained across the full experimental matrix, reflecting the substantial variability in material removal induced by the progressive alteration of cutting conditions.

Conclusion

The effects of three key input parameters - cutting speed, feed rate, and depth of cut - on the metal removal rate were comprehensively examined through cylindrical turning of mild steel bar stock. The most significant outcomes of this investigation are outlined below:

- the metal removal rate exhibited significant variability, directly attributable to the systematic variation of the applied cutting parameters;
- feed rate was identified as the most influential cutting parameter governing MRR, producing a steady and substantial rise in material removal rate with each incremental increase in feed rate magnitude;
- the reduction in MRR observed at elevated feed rates was ascribed to the progressive deterioration of the cutting tool;
- cutting speed demonstrated a moderate influence on MRR, whereas depth of cut contributed the least significant effect among the three parameters investigated.

The recorded mean MRR of 4.264 cm³/min with a standard deviation of 2.31 underscores the pronounced sensitivity of the machining process to variations in the applied cutting conditions. Future investigations are encouraged to integrate tool wear measurements in conjunction with MRR data, whilst employing response surface methodology or artificial neural network techniques to establish robust predictive models for the optimisation of cutting conditions in mild steel turning operations.

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STATUS AND PROSPECTS OF MINERAL FERTILIZER PRODUCTION IN UZBEKISTAN

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Annotatsiya. Ushbu maqolada O'zbekistonda mineral o'g'itlar ishlab chiqarishning hozirgi kundagi holati, mineral o'g'itlarga talab va ayniqsa mahalliy xomashyolaridan olish, Markaziy Qizilqum fosforitidan fosforli o'g'itlar olishning ilmiy asoslari keng yoritilgan. Karbamid o'g'itining sekin erishini amalga oshirish bo'yicha olib borilgan tadqiqotlar, bundan tashqari mineral o'g'itlarning qishloq xo'jaligidagi ahamiyati va o'simliklardan mo'l hosil olish uchun kerakli me'yorlari keltirilgan. Ayniqsa o'g'itlarga bo'lgan ehtiyojni qondirish uchun, yangi turdagi, tarkibida fosfor tutgan kompleks o'g'itlarni ishlab chiqarish zarurati borligi asoslangan.

Kalit so'zlar: *Mineral o'g'itlar, fosforit, silvinit, azotli, fosforli, kaliyli, murakkab o'g'itlar, ammos, suprefos, fosfat va nitrokaltsiyfosfat, talab, qishloq xo'jaligi, me'yorlar.*

Аннотация. В этой статье описывается текущее состояние производства минеральных удобрений в Узбекистане, спрос на минеральные удобрения и особенно роль местного сырья в производстве фосфорных удобрений из Центрального Кызылкумского фосфорита. В частности, минеральные удобрения имеют необходимые характеристики в сельском хозяйстве для получения большого количества сельскохозяйственных культур. В частности, необходимо производить комплексные удобрения, содержащие свежий фосфор, для удовлетворения потребностей в фосфорных удобрениях.

Ключевые слова: *Минеральное удобрение, фосфорит, силвинит, азотных, фосфорных, калийных,*



аммофос, суперфос, фосфат и нитрокальцийфосфат, потребности, сельское хозяйство, нормы.

Abstract. This article outlines the current condition of mineral fertilizers production in Uzbekistan, the demand for mineral fertilizers, and especially the role of local raw materials in the production of phosphorus fertilizers from the Central Kyzylkum Phosphorite. Especially, mineral fertilizers have the necessary characteristics in agriculture to obtain plenty of crops. In particular, it is necessary to produce complex fertilizers containing fresh phosphorus to meet the need for phosphorus fertilizers.

Keywords: *mineral fertilizers, phosphorite, silvinite, nitrogen, phosphorus, potassium, complex fertilizers, ammophos, superphosphate, phosphate and nitrocalcium phosphate, agriculture.*

Introduction

The Republic of Uzbekistan currently has 25 million 736 thousand ha of designated agricultural land, including more than 4.3 million ha of irrigated land. The 97% of all agricultural products in the republic obtained from irrigated land. Uzbekistan ranks 5th in the world in cotton production. It has achieved independence in grain production, mainly wheat cultivation, with more than 6.1 million tons of grain crops in recent years. As a country with a rapidly growing population, Uzbekistan had 14 million 79 thousand people in 1975, and now it has 35.8 million population. Because the annual growth rate is 800 thousand, people. Due to water scarcity, the possibilities for increasing irrigated arable land, as a result of water shortage, crop productivity is quite low. Even when calculated per capita, the population cannot be high. In 1970, 0.22 hectares of cultivated land was per person, and in current indicators, it is 0.12 hectares decreased [1]. In such conditions, the country's growing population and agricultural production can only be met by accelerating, increasing crop yields and chemicalizing them.

Research Methodology

It has been established that each ton of mineral fertilizers provides food for 5-6 people. The costs of production and use of fertilizers are covered by additional agricultural products 2-3 times. Thanks to the use of mineral fertilizers, the productivity of agricultural crops increases by an average of 40-50%. The effectiveness of the use of mineral fertilizers and protective agents in plant protection is expressed not only in increasing productivity and preserving products, but also in a significant increase in labor productivity in agriculture. This is evident in the following: while on our planet, during the period from 1900 to 1940, labor productivity in agriculture increased by 60%, in the 1980s after 40 years, it increased by 11 times due to the widespread use of chemical means [4].

That is why in Uzbekistan large chemical industry sectors used in agriculture have been established. Of these, three joint-stock companies: "MAXAM-CHIRCHIQ", "Navoiyazot" and "Ferghanaazot" JSC produce nitrogen fertilizers consisting of ammonium nitrate, urea and ammonium sulfate. In Almalyk, the AMMOFOS-MAXAM Samarkand Chemical and Kokand Superphosphate Enterprises produce

phosphorus-containing fertilizers, including ammophos, superphos, ammonium sulfate phosphate, nitrocalcium phosphate and simple ammonium superphosphate. 75% of the Kokand plant is supplied with raw materials from the Kyzylkum Phosphorite Combine, a Russian company that produces phosphorus-containing fertilizers. The Elektrokimyo JV plant produces various types of plant protection chemicals and a small amount of simple ammonium superphosphate (UFAU). Potash fertilizers were not produced in our republic until recent years, currently the Dekhkanabad Potash Plant produces 200 thousand tons of K_2O per year, which fully covers the needs of our republic in potash fertilizers and ensures their sale abroad. In 2016, chemical industry enterprises in Uzbekistan produced 944.2 thousand tons of nitrogen, 143.5 thousand tons of phosphorus fertilizers (based on 100% nutrient content) and 137 thousand tons of potash fertilizers. By 2017, the demand for agriculture in our republic, based on 100% nutrient content, amounted to 839.58 thousand tons of nitrogen, 525.21 thousand tons of phosphorus and 278.92 thousand tons of potassium fertilizers.

Analysis and Results

If the demand for agriculture in terms of the production volume of nitrogen fertilizers has increased, then for phosphorus fertilizers it is much lower than the need. It follows that for 1 ha of irrigated land in our country (in net terms) - 233.4 kg of nitrogen, 39.8 kg of P_2O_5 and 6.7 kg of K_2O . In this case, under the scientifically based norms of mineral fertilizers, it is required to apply 100-120 kg/ha of P_2O_5 and 50 kg/ha of K_2O to agricultural crops (in pure form), 100-110 kg/ha of P_2O_5 and 70-75 kg/ha of K_2O to vegetable crops, and 140-145 kg/ha of P_2O_5 and 150-180 kg/ha of K_2O to rice [2].

The lack of phosphorus fertilizers and the practical absence of potassium fertilizers lead to the fact that the average cotton yield in our country is only 45 centners per hectare. Long-term research in the field of cotton growing by scientists from the Uzbek Research Institute has shown that when cotton is grown without fertilizers, it yields 12 c/ha of raw cotton, but if 225 kg of nitrogen, 150 kg of phosphorus, and 100 kg of potassium are applied per hectare, a guaranteed yield of 30-35 c/ha is provided. Due to the lack of phosphorus and potassium fertilizers, a large amount of nutrients is removed from the soil along with the harvest. It is known that for 1 ton of cotton raw material, 45 kg of nitrogen, 15 kg of P_2O_5 and 45 kg of K_2O are removed from the soil per year (in pure form), while 1 ton of wheat removes 35 kg of nitrogen, 10 kg of P_2O_5 and 24 kg of K_2O from the soil per year [3].

When harvesting 3 million tons of cotton raw material and 6.1 million tons of wheat, only these two crops, i.e., remove 348.5 thousand tons of nitrogen, 106 thousand tons of phosphorus and 281.4 thousand tons of potassium from the soil per year along with the harvest. Other crops also remove large amounts of nutrients from the soil. Their deficiency in the soil must be replenished. Should also be noted that the utilization rate of plant nutrients from mineral fertilizers is low. On average, 60-70% of nitrogen and potassium fertilizers are used, and about 20-25% of phosphorus fertilizers are used annually, and about 40% in the last 2-3 years. The low use of phosphorus fertilizers leads to the fact that since phosphorus compounds in the soil are

inactive or slightly inactive, they are not fully absorbed by plant roots, therefore, in order to obtain the required amount of phosphorus fertilizers, the input of phosphorus is increased 4-5 times (in some crops) to increase additional productivity [3]. This indicates that the production of phosphorus and potassium fertilizers in Uzbekistan needs to be increased.

Naturally, in order to increase the production of phosphorus fertilizers, it is necessary to increase the capacity of the Kyzylkum Phosphorite Plant. The plant mainly extracts Kyzylkum phosphorites from new deposits. These phosphorites are considered poor as a phosphorus raw material in terms of the useful substance P_2O_5 , since they contain a number of unnecessary additional impurities. The composition of the Dzheroy-Sardara deposits, approximated to average samples, is as follows (in weight, %): 16.2 - P_2O_5 ; 4.2 - CaO; CaO: P_2O_5 =2.85; 17.7 - CO_2 ; 0.6 - MgO; 2.9 - (FeO+ Al_2O_3); 1.5 - (K_2O + Na_2O); 2.65 - SO_2 ; 1.94 - F; 0.1 - Cl; and 7.8% insoluble residue. The low phosphorus content is due to the high calcium modulus (2.85), the high carbonate content (17.7 - CO_2), and the presence of chlorine - 0.1%.

Table 1. Scientifically approximated standards of mineral fertilizers under agricultural crops (kg/ha for 100% nutrients).

№	Agricultural crops	Nitrogen	Phosphorus	Potassium
	Cereal grains:			
1.	Asking lalmikor	150-200	100-120	50
		50-60	40-50	-
2.	For corn grain	180-220	12-10	85-90
3.	Rice	200-220	140-145	150-180
4.	Cotton:			
5.	medium fiber thin fiber	215-240	145-165	95-110
		230-250	155-165	100-110
6.	Hemp	160-180	130-140	80-90
7.	Tobacco	120-150	80-100	40-45
8.	Potatoes	120-150	85-100	60-75
9.	Vegetables	145-200	100-110	70-75
10.	vegetable crops	50-75	100-110	45-50
11.	Nutrients with roots	220	90	60
12.	Livestock hay corn	200	90	60
13.	Last year's clover	100	90-100	50-60
14.	Fruit gardens	120-130	85-90	65
15.	Fruit-bearing vineyards	135-140	90-95	70
16.	Mulberry plantations	100	60	40

Concentrated phosphorus-containing fertilizers obtained from Central Kyzylkum phosphate ores are practically unsuitable for acid processing. The high calcium modulus leads to excessive consumption of the acid reagent. The high content of carbonates leads to the formation of a large amount of foam. Excess chlorine leads to

severe corrosion of the metal. Kyzylkum phosphate ores are not suitable for enrichment by flotation due to the mutual density of phosphate minerals with calcium carbonate. The Kyzylkum Phosphate Combine carries out ore mining, crushing, classification, washing of raw materials from chlorine and separation of CO_2 using the method of burning to decompose carbonates. Since 2006, this enterprise has been preparing to produce concentrated phosphorus fertilizers for AMMOFOS-MAXAM JSC from 400 thousand tons of washed and burned phosphorus concentrate (28-30% P_2O_5) per year, to produce ammoniated (18-19% P_2O_5) superphosphate from 200 thousand tons of washed and dried phosphorus concentrate for the Kokand Superphosphate Plant and to produce 200 thousand tons of phosphate rock flour (16-18% P_2O_5) per year for the production of nitrocalcium phosphate fertilizers for the Samarkand Chemical Superphosphate Plant. Currently, the combine is supplying more raw materials than the specified amount.

The average mineralogical composition of the ore (%) is: francolite – 56.0, calcite – 26.5, quartz – 7.5-8.0, hydromica minerals and feldspars – 4.5, gypsum – 3-5, goethite – 1.0, zeolite < 1.0, and organic matter - about 0.5% [4]. The average chemical composition of the phosphate material (%) is: P_2O_5 – 32.10; CaO – 48.34; CO_2 – 5.0; F – 3.19; MgO – 0.04; Al_2O_3 – 0.2; Fe_2O_3 – 0.18; Na_2O – 0.10; K_2O – 0.05; SO_3 – 0.08; SiO_2 – 0.05 [12]. Its density is 2.96 - 3.2 g/cm³, and its refractive index is 1.596 - 1.621. The phosphate substance in granular phosphorite corresponds to carbonate fluorapatite, which is called "kursite" in the literature. As a waste, the mineralized mass (12.14 P_2O_5) and the dust fraction will continue to accumulate in production until a suitable technology for their processing is found. The presented mineralized sample contains the following in mass (% weight); 14.68 P_2O_5 ; 40.8 CaO; CaO: P_2O_5 =2.78; 1.17 Al_2O_3 ; 1.37 Fe_2O_3 ; 0.53 MgO; 1.85 F; 12.84 CO_2 ; dust fraction composition (% weight); - 18.54 P_2O_5 ; 44.72 CaO; CaO: P_2O_5 =2.41; 0.95 Al_2O_3 ; 0.85 Fe_2O_3 ; 0.80 MgO; 2.22 F; 14.8 CO_2 .

In 2010, AMMOFOS-MAXAM JSC produced 139.4 thousand tons of ammophos (10% N_2 and 46% P_2O_5) in pure form, or 65.6 thousand tons of 100% P_2O_5 , 218.1 thousand tons of superphosphate (8-15% N_2 and 20-24% P_2O_5) or 53.3 thousand tons of 100% P_2O_5 , and 1.44 thousand tons of ammonium superphosphate (15-19% N_2 and 20-24% P_2O_5) or 0.36 thousand tons of 100% P_2O_5 . Samarkand Chemical Plant produced 30.72 thousand tons of nitrocalcium phosphate fertilizers (6% N_2 and 16% P_2O_5) in pure form, or 4.9 thousand tons. P_2O_5 , Kokand Superphosphate Plant also supplied 168.5 thousand tons of simple ammonium superphosphate (1.5% N_2 and 13.5% P_2O_5) or 22.9 thousand tons of P_2O_5 in the same pure state. Similarly, Navoi Electrochemical Plant produced 1.44 thousand tons of 100% simple superphosphate in a smaller amount. In total, 148.5 thousand tons of phosphorus-containing fertilizers were produced, calculated on 100% P_2O_5 . Suprephos, ammonium superphosphate and nitrocalcium phosphate fertilizers are a new type of mineral fertilizers, recently developed by Almalyk "AMMOFOS-MAXAM" JSC and Samarkand Chemical Plant. The technology for obtaining Suprephos is based on the conversion of calcium sulfate with dicalcium phosphate and sulfate ammonium diammonium phosphate in a phosphate acid gypsum mixture (pulp) [5-6].

The technology for producing nitrocalcium phosphate fertilizers is based on the principle of incomplete decomposition of ordinary phosphorite flour from the Kyzylkum deposits in the presence of nitric acid. These new types of fertilizers were developed and produced on existing ammophos production facilities.

The main difficulty in the production of mineral fertilizers is that the four types of phosphorus fertilizers produced in Uzbekistan (ammophos, superphosphate, phosphate and nitrocalcium phosphate) are classified as complex nitrogen-phosphorus fertilizers. Only simple ammonium superphosphate belongs to primary phosphorus fertilizers. The annual distribution rate of complex fertilizers according to the agrotechnical terms of mineral fertilizers is scientifically substantiated and given in Table 2 [3].

Table 2. Annual distribution rate of mineral fertilizers according to the agrotechnical terms (% , based on the annual rate).

№	Crops	Type of fertilizer	Delivery time (net)					
			Under plowed land	before planting	by planting	in fertilization		
1.	Cotton	N		25	5	20	25	25
		P	60-70	-	15-20	-	-	15-20
		K	50	-	-	-	50	-
2.	Spiked grain	N	-	15	-	40	45	-
		P	100	-	-	-	-	-
		K	100	-	-	-	-	-
3.	For corn grain	N	-	30	-	35	35	-
		P	50	-	-	-	50	-
		K	50	-	-	50	-	-
4.	Rice	N	-	30	-	40	30	-
		P	-	70	-	-	30	-
		K	-	50	-	-	50	-
5.	Vegetable	N	-	30	-	35	35	-
		P	75	-	25	-	-	-
		K	100	-	-	-	-	-
6.	Fruit-bearing vineyards	N	50	-	-	25	25	-
		P	50	-	-	25	25	-
		K	50	-	-	25	25	-

Conclusion

Phosphorus fertilizers are effective during winter tillage. The table shows that 60-70% of the annual norm of phosphorus fertilizers is applied under cotton during autumn tillage. When growing cereal crops, 100% of the annual norm of phosphorus fertilizers is applied under the plow. Thus, for the two main crops - cotton and grain - 272-292 thousand. tons of P_2O_5 are required per year in the form of primary phosphorus fertilizers. The Kokand superphosphate plant produces only 22.9 thousand. tons of simple ammonium superphosphate with P_2O_5 per year.

Primary phosphorus fertilizers include simple superphosphate, precipitate (44% P_2O_5 uptake, TU 113-08-513-82) and secondary superphosphate (43-49% P_2O_5 uptake, GOST 16306-80). The latter is the most concentrated phosphorus fertilizer. Its production requires high-quality phosphate raw materials (washed and calcined



phosphate concentrate) and concentrated phosphoric acid. Extractive phosphoric acid (18.69% P_2O_5) obtained at AMMOFOS-MAXAM JSC is slightly concentrated by evaporation from washed and calcined phosphate concentrate of Central Kyzylkum phosphates to a high content [7-8]. It is possible to organize the production of secondary superphosphate by building a sufficient acid evaporation plant in Almalyk.

In conclusion, it can be said that the productivity of chemical plants in the Republic of Uzbekistan in the case of nitrogen and potassium fertilizers is sufficient, and they are even sold abroad. However, to meet the demand for phosphorus fertilizers, it is extremely necessary to produce new types of complex fertilizers containing phosphorus.

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UDC: 677.2

THE EFFECT OF GRID BAR GRATE PARAMETERS ON COTTON FLOW DYNAMICS AND THE EFFICIENCY OF LARGE IMPURITY SEPARATION

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Annotatsiya. Ushbu maqolada arra tishli baraban va panjarali rejnok orasida harakatlanuvchi paxta tutami dinamikasi hamda yirik ifloslik zarralarini ajratish jarayonining nazariy tadqiqoti keltirilgan. Gravitatsiya, ishqalanish va davriy elastik kuchlar ta'sirini hisobga olgan holda, paxta tutamining rejnok tayoqchalari yuzasi bo'ylab tezligi va bosib o'tgan yo'lini tavsiflovchi analitik tenglamalar keltirib chiqarilgan. Massa saqlanish qonuniga asoslanib, rejnok tayoqchasi diametri, qo'shni tayoqchalar orasidagi masofa, o'rash burchagi va rejnok yuzasi geometriyasining paxta oqimi tezligiga ta'siri baholangan. Hisoblash natijalari shuni ko'rsatadiki, o'rash burchagi va tayoqcha diametrining ortishi paxta oqimi tezligini kamaytiradi, tayoqchalar orasidagi masofaning ortishi esa zarba kuchini oshiradi. Nazariy tahlil asosida 15 mm diametrli va tayoqchalar orasi 30 mm bo'lgan rejnok konstruksiyasi barqaror paxta oqimi, yirik ifloslarni samarali ajratish va tola sifatini saqlashni ta'minlovchi oqilona yechim sifatida asoslab berilgan.

Kalit so'zlar: paxta tutami; arra tishli baraban; panjarali rejnok; rejnok tayoqchasi diametri; o'rash burchagi; oqim tezligi; markazdan qochma kuch; ifloslik konsentratsiyasi; tozalash samaradorligi; analitik model.

Аннотация. В данной статье представлено теоретическое исследование динамики хлопкового валика, движущегося между пальчатый барабаном и колосниковой решёткой, а также процесса отделения крупных сорных примесей. С учётом воздействия гравитационных, фрикционных и периодических упругих сил выведены аналитические уравнения, описывающие скорость и путь перемещения хлопкового валика по поверхности колосников. На основе закона сохранения массы оценено

влияние диаметра колосника, расстояния между смежными колосниками, угла охвата и геометрии поверхности решётки на скорость потока хлопка. Результаты расчётов показывают, что увеличение угла охвата и диаметра колосника снижает скорость потока хлопка, тогда как увеличение расстояния между колосниками повышает ударную силу. На основе теоретического анализа обоснована рациональная конструкция решётки с диаметром колосника 15 мм и расстоянием между колосниками 30 мм.

Ключевые слова: хлопковый валик; пильчатый барабан; колосниковая решётка; диаметр колосника; угол охвата; скорость потока; центробежная сила; концентрация примесей; эффективность очистки; аналитическая модель.

Abstract. This paper presents a theoretical investigation of the dynamics of a cotton tuft moving between a saw-toothed drum and a grid bar grate, as well as the process of large impurity separation. Analytical equations describing the velocity and travel distance of the cotton tuft along the surface of the grid bars were derived by considering the effects of gravitational, frictional, and periodic elastic forces. The influence of grid bar diameter, spacing between adjacent grid bars, contact wrap angle, and grate surface geometry on the cotton flow velocity was evaluated based on the law of conservation of mass. A mathematical model describing the variation of centrifugal force and impurity concentration along the grate arc was also developed. The calculation results show that increasing the wrap angle and the grid bar diameter reduces the cotton flow velocity, whereas increasing the spacing between the grid bars enhances the impact force. Although a smaller grid bar diameter increases the impact intensity and improves impurity removal, it also raises the risk of fiber damage. Conversely, a larger diameter provides a wider contact surface but reduces the impact effect. Based on the theoretical analysis, a grate configuration with a 15 mm grid bar diameter and 30 mm spacing between adjacent grid bars was theoretically substantiated as the rational design, ensuring stable cotton flow, efficient separation of large impurities, and preservation of fiber quality.

Keywords: cotton tuft; saw-toothed drum; grid bar grate; grid bar diameter; wrap angle; flow velocity; centrifugal force; impurity concentration; cleaning efficiency; analytical model.

Introduction

During the primary processing of cotton, an important objective is not only the efficient removal of large impurities contained in the raw cotton but also the preservation of the natural quality characteristics of the seeds and fibers. In saw-toothed drum–grid bar grate cleaning systems used at cotton ginning enterprises, impurity separation occurs as a result of the combined action of impact, frictional, gravitational, and centrifugal forces acting on the cotton tuft. Excessive intensification of the cleaning process may lead to the loss of good-quality fibers with the waste, mechanical damage to cotton seeds, and an increase in the content of short fibers and neps in the cleaned cotton fiber [6, 8, 9].

The performance of saw-toothed cleaners largely depends on the geometric configuration of the grid bars, their diameter, spacing, clearance from the saw-toothed drum, wrap angle, and the rotational speed of the drum. Previous studies have shown that increasing the open area between adjacent grid bars enhances impurity separation but simultaneously increases the probability of cotton tufts being discharged together with the impurities. Furthermore, the grid bar diameter and the spacing between adjacent grid bars are among the principal design parameters governing both the efficiency of large impurity removal and the level of raw material losses [1, 2, 7].

Previous studies devoted to domestic cotton cleaning technologies have extensively investigated the design of saw-toothed drums and grid bar grates, their operating conditions, and cleaning performance [4, 5, 10]. However, insufficient attention has been paid to the development of a unified analytical model describing the velocity and travel distance of a cotton tuft along the grid bar surface, the relationship between the grid bar diameter and the contact arc, the compressibility of the cotton flow, the variation of the flow cross-sectional area, and the distribution of impurity concentration along the grate arc. The theoretical clarification of these relationships makes it possible to determine an optimal compromise between cleaning efficiency and the preservation of fiber quality.

The objective of this study is to perform a theoretical analysis of the dynamic behavior of cotton flow moving in the gap between the saw-toothed drum and the grid bar grate and to determine the effects of grid bar diameter, spacing between adjacent grid bars, and wrap angle on cotton tuft velocity, centrifugal force, and the efficiency of large impurity separation. Based on these theoretical results, rational design parameters are substantiated to ensure stable cotton flow, intensive removal of large impurities, and preservation of raw cotton quality.

The motion of a cotton tuft along the tangential surface of a grid bar is considered below. The schematic diagram of cotton flow movement between the saw-toothed drum and the grid bar grate is presented in Figure 1.

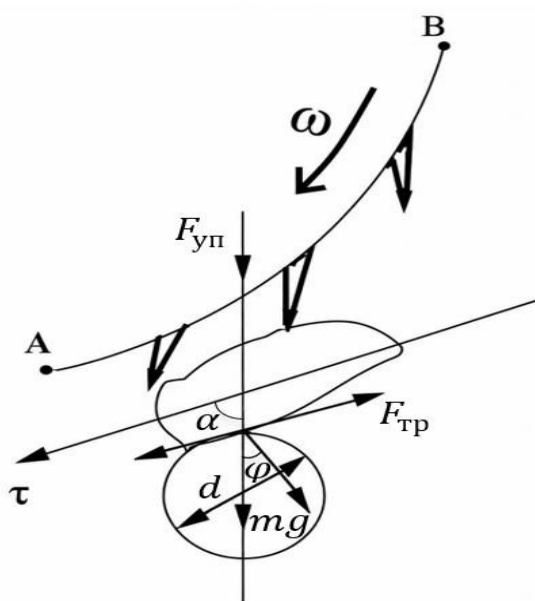


Figure 1. Schematic diagram of cotton flow movement between the saw-toothed drum and the grid bar grate.

Research Methodology

Under the action of the grid bars, the cotton tuft undergoes deformation according to the law ($\Delta x = a \sin \Omega t$) and moves along the tangential direction ($0 < a < d_i/2$). When the inclination angle of the grid bar surface is (φ), the equation of motion in the tangential direction can be expressed as follows:

$$m \frac{d\vartheta_\tau}{dt} = mg \sin \varphi - f mg \cos \varphi + k a \sin \Omega t, \quad (1)$$

where the first term represents the tangential component of the gravitational force, and the second term represents the frictional force. $F_{ish} = f N$, $N = mg \cos \varphi$ is the normal reaction force. The third term represents the periodic elastic action of the grid bars: ($F_{el} = k \Delta x = k a \sin \Omega t$.)

Dividing Equation (1) by (m) and integrating with respect to time, we obtain:

$$\vartheta_\tau = (g \sin \varphi - f g \cos \varphi) t - \frac{k a}{m \Omega} \cos \Omega t + C_1. \quad (2)$$

Using the initial condition ($t=0$), ($\vartheta_\tau = 0$), it follows that ($C_1 = \frac{k a}{m \Omega}$) therefore:

$$\vartheta_\tau(t) = (g \sin \varphi - f g \cos \varphi) t + \frac{k a}{m \Omega} (1 - \cos \Omega t). \quad (3)$$

By integrating Equation (3) once more with respect to time and applying the initial condition ($L(0)=0$), the distance traveled by the cotton tuft along the arc AB is determined as follows:

$$L(t) = (g \sin \varphi - f g \cos \varphi) \frac{t^2}{2} + \frac{k a}{m \Omega} \left(t - \frac{1}{\Omega} \sin \Omega t \right). \quad (4)$$

The calculations were performed for the parameters $\varphi = 30^\circ \div 45^\circ$, $\Omega = 250 \text{ s}^{-1}$ ($l = 30 \text{ mm}$ }). The obtained results are presented in Figures 2 and 3.

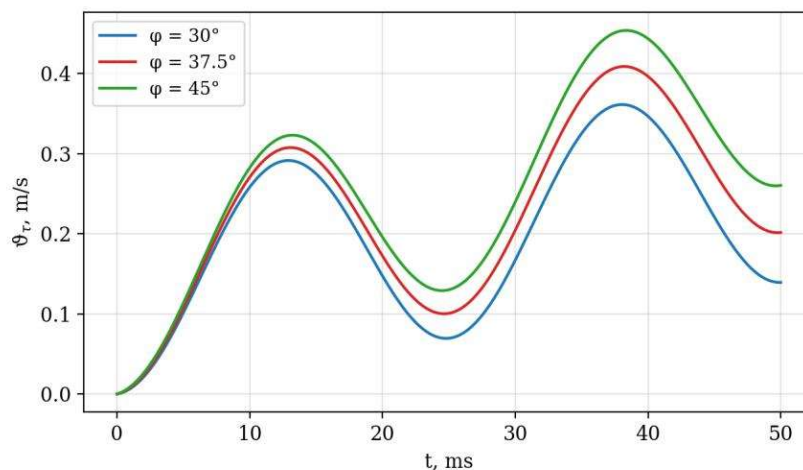


Figure 2. The velocity of cotton tuft movement along the grid bar surface. $\vartheta_\tau(t)$: $\varphi = 30^\circ; 37.5^\circ; 45^\circ$ ($f = 0.25$; $l = 30 \text{ mm}$).

The graphs show that the velocity of the cotton tuft fluctuates due to the periodic action of the grid bars against the background of an approximately linear increase. As the inclination angle (φ) increases, the intensity of movement along the surface becomes higher. At a grid bar diameter of ($d_2 = 15$) mm and a spacing between

adjacent grid bars of ($l_2 = 30$) mm, uniform and continuous movement of the cotton tufts along the grate is ensured. This is an important condition for maintaining the stability of cotton flow passing through the gap between the saw-toothed drum and the grid bars.

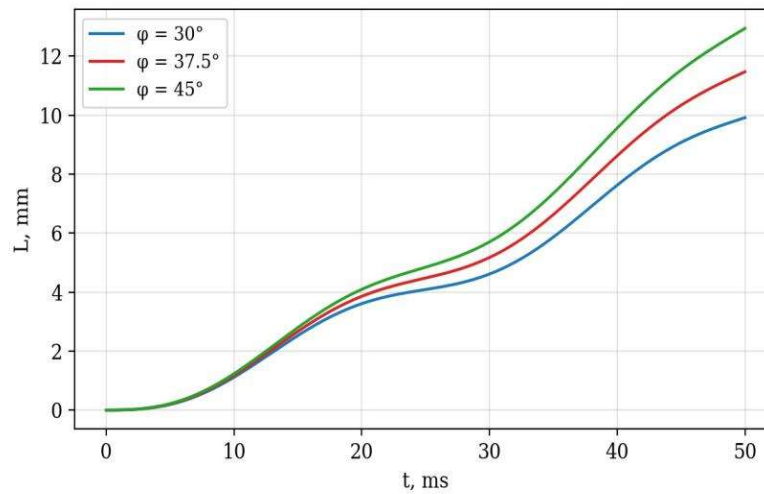


Figure 3. The distance traveled by the cotton tuft along the arc AB. $L(t)$: $\varphi = 30^\circ; 37,5^\circ; 45^\circ$ ($f = 0,25$; $l = 30$ mm).

A theoretical analysis of increasing impurity separation efficiency in the cleaning of cotton from large impurities is carried out by properly selecting the positions and diameters of the improved grid bars. The scheme showing variations in the spacing and diameters of the grid bars is presented in Figure 4.

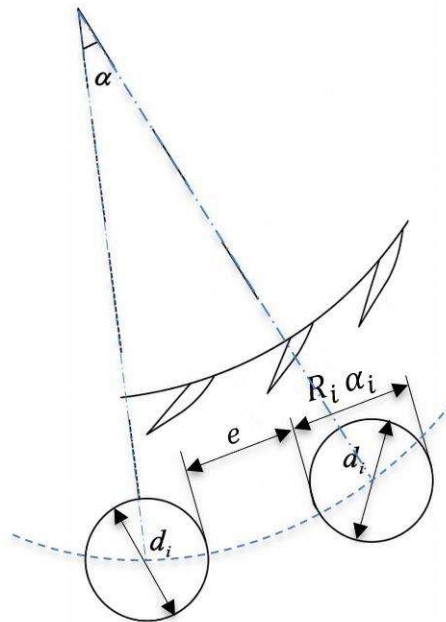


Figure 4. Scheme showing variations in the spacing and diameters of the grid bars.

The pitch (l) between adjacent grid bars is expressed as the sum of the free gap (e) and the length of the contact arc:

$$l = e + L_i = e + R_i \alpha_i, \quad (5)$$

where ($R_i = d_i/2$) is the radius of the grid bar, and (α_i) is the corresponding central (wrap) angle. The dependence on the grid bar diameter can be derived from Equation (5).

$$l = e + \frac{d_i}{2} \alpha_i \Rightarrow e = l - \frac{d_i}{2} \alpha_i. \quad (6)$$

Thus, without changing the grid bar pitch, the free gap (e), i.e., the surface area through which impurities are discharged, can be controlled by selecting only the rational value of the grid bar diameter.

To account for the compressibility of the cotton tuft flow, the relationship between density and pressure is assumed in the following form [1]:

$$\rho = \rho_0(\mu(p - p_0) + 1), \quad (7)$$

where (ρ_0) and (p_0) are the initial density and pressure of the cotton flow, respectively; (p) is the current pressure; and (μ) is the compressibility coefficient (measured in (Pa^{-1});, determined experimentally)

The velocity of the cotton flow passing through the cross-section between the grid bars is expressed as a function of the mass flow rate, density, and cross-sectional area as follows:.

$$V = \frac{Q_0}{\rho S}, \quad Q_0 = \rho_0 V_0 S_0, \quad (8)$$

where (Q_0) is the mass flow rate; (V_0) and (S_0) are the inlet velocity and cross-sectional area, respectively. The inlet cross-section corresponds to the free gap, while the outlet cross-section corresponds to the contact arc (Figures 5 and 6):

$$S_0 = e \cdot b = \left(l - \frac{d}{2} \alpha\right) b, \quad S = \frac{d}{2} \alpha \cdot b, \quad (9)$$

where (b) is the working width of the grate (the length of the grid bar).

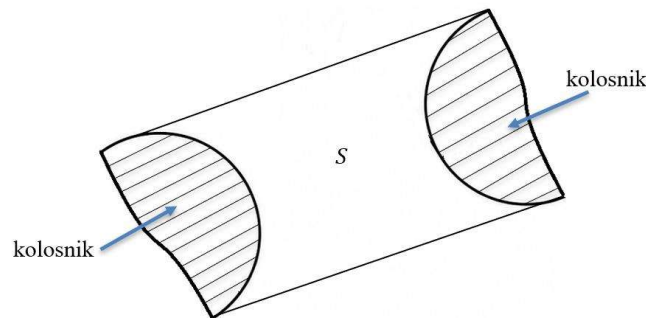


Figure 5. Schematic diagram of the gap area (S) between the grid bars.

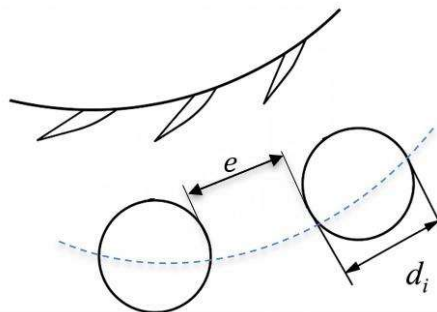


Figure 6. Schematic diagram of the surface between the grid bars and the saw-toothed drum.

By substituting Equations (7) and (9) into Equation (8), the dependence of the flow velocity on the grid bar diameter, pitch, and wrap angle is obtained (the parameter (b) is reduced):

$$V = \frac{V_0 \left(l - \frac{d}{2} \alpha \right)}{(\mu(p - p_0) + 1) \frac{d}{2} \alpha}. \quad (10)$$

For the stationary motion of the cotton tuft mass, the centrifugal force acting on the flow directed along the saw-toothed drum is determined from the expression:

$[F = (m_1 + m_2)V^2/R_b]$ where $(R_b = D/2)$ is the radius of the saw-toothed drum; (m_1) is the mass of cotton, and (m_2) is the mass of impurities. Substituting Equation (10), we obtain:

$$F = \frac{(m_1 + m_2) V_0^2 \left(l - \frac{d}{2} \alpha \right)^2}{R_b (\mu(p - p_0) + 1)^2 \left(\frac{d}{2} \alpha \right)^2}. \quad (11)$$

Equations (10) and (11) are dimensionally consistent: $([V] = m/s, [F] = N.)$. The calculations were performed using the following values: $V_0 = v_1 = 7,5 \text{ m/s}$, $\mu(p - p_0) = 0,2$, $m_1 + m_2 = 6 \cdot 10^{-3} \text{ kg}$, $R_b = 0,24 \text{ m}$. The obtained results are presented in Figures 7–9.

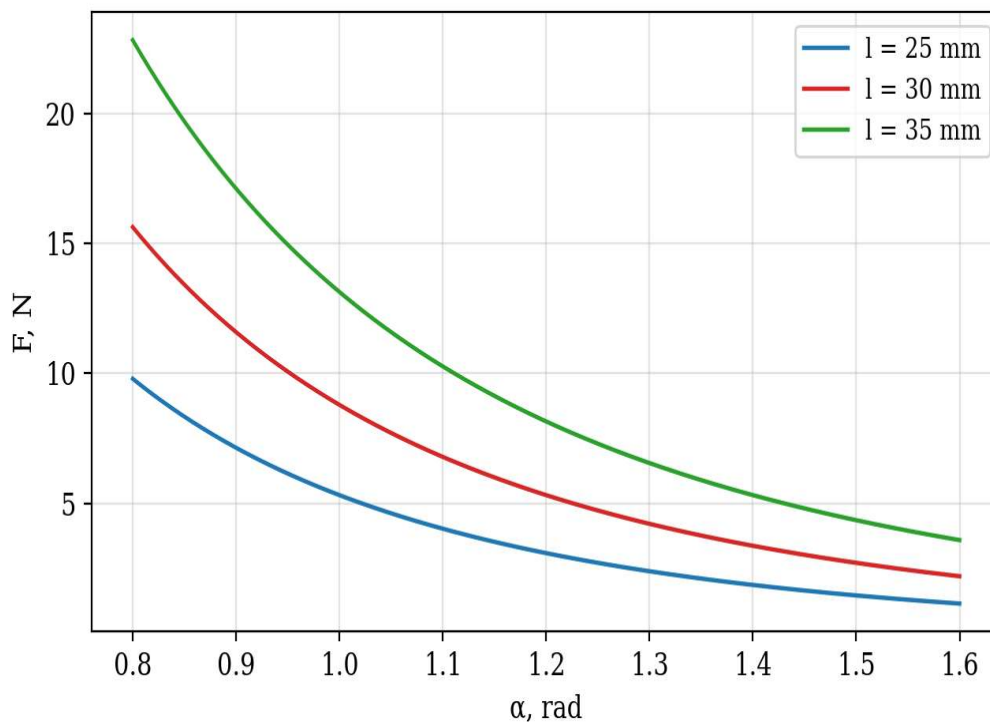


Figure 7. Dependence of the force acting on the cotton flow on the wrap angle for the spacing between grid bars ($l = 25; 30; 35 \text{ mm}$ ($d = 15 \text{ mm}$)).

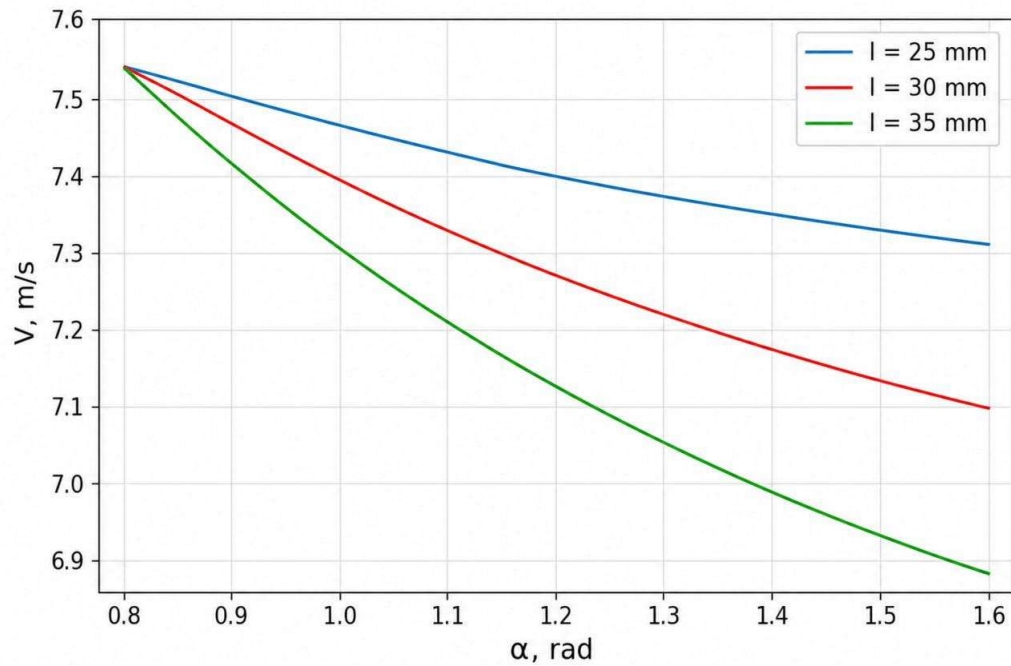


Figure 8. Dependence of cotton flow velocity on the wrap angle for the spacing between grid bars ($l = 25; 30; 35$ mm) ($d = 15$ mm).

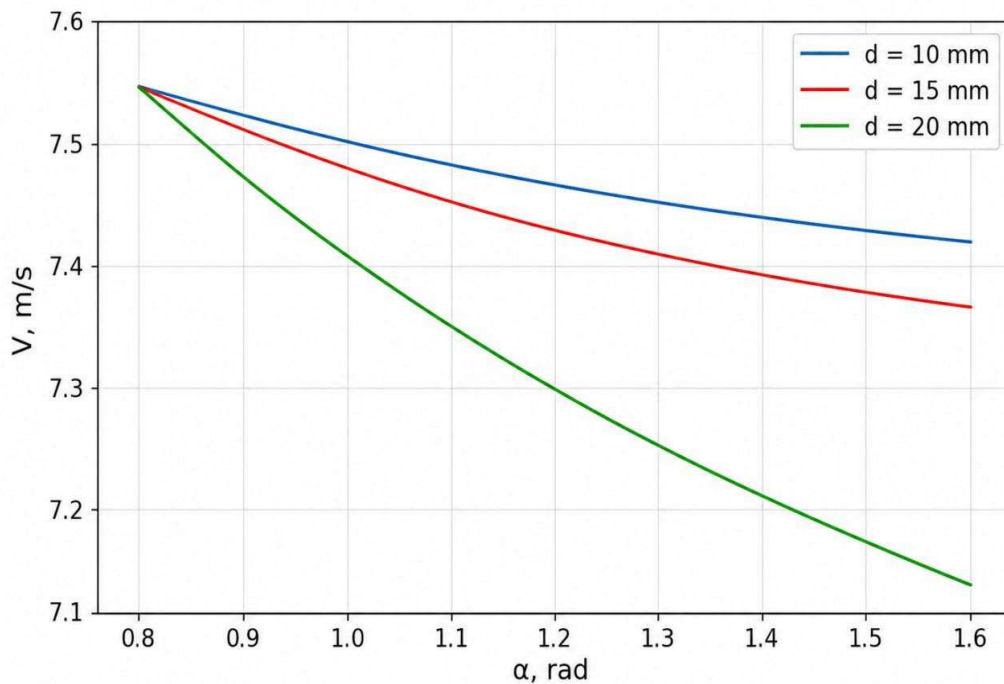


Figure 9. Dependence of cotton flow velocity on the wrap angle for grid bar diameters ($d = 10; 15; 20$ mm) ($l = 30$ mm).

Analysis and Results

The graphs show that an increase in the wrap angle and grid bar diameter enlarges the flow passage cross-section, resulting in a decrease in the flow velocity and the corresponding centrifugal force, whereas an increase in the grid bar pitch (l) leads to an increase in both velocity and force. Although a smaller diameter ($d = 10$ mm) provides a higher velocity and stronger impact action, it also increases the risk of mechanical fiber damage and the loss of cotton tufts through the grate openings. In

contrast, a larger diameter ($d=20$) mm) significantly reduces the impact effect. Therefore, as a compromise between minimizing mechanical damage and improving cleaning efficiency, the grid bar diameter ($d_2 = 15$) mm and the spacing between grid bars ($l_2 = 30$) mm are considered rational values [2].

Now, the amount of impurities separated from the cotton flow as a result of its transfer from the saw-toothed drum and interaction with the grid bars is analyzed. According to the method proposed by A.G. Sevostyanov [3], considering the cotton flow as continuous, the variation of impurity concentration along the grate arc is investigated. The impurity concentration is expressed as follows:

$$C(x) = \frac{m_0(x)}{m_1} \quad (12)$$

where $m_0(x)$ is the mass of impurities in the flow, (m_1) is the total mass of the flow, and (x) is the coordinate along the grate arc. The difference between the densities of the cotton flow and impurities is expressed as:

$$\Delta\rho = \rho_1 - \rho_{if} \quad (13)$$

is taken into account through this relationship, where (ρ_1) is the density of the cotton flow and (ρ_{if}) is the density of impurities. The impurity separation process is described by the following differential equation:

$$\frac{dC(x)}{dx} = -\lambda C(x), \quad (14)$$

Integrating this equation, we obtain:

$$C(x) = C_0 e^{-\lambda x}, \quad \lambda = \frac{\beta \Delta\rho S}{u Q}, \quad (15)$$

where (C_0) is the impurity concentration at the inlet; (λ) is the separation coefficient (dimension: (m^{-1})); (β) is the resistance coefficient of impurity separation (dimension: (m/s^2)); (u) is the flow velocity; (S) is the contact surface area with the grid bars; and (Q) is the mass flow rate. The separation (cleaning) efficiency and the mass of impurities removed from the flow are determined as follows:

$$\eta = 1 - \frac{C}{C_0} = 1 - e^{-\lambda x}, \quad (16)$$

$$\Delta m = m_1 C_0 (1 - e^{-\lambda}). \quad (17)$$

The graphical analysis shows that, as the grid bar diameter increases, the contact surface area (S) becomes larger, resulting in higher values of the separation coefficient (λ) and the cleaning efficiency (η). However, a larger grid bar diameter reduces the impact intensity and decreases the cotton flow velocity. As a compromise between these competing effects, the grid bar diameter ($d_2 = 15$) mm is considered the rational value. At a grate arc length of ($x = 0,35$) m, the theoretical cleaning efficiency of the improved grate reaches approximately ($\eta \approx 41,8\%$), whereas that of the conventional grate (with uniform dimensions and ($\lambda_b = 1,29 m^{-1}$)) is approximately ($\eta \approx 36,3\%$), corresponding to a theoretical improvement in cleaning efficiency of about 5.5 percentage points.

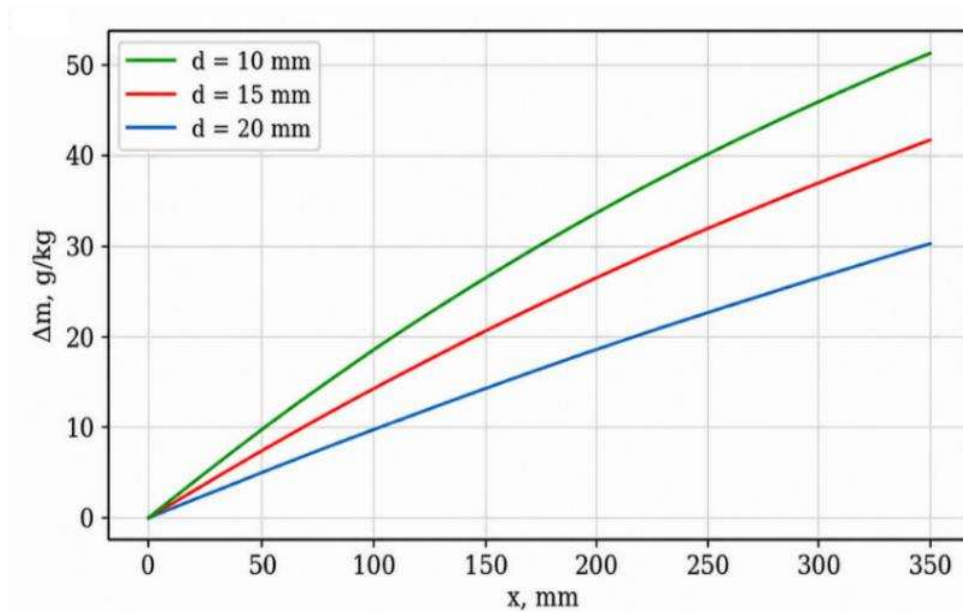


Figure 10. Variation in the mass of impurities separated from the cotton flow along the grate arc for grid bar diameters ($d = 10$), 15, and 20 mm.

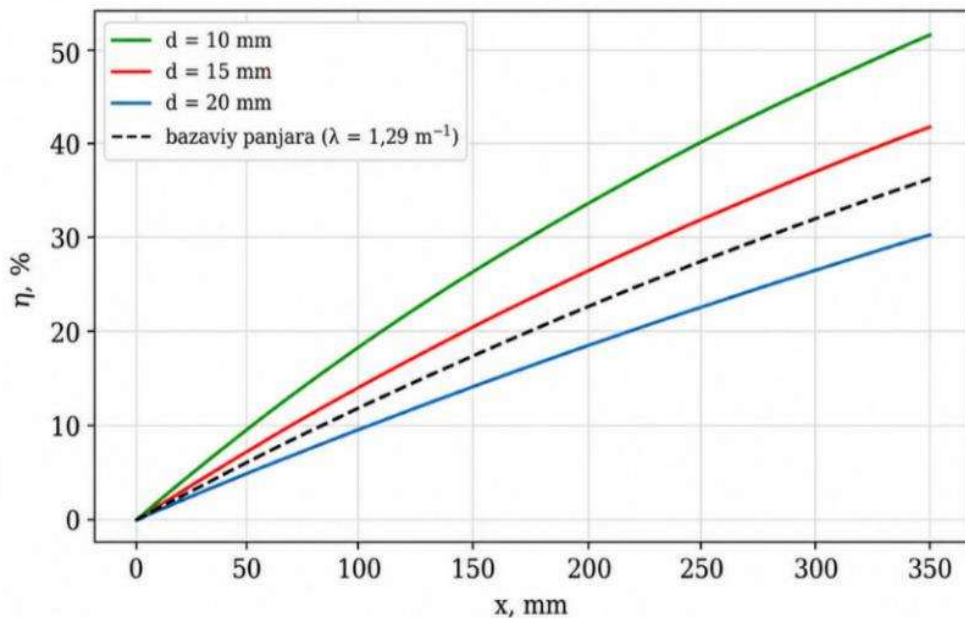


Figure 11. Variation in cleaning efficiency along the grate arc for grid bar diameters ($d = 10$), 15, and 20 mm; the dashed line represents the conventional grate (with uniform grid bar dimensions).

Conclusion

Analytical relationships have been derived to determine the velocity of a cotton tuft moving along the grid bar surface and the distance traveled along the arc, taking into account gravitational, frictional, and periodic elastic forces. The results demonstrate that an increase in the inclination angle accelerates the movement of the cotton tuft and causes velocity fluctuations due to periodic impacts.

A model has been developed to determine the flow passage cross-section, cotton flow velocity, and centrifugal force as functions of the grid bar diameter, pitch, and wrap angle. It has been established that an increase in the wrap angle and grid bar diameter reduces the impact intensity, while the free gap between the grid bars controls the discharge area for impurities.

Grid bars with a diameter of 10 mm provide higher velocity and stronger impact action but increase the risk of fiber damage and cotton losses. In contrast, grid bars with a diameter of 20 mm reduce the intensity of impact action. A grid bar diameter of 15 mm and a spacing of 30 mm between adjacent grid bars were substantiated as a rational compromise between cleaning intensity, flow stability, and preservation of raw material quality.

Based on the developed model describing the variation of impurity concentration along the grate arc, the theoretical cleaning efficiency of the improved grate was estimated to increase by approximately 5.5 percentage points compared with the conventional grate.

The obtained relationships provide a theoretical basis for selecting the design parameters of grid bar grates and improving UXK-type cleaners. Further experimental validation of the calculated results under industrial operating conditions is recommended.

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Section 3. ACTUAL PROBLEMS OF HISTORY, PHILOSOPHY AND SOCIOLOGY

UDC: 94(575.171):33"17/19"

THE MAIN SECTORS OF THE ECONOMY OF THE KHIVA KHANATE

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Annotatsiya. Davlatchiligimiz tarixida va Xiva xonligi tarixida XVIII-asr oxiri XX- asr boshlaridagi Xiva xonligidagi savdo va iqtisodiy aloqalarning oʻrni beqiyos boʻlib, Xiva xonligining kuch-qudrat va qadimiyligini timsoli hisoblangan. Xiva xonligi tarixida sodir boʻlib oʻtgan siyosiy-iqtisodiy jarayonlarning rivojlanishi bugungi kundagi iqtisodiy rivojlanishlarning tarixiy ildizlari hisoblanadi. Xiva xonligida XIX asrning boshlarida hokimiyat tepasiga kelgan Qoʻngʻirotlar sulolasi davrida ayniqsa xonlikda iqtisodiy jarayonlar, aloqalar rivojlantirilgan.

Kalit soʻzlar: *Xiva xonligi, iqtisodiyot, dehqonchilik, hunarmandchilik, savdo - sotiq, baliqchilik, vaqf yerlari, mulkchilik, sugʻoriladigan yerlar, yer egaligi.*

Аннотация. В истории узбекской государственности и истории Хивинского ханства конца XVIII и начала XX веков роль торговли и экономических связей в Хивинском ханстве была несравненной и является символом могущества и древности ханства. Политические и экономические процессы, происходившие в истории Хивинского ханства, являются историческими корнями современного экономического развития. В период правления династии Кунгират, пришедшей к власти в Хивинском ханстве в начале XIX века, экономические процессы и связи особенно развивались в оазисе.

Ключевые слова: *Хивинское ханство, экономика, сельское хозяйство, ремесла, торговля, рыболовство, ваучные земли, собственность, орошаемые земли, землевладение.*

Abstract. In the history of Uzbek statehood and in the history of the Khiva Khanate at the end of the 18th and beginning of the 20th centuries, the role of trade and economic relations in the Khiva Khanate was incomparable and was considered a symbol of the power and antiquity of the khanate. The political and economic processes that took place in the history of the Khiva Khanate are the historical roots of today's economic developments. During the reign of the Kungrat dynasty, which came to power in the Khiva Khanate at the beginning of the 19th century, economic processes and relations were especially developed in the oasis.

Keywords: *Khiva Khanate, economy, agriculture, crafts, trade, fishing, endowment lands, property, irrigated lands, land ownership.*

Introduction

The population of the Khiva Khanate was mainly engaged in agriculture, and agriculture and related livestock breeding were considered the two main branches of agriculture. The cultivation of grain, cotton, and melons was the leading crop in agriculture. Grain was grown on more than half of the arable land, and winter wheat was the leading crop in grain production. The peasants' abundant harvests from grain crops were even noted in the sources of foreign researchers. Among grain crops, the cultivation of sorghum was in second place after wheat, and rice was grown mainly in irrigated areas. Cotton was grown on 1/5 of the arable land, and cotton growing and sericulture were of particular importance in the khanate's economy. Among melon products, the Khorezm melon variety was widely distributed. In his travelogue, A. Vamberi described the area as "a fertile land, continuously cultivated" when he passed through the Khanate [1-3].

In addition, horticulture was also one of the developed branches of agriculture in the khanate. In horticulture, grapes, apples, pomegranates, pears, peaches, and mulberries, which were the main food of silkworms, were widely planted. These products not only supplied the domestic market, but also played an important role in foreign trade. In Mahmud ibn Wali's work "Bahr ul-asrar," the author states that all types of fruits were grown in this region, except for walnuts [1, 4].

Literature Review

The internal and external trade of the khanate was especially developed in the 18th-19th centuries, and the covered markets of the Khiva Khanate in the city squares and on top of them were of particular importance in internal trade. Workshops and shops were built on both sides of the bazaar road. A special tax called tagijoy was collected from merchants for using the trading places in the market. The khanate mainly exported karakul skins, carpets, and handicraft products to countries such as Iran, India, China, and Turkey. Since the end of the 16th century, trade with Russia has also been established to some extent, and Khiva ambassadors mainly exported fabrics and textiles. For example, sources record that the Khiva ambassador sold 670 pieces of cloth in Kazan in 1620. Carpets, acacia fruit, karakul skins, and plant dyes were also exported to Russia. Khiva merchants actively participated in the Nizhny Novgorod fair in Russia. According to N. Muravyov, who came to Khiva in the 1820s, the khan's authority prohibited trading in several places at the same time [5-6].

Crafts were one of the leading sectors of the khanate's economy. Historical sources of the Khiva Khanate mention 27 branches of crafts, and in practice there were even more. Craftsmen worked hard for many years to become qualified masters. They had their own associations. These associations regulated the activities of craftsmen. In this way, they also protected their interests. The head of the association was also considered the person who carried out the khan's treasury policy. Very few of the Khiva craftsmen had their own private workshops - shops. Craftsmen could also open a shop in their own home. Most craftsmen worked by renting shops belonging to the khan and other wealthy people. Jewelry, textiles, locksmithing, blacksmithing, coppersmithing, and carpet weaving were the leading types of crafts. In the Khiva Khanate, economic relations were mainly based on agriculture, livestock breeding, crafts, and trade. In the khanate, land was considered state property, and various social

classes - owners, tenants, and herders - paid a fixed amount of tax to the state for its use.

As a result of the economic reforms carried out during the reign of Muhammad Rahimkhan I of the Kungrats, the tax system was simplified, and a monetary tax (solgut) was introduced instead of a product tax. Taxes began to be controlled by the central government. This led to an increase in revenues to the treasury and the stabilization of economic management [2]. Also, new lands were developed through the construction and repair of irrigation facilities, which further increased the potential of agriculture. In general, the economy of the Khiva Khanate was a complex but consistently developing system for its time.

Research Methodology

During the reign of Muhammad Rahimkhan I, a system of taking tax collection over to the central government, keeping the khan's income through special financial books, and direct control by the khan was introduced. This created an opportunity to limit the arbitrary appropriation of taxes by local officials, further increase the income of the state treasury, and strengthen the economic system.

Also, in the new system, taxes were set depending on the size of the land area, the type of products and the level of productivity. These reforms carried out by Muhammad Rahimkhan I were, of course, an important historical stage in restoring not only economic, but also social stability. As a result of the tax reform introduced by the Khan, the owners of the Khiva Khanate were divided into three groups in a clear order depending on their economic capabilities. The first group included large landowners with more than 10 tanobs of land, who paid a fixed tax of 3 gold coins to the state per year, regardless of the size of the land. The second group included owners with 5-10 tanobs of land, who paid 2 gold coins per year, and the third group consisted of small landowners (with land up to 5 tanobs) who paid a tax of 1 gold coin. Landless or small-land tenants, i.e., landless peasants, landless farmers, and users of waqf lands, also formed a separate category [2].

Their tax liability was determined according to the area of land they rented. In addition, the economic activities of the semi-nomadic and sedentary pastoralists in the territory of the Khiva Khanate were also taxed, and they paid the state not only a land tax, but also a zakat (cattle tax) related to livestock breeding. These aspects indicate that the state sought to keep the agrarian layer under full economic control. In the khanate, infrastructure and improvement work related to the agricultural sector significantly accelerated in recent years. In particular, during the reign of Said Muhammad Khan (1860-1863), the barren lands on the right bank of the Amu Darya were irrigated and new fertile lands were developed. This situation, along with expanding the demographic and economic potential of the oasis, marked a new stage in the agrarian strategy of the Khiva Khanate. During the reign of Said Muhammad Rakhimxon II (1863-1864), a broad path was opened for the development of entrepreneurship, trade, and crafts to stabilize the country's economy. The domestic market infrastructure was strengthened through the expansion of stalls, shops, and workshops in urban centers [6].

The Khanate's trade relations with Bukhara, Afghanistan, Iran, India, and Russia provided the foreign trade potential of the Khiva economy. During this period, the activity of more than 700 artisans was recorded in the city of Khiva itself, which strengthened the city's role as an economic center. During the reign of Khan Muhammad Rakhimkhan II of Khiva, special attention was paid to further improving the agricultural sector and water supply. Ancient canals such as Shahabad (Shovot), Polvan, Kilichniyozboy, and Lavzon were repaired and water transfer capabilities were expanded. In addition, the Shurakhon and Bozyop canals were reconstructed, and a new 39-kilometer canal was built downstream of the Lavzon canal, receiving water from the Amu Darya. As a result of these works, thousands of acres of land were redeveloped and old land plots were made suitable for irrigation [1].

The following types of land ownership existed in the Khiva Khanate:

- State-owned lands or royal lands;
- Lands belonging to private individuals;
- Lands belonging to religious institutions, that is, endowment lands [7].

Analysis and Results

Royal lands were lands directly belonging to the state, the khan, and were inherited from generation to generation. In addition to constantly irrigated arable land, state lands also included abandoned lands, sand dunes, hills and pastures, lakes and groves. State lands expanded due to the conquered territories, the confiscated lands of landowners against the khan, and the development of new lands, and state lands were allocated by the khan for use by landowners and tenant farmers, and landless people.

From such lands, up to 40-50 percent of the harvest received by the state was taxed in the form of products or money, and state lands were considered the main source of the khanate treasury. The khan gave state lands to officials who served him impartially, close relatives, servants who served him faithfully, and believers. Such lands were exempt from taxes.

The second type of private (property) lands belonged to the khan personally, his close relatives, large wealthy people, court officials, military and other nobles. The main part of the fertile and fertile lands in the central districts of the khanate, located near water, was concentrated in the hands of landowners, and according to data for the first half of the 19th century, the lands belonging to property owners accounted for more than half of all irrigated land in the khanate. According to sources, some landowners had from two to three thousand tanobs to tens of thousands of tanobs of land at their disposal. For example, the cities of Pitnak, Khazorasp and Shorokhan and the villages adjacent to them belonged to the amir ul-umaro. Muhammadaminkhan's son Abdullah granted more than 20 thousand tanobs of land to Tora, etc.

The third type of Waqf lands included lands and properties belonging to religious institutions, mosques, madrasas, cemeteries, and khanates. These properties were donated to religious institutions by the khan, officials, and certain individuals. The income from such lands was spent on the needs of religious institutions. According to information, in the middle of the 19th century, the total volume of waqf property in the khanate amounted to 170-175 thousand talibs. The majority of the Khiva Khanate's

peasants, who had little land and were generally landless and without horses and horses, worked on lease on state, property, and waqf lands.

Conclusion

These tax reforms and the reconstruction of irrigation facilities were an important stage in the Khiva Khanate in increasing economic efficiency, stabilizing the living standards of the population, and increasing revenue to the state treasury. These historical events indicate that specific changes began in the economic policy of the Khiva Khanate. Until the end of the 18th and beginning of the 20th centuries, the main areas of the khanate's economy were agriculture, horticulture, animal husbandry, crafts, trade, and fishing. Fishing also had a special importance in the khanate's economy and had its own multi-sectoral characteristics. It was considered not only a source of consumption for the population, but also a sector with its own characteristics in internal and external trade.

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Section 4. ACTUAL PROBLEMS OF NATURAL SCIENCES

UDC: 546:547

SYNTHESIS, STRUCTURAL CHARACTERIZATION, AND ANALYSIS OF THE Co(II) COMPLEX WITH 2-HYDROXYBENZAMIDE AND MONOETHANOLAMINE

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Annotatsiya. Ushbu maqolada, Co(II) ionining 2-gidroksibenzamid (salitsilamid, 2-OHBZA) va monoetanolamin (MEA) ligandlari bilan aralash ligandli kompleks birikmasi sintezi hamda uning fizik-kimyoviy xossalari bo'yicha ma'lumotlar keltirilgan. Kompleks birikma GT SONIC-D3 professional ultratovushli tozalagich (ultratovush to'lqinlari 40 kHz) qurilma yordamida spirt-suv muhitida sintez qilinib, IQ-spektroskopiya, SEM va element tarkibini aniqlash esa rentgen-flyuorestsent (XRF) tahlili orqali o'rganildi. IQ-spektr natijalari ligandlarning kislorod va azot donor atomlari orqali Co(II) ioniga koordinatsiyalanganligini ko'rsatdi. SEM tahlillari kompleks birikmaning ignasimon kristall morfologiyaga ega ekanligini tasdiqladi. XRF tahlili esa kompleks tarkibida kobalt elementi mavjudligini isbotladi. Olingan natijalar Co(II)-salitsilamid-MEA tizimida barqaror aralash ligandli kompleks hosil bo'lganini ko'rsatdi.

Kalit so'zlar: Co(II) atsetat, 2-gidroksibenzamid (salitsilamid, 2-OHBZA), monoetanolamin (MEA), IQ spektroskopiya, SEM tahlil, XRF tahlili.

Аннотация. В данной статье представлены результаты синтеза смешаннолигандного комплекса Co(II) с салициламидом и моноэтаноламином (MEA), а также исследованы его физико-химические свойства. Комплекс был синтезирован в водно-спиртовой среде с использованием профессионального ультразвукового очистителя GT SONIC-D3 с рабочей частотой 40 кГц. Полученное соединение было охарактеризовано методами ИК-Фурье-спектроскопии (FTIR) и сканирующей электронной микроскопии (SEM), а элементный состав определяли методом рентгенофлуоресцентного анализа (XRF). Результаты FTIR-спектроскопии показали, что координация к иону Co(II) осуществляется через донорные атомы кислорода и азота лигандов. SEM-анализ выявил игольчатую морфологию кристаллов комплекса. XRF-анализ подтвердил присутствие кобальта в структуре комплекса. Полученные результаты свидетельствуют об образовании стабильного смешаннолигандного комплекса в системе Co(II)–салициламид–MEA.

Ключевые слова: *Ацетат Co(II), 2-гидроксibenзамид (салициламид, 2-OHBZA), моноэтаноламин (MEA), ИК-спектроскопия, SEM-анализ, XRF-анализ.*

Abstract. This article presents the synthesis and physicochemical characterization of a mixed-ligand Co(II) complex with salicylamide and monoethanolamine (MEA) ligands. The complex was synthesized in an alcohol–water medium using a GT SONIC-D3 professional ultrasonic cleaner operating at a frequency of 40 kHz. The obtained product was characterized by Fourier-transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM), while its elemental composition was determined by X-ray fluorescence (XRF) analysis. FTIR results indicated that coordination to the Co(II) ion occurs through the oxygen and nitrogen donor atoms of the ligands. SEM analysis revealed a needle-like crystal morphology of the synthesized complex. XRF analysis confirmed the presence of cobalt in the complex structure. The obtained results demonstrate the formation of a stable mixed-ligand complex in the Co(II)–salicylamide–MEA system.

Keywords: *Co(II) acetate, 2-hydroxybenzamide (salicylamide, 2-OHBZA), monoethanolamine (MEA), IR spectroscopy, SEM analysis, XRF analysis.*

Introduction

Coordination chemistry is one of the rapidly developing fields of modern inorganic chemistry, and the synthesis of mixed-ligand coordination compounds together with the investigation of their physicochemical properties is of considerable scientific and practical importance. Owing to the simultaneous presence of ligands of different chemical nature within the coordination sphere, such compounds often exhibit higher stability, distinctive electronic structures, enhanced catalytic activity, and diverse biological properties compared with simple coordination compounds [1].

Therefore, the synthesis of mixed-ligand complexes based on transition metals and the elucidation of their structures using modern spectroscopic techniques represent one of the current priorities in coordination chemistry. Cobalt(II) ions are characterized by their ability to form complexes with various coordination numbers and geometries. The d7 electronic configuration of the Co(II) ion is highly sensitive to ligand field effects, which significantly influence the magnetic, spectroscopic, and catalytic properties of the resulting complexes [2]. Consequently, Co(II)-based coordination compounds have attracted considerable interest owing to their potential applications in catalysis, bioinorganic chemistry, pharmaceutical science, and materials engineering [3]. In particular, complexes containing ligands with nitrogen- and oxygen-donor atoms have received special attention because of their high coordination stability and pronounced biological activity.

2-Hydroxybenzamide (2-OHBZA) contains both phenolic hydroxyl and amide functional groups and can serve as a potential O- and N-donor ligand. Depending on the coordination environment, this ligand is capable of coordinating to metal ions in either monodentate or bidentate modes, leading to the formation of stable chelate complexes. Furthermore, salicylamide derivatives are pharmacologically important

compounds and are known to possess anti-inflammatory, analgesic, and antimicrobial activities against bacteria, fungi, certain viruses, and protozoa [4].

Monoethanolamine (MEA) is a bifunctional ligand containing amino and hydroxyl groups. It coordinates to metal ions through the amino nitrogen atom and the hydroxyl oxygen atom, resulting in the formation of five-membered chelate rings. Such coordination enhances both the thermal and coordination stability of the complexes. Moreover, ethanolamine derivatives are widely employed in catalytic systems, sol-gel technologies, and the synthesis of biologically active coordination compounds [5].

A survey of the available literature reveals that although complexes of salicylamide with several transition metals have been reported, mixed-ligand complexes formed by Co(II) ions with 2-hydroxybenzamide and monoethanolamine have not been sufficiently investigated. In particular, comprehensive studies concerning their spectral characteristics, morphology, and elemental composition remain scarce.

Therefore, the aim of the present work was to synthesize a novel mixed-ligand coordination compound based on cobalt(II) acetate, 2-hydroxybenzamide, and monoethanolamine, and to investigate its structure and properties using Fourier-transform infrared (FT-IR) spectroscopy, scanning electron microscopy (SEM), and X-ray fluorescence (XRF) analysis.

Literature Review

In recent years, interest in mixed-ligand coordination compounds has increased considerably. This is primarily due to their high thermal and chemical stability, catalytic activity, and biological properties. In mixed-ligand complexes, the coordination of ligands of different chemical nature around a single metal center modifies the electronic structure and coordination environment of the metal ion, thereby enabling control over the physicochemical and biological properties of the resulting complexes [6]. In particular, ligands containing oxygen- and nitrogen-donor atoms form strong coordination bonds with transition metals, making it possible to synthesize highly stable complexes [7, 8].

Studies carried out by Mohapatra and co-workers demonstrated, through molecular docking analysis, that mixed-ligand complexes interact effectively with biologically active sites, indicating their potential pharmaceutical applications [9].

Among the ligands employed in the synthesis of mixed-ligand complexes, aromatic amide-containing ligands occupy a special position. One such ligand is salicylamide, whose molecular structure contains both phenolic and amide functional groups, allowing the formation of chelate complexes with metal ions. The coordination properties of salicylamide toward Fe(III), Co(II), and Ni(II) ions were investigated by Pannu and Chopra. The authors established that salicylamide forms stable complexes with these metal ions. According to FT-IR spectral data, the ligand coordinates mainly through the phenolic oxygen atom and the carbonyl oxygen atom. Magnetic susceptibility measurements revealed that the Fe(III) complex possesses an octahedral geometry, whereas the Co(II) and Ni(II) complexes exhibit tetrahedral geometries. These findings confirm the ability of salicylamide to act as an oxygen-donor ligand and to form stable coordination compounds with transition metals [10].

Salicylamide and structurally related hydroxybenzamide derivatives are also widely used ligands in coordination chemistry. The presence of both hydroxyl and amide groups within the same molecule provides various coordination possibilities toward metal ions. Shang and co-workers investigated the biological activity of tin(IV) complexes derived from N-hydroxybenzamide ligands and demonstrated that the presence of halogen substituents in the ligand framework significantly influences the cytotoxic properties of the complexes [11]. These results indicate that hydroxybenzamide derivatives are promising ligands not only in coordination chemistry but also in bioinorganic chemistry.

The coordination properties of amide derivatives toward cobalt ions have also been investigated by several researchers. In particular, Koikawa and co-workers synthesized Co(III) and Co(IV) complexes based on N-(2-hydroxyphenyl)salicylamide ligands and demonstrated that ligand field effects significantly influence the oxidation state and coordination geometry of the cobalt center [12]. These studies showed that cobalt ions are capable of forming diverse coordination environments with ligands containing amide and phenolic functional groups.

In mixed-ligand systems, amino alcohols, particularly monoethanolamine (MEA), have attracted considerable attention as secondary ligands. The simultaneous presence of hydroxyl and amino groups within the monoethanolamine molecule enables it to act as a bidentate ligand and to form stable complexes with metal ions. Yilmaz and co-workers investigated the thermal properties of transition metal complexes containing monoethanolamine and reported that strong coordination between the MEA ligand and the metal center enhances the thermal stability of the resulting complexes [13]. Furthermore, the nitrogen and oxygen donor atoms of monoethanolamine play an important role in determining the coordination number and geometry of the metal ion.

Spectroscopic techniques are indispensable tools for elucidating the structures of coordination compounds. In his fundamental studies, Nakamoto comprehensively described the capabilities of infrared spectroscopy for identifying metal–ligand interactions [14]. The author demonstrated that the $\nu(\text{M}-\text{O})$ and $\nu(\text{M}-\text{N})$ vibrational bands serve as key diagnostic features confirming complex formation. Consequently, FT-IR spectroscopy, elemental analysis, and magnetic measurements are regarded as complementary techniques for the characterization of coordination compounds.

The literature survey indicates that numerous investigations have been devoted to individual metal complexes of salicylamide and monoethanolamine, as well as cobalt complexes of salicylamide derivatives. However, mixed-ligand complexes formed by Co(II) ions with salicylamide and monoethanolamine, including their synthesis, coordination features, morphological characteristics, elemental composition, and spectroscopic properties, have not been sufficiently investigated. Therefore, comprehensive investigation of the Co(II)–2-hydroxybenzamide–monoethanolamine system is of considerable scientific significance for filling the existing knowledge gap in coordination chemistry and for the development of novel coordination compounds with potentially valuable properties.

Research Methodology

Initially, 0.177 g (1 mmol) of cobalt(II) acetate, $\text{Co}(\text{CH}_3\text{COO})_2$, was weighed and dissolved in a mixed solvent consisting of 5 ml of distilled water and 5 ml of ethanol. Separately, solutions of 2-hydroxybenzamide (2-OHBZA) (0.274 g, 2 mmol) and monoethanolamine (MEA) (0.061 ml, $\rho = 1.01 \text{ g/cm}^3$, 1 mmol) were prepared in 10 ml of ethanol. The pH value of the 2-OHBZA solution at room temperature (25 °C) was found to be 6.36. The MEA solution was subsequently mixed with the 2-OHBZA solution. Thereafter, the cobalt(II) acetate solution was added dropwise to the resulting reaction mixture. The synthesis was carried out under ultrasonic irradiation (40 kHz) at 60–70 °C for 20 min. During the reaction, the pH was maintained within the range of 6–7 using an ammonium buffer solution. Upon completion of the reaction, the solution was cooled to room temperature and kept in a thermostatically controlled chamber at 40 °C for six days. The pale pink crystals obtained were purified by recrystallization from an ethanol–water mixture. The synthesis reaction can be represented by the following equation:

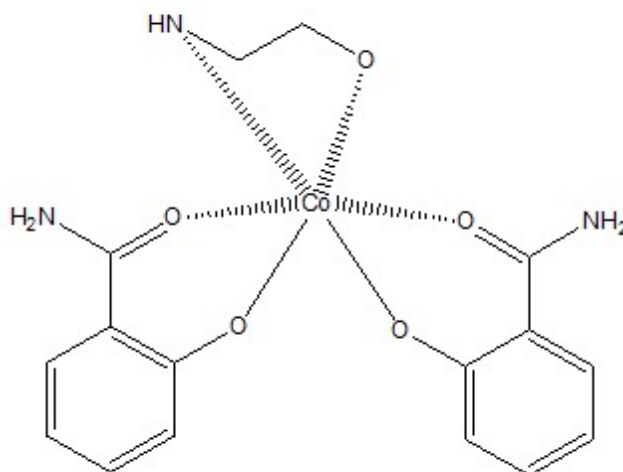
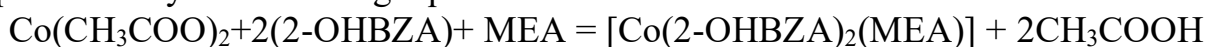


Figure 1. Proposed structure of the $[\text{Co}(2\text{-OHBZA})_2(\text{MEA})]$ complex inferred from the experimental data.

Analysis and Results

To determine the composition and coordination characteristics of the mixed-ligand complex formed by Co(II) ions with 2-hydroxybenzamide (2-OHBZA) and monoethanolamine (MEA), FT-IR spectroscopy, scanning electron microscopy (SEM), and X-ray fluorescence (XRF) analyses were performed. The obtained results confirmed the successful formation of the complex. According to the FT-IR spectral analysis (Figure 2), the sharp stretching vibrations of the amino group, $\nu(\text{NH}_2)$, observed at 3408 cm^{-1} and 3360 cm^{-1} in the spectrum of 2-hydroxybenzamide, as well as the broad band at 3203 cm^{-1} assigned to the hydrogen-bonded phenolic hydroxyl group, $\nu(\text{OH})$, undergo significant changes upon complex formation. In particular, the characteristic Amide I band ($\text{C}=\text{O}$) of the ligand observed at 1693 cm^{-1} shifted to 1633 cm^{-1} in the spectrum of the complex ($\Delta\nu = 60 \text{ cm}^{-1}$), suggesting the involvement of the carbonyl oxygen atom in coordination with the metal ion [14]. Furthermore, the appearance of $\nu(\text{Co}-\text{O})$ and $\nu(\text{Co}-\text{N})$ vibrational bands in the fingerprint region ($600\text{--}400 \text{ cm}^{-1}$), which are absent in the spectrum of the free ligand, indicates coordination

between the cobalt ion and the ligands and constitutes one of the spectral features supporting the formation of the mixed-ligand complex. To investigate the morphology and elemental composition of the synthesized mixed-ligand complex based on Co(II), 2-hydroxybenzamide (2-OHBZA), and monoethanolamine (MEA), scanning electron microscopy (SEM) coupled with elemental mapping analysis was performed, and the obtained results were subsequently analyzed (Figure 2).

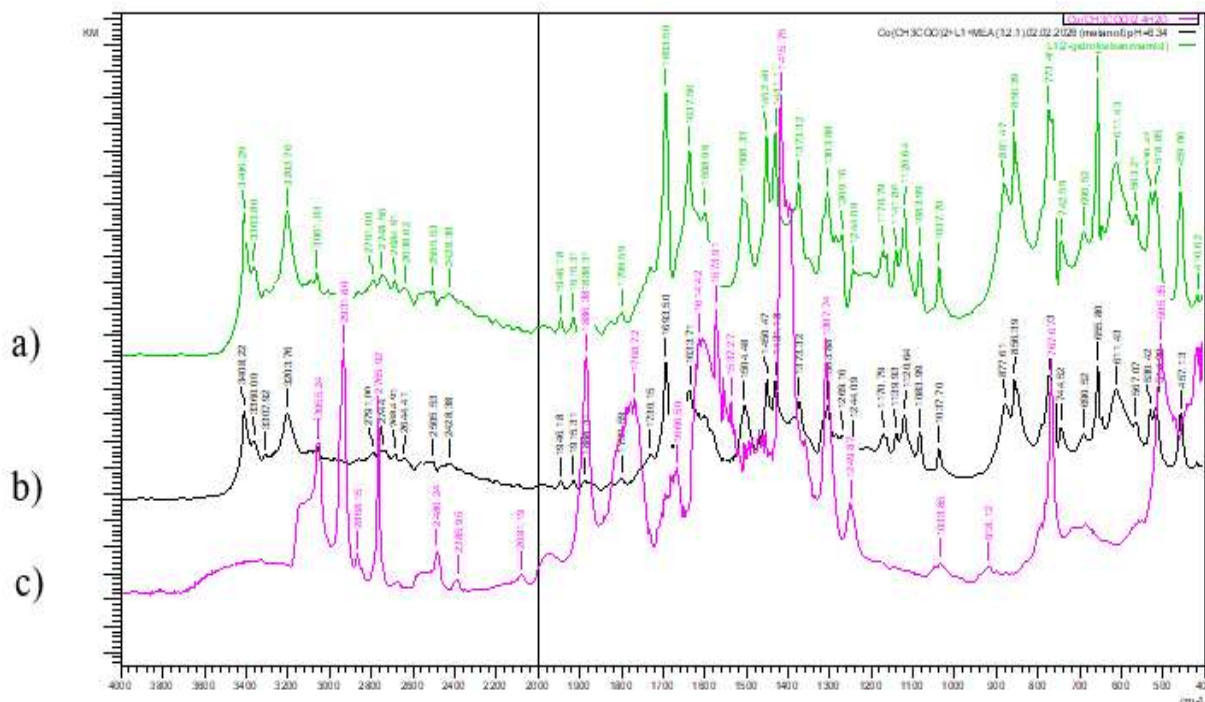


Figure 2. FT-IR spectra of (a) 2-hydroxybenzamide (2-OHBZA), (b) the $[\text{Co}(\text{2-OHBZA})_2(\text{MEA})]$ complex, and (c) $\text{Co}(\text{CH}_3\text{COO})_2$.

SEM micrographs revealed that the sample exhibits a micrometer-scale, needle-like crystalline morphology. The complex shows a high degree of crystallinity and phase homogeneity, indicating the absence of distinguishable crystalline domains corresponding to the initial reactants. This confirms the formation of a uniform crystalline morphology characteristic of the complex compound. In the 0.2–0.6 keV energy range, intense and well-defined characteristic peaks corresponding to carbon (C-K), nitrogen (N-K), and oxygen (O-K) are clearly observed. The presence of nitrogen and oxygen signals confirms the successful coordination of salicylamide and MEA molecules within the complex structure. In the 0.7–0.8 keV range, a weak-intensity peak attributable to cobalt is detected, while at approximately 6.9 keV and 7.5 keV, the characteristic and intense Co-K α and Co-K β peaks are observed, respectively. These signals unambiguously confirm the presence of cobalt as the central metal ion in the investigated sample [15].

The graph presented in Figure 4 was obtained using a Rigaku X-ray fluorescence (XRF) spectrometer and provides a qualitative characterization of the elemental composition of the sample. In the “Heavy” region of the spectrum (right-hand side of the graph), the Co-K α and Co-K β_1 peaks exhibit the highest intensity. This confirms that cobalt is the primary metallic component of the sample, serving as its central metal basis.

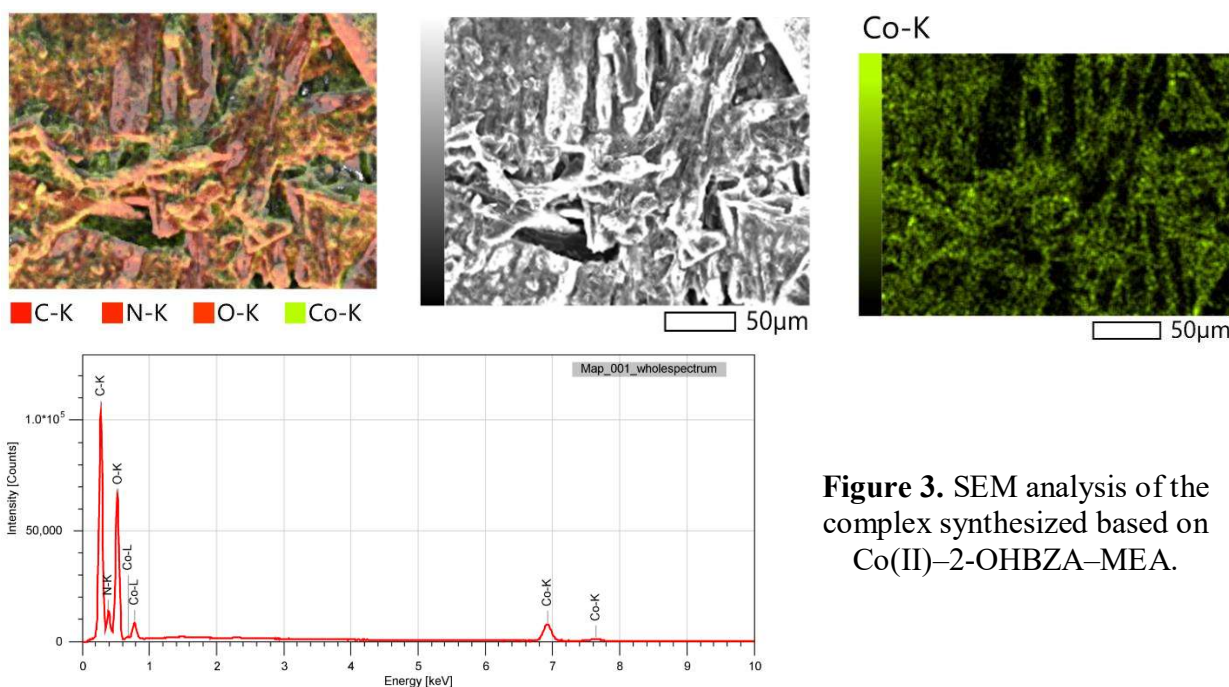


Figure 3. SEM analysis of the complex synthesized based on Co(II)–2-OHBZA–MEA.

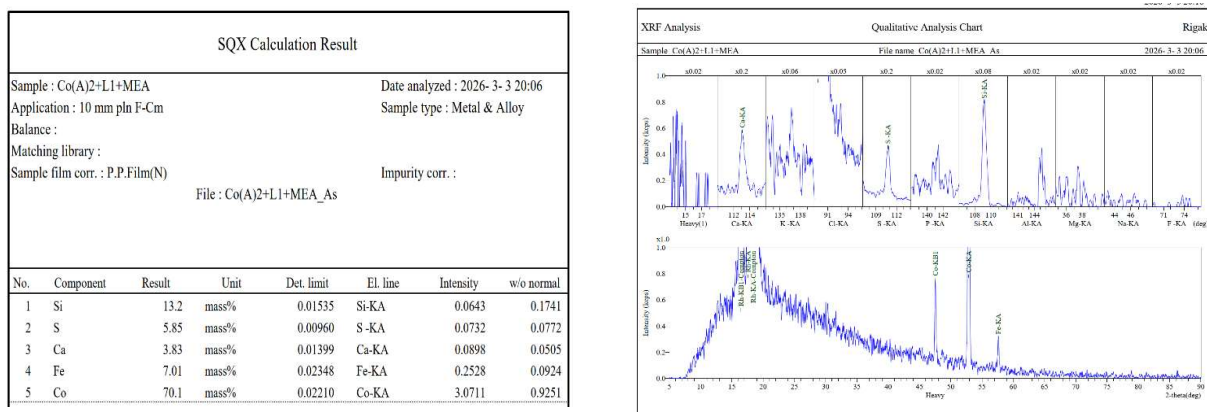


Figure 4. X-ray fluorescence (XRF) spectrum of the complex synthesized based on Co(II) + 2-OHBZA + MEA.

The low-intensity peaks of silicon (Si), calcium (Ca), chlorine (Cl), and other light elements observed in the spectrum are attributed to trace amounts of technological impurities in the sample or to background noise arising during the analysis process. In addition, the Rh (rhodium) signals correspond to characteristic radiation reflected from the X-ray tube of the instrument [16].

Conclusion

In this study, a new mixed-ligand coordination compound of Co(II) based on 2-OHBZA and MEA was successfully synthesized using an ultrasonic-assisted method. The infrared (IR) spectroscopic results indicate the probable coordination of the ligands to the Co(II) ion, suggesting the formation of new Co–O and Co–N coordination bonds (Figure 2). SEM analysis revealed that the obtained compound exhibits a high degree of crystallinity together with a homogeneous needle-like micro-morphology (Figure



3). Furthermore, XRF analysis confirmed the presence of cobalt in the sample (Figure 4). The synthesized complex is considered promising for further investigation as a biologically active compound or as a potential antibacterial agent for medical applications.

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Section 5. ACTUAL PROBLEMS IN MODERN AGRICULTURE

UDC: 631.4, 528.8

INTEGRATING EMI, MULTI-SENSOR REMOTE SENSING, AND MACHINE LEARNING FOR HIGH-RESOLUTION DIAGNOSTICS OF SOIL SALINITY IN THE AMU DARYA RIVER DELTA

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Annotatsiya. Tuproq sho'lanishi qurg'oqchil hududlarning sug'oriladigan yerlarida, xususan Markaziy Osiyodagi Orol dengizi havzasida, yer degradatsiyasini keltirib chiqaruvchi keng tarqalgan ekologik omil hisoblanadi. Ushbu tadqiqotda Google Earth Engine (GEE) platformasida yaqin masofali elektromagnit induksiya (EMI) so'rovlarini ko'p sensorli sun'iy yo'ldosh tasvirlari bilan birlashtirgan holda tuproqning zohiriy elektr o'tkazuvchanligini (ECa) yuqori aniqlikda xaritalash usuli taqdim etiladi. EM38-MK2 sensori yordamida O'zbekistonning Xorazm viloyatidagi 526,4 gektar qishloq xo'jaligi yerlarida 21396 ta nuqtada ECa o'chovlari to'plandi. Bu ma'umotlar 2024-yilgi sug'rish mavsumiga oid ko'p vaqtli Sentinel-2 (NDVI, NDWI, EVI), Sentinel-1 (VV, VH) va ALOS-2 PALSAR-2 (HH, HV) kompozitlari bilan birlashtirildi. ECa ni bashorat qilish uchun tasodifiy o'rmon (Random Forest) regressiya modeli o'qitildi va yuqori aniqlikdagi tekshiruv natijalarini ko'rsatdi ($R^2 = 0,925$, RMSE

= 4,27 dS/m). Tahlilga ko'ra, ekinlarning muhim rivojlanish bosqichlaridagi NDVI va Sentinel-1 VH orqa sochilishi eng ta'sirchan omillar sifatida aniqlandi. 20 metr aniqlikdagi sho'rlanish xaritasi tasnifi shuni ko'rsatdiki, tadqiq etilgan hududning 69,3 foizi yuqori va o'ta yuqori sho'lanishga uchragan, 18,4 foizi (96,4 gektar) esa og'ir sho'lanish toifasiga kiradi. Natijalar ko'p sensorli masofadan zondlashni zich EMI so'rovlari bilan birlashtirish sug'riladigan ekin maydonlarida tuproq sho'lanishini aniq baholash uchun kengaytiriladigan, tejamkor yondashuv ekanligini ko'rsatadi.

Kalit so'zlar: raqamli tuproq xaritalash, elektromagnit induksiya (EMI), EM38-MK2, Google Earth Engine, tasodifiy o'rmon, tuproq sho'lanishi diagnostikasi, Markaziy Osiyo, Sentinel.

Аннотация. Засоление почв является широко распространённым экологическим фактором, вызывающим деградацию земель на орошаемых территориях засушливых регионов, в частности в бассейне Аральского моря в Центральной Азии. В данном исследовании представлен высокоточный диагностический подход к картированию кажущейся электропроводности почвы (ЕСа) путём интеграции наземных съёмок методом электромагнитной индукции (EMI) с многоспектральными спутниковыми снимками на платформе Google Earth Engine (GEE). С помощью датчика EM38-MK2 было собрано 21396 наземных измерений ЕСа на площади 526,4 га сельскохозяйственных полей Хорезмской области Узбекистана. Эти данные были объединены с разновременными композитами Sentinel-2 (NDVI, NDWI, EVI), Sentinel-1 (VV, VH) и ALOS-2 PALSAR-2 (HH, HV) за ирригационный сезон 2024 года. Для прогнозирования ЕСа была обучена модель регрессии случайного леса (Random Forest), показавшая высокую точность валидации ($R^2 = 0,925$, RMSE = 4,27 дСм/м). Согласно анализу, NDVI на критических стадиях роста культур и обратное рассеяние Sentinel-1 VH оказались наиболее значимыми предикторами. Классификация полученной карты засоления с разрешением 20 м показала, что 69,3% исследуемой территории подвержено высокому и экстремальному засолению, а 18,4% (96,4 га) земель относится к категории сильного засоления.

Ключевые слова: цифровое картирование почв, электромагнитная индукция (EMI), EM38-MK2, Google Earth Engine, случайный лес, диагностика засоления почв, Центральная Азия, Sentinel.

Abstract. Soil salinity is a pervasive environmental stressor triggering land degradation in irrigated areas of arid regions, notably in the Aral Sea Basin of Central Asia. This study presents a high-resolution diagnostic approach to map soil apparent electrical conductivity (ECa) by integrating proximal Electromagnetic Induction (EMI) surveys with multi-sensor satellite imagery within the Google Earth Engine (GEE) platform. Using an EM38-MK2 sensor, we collected 21,396 in-situ ECa measurements across 526.4 ha of agricultural fields in the Khorezm region of Uzbekistan. These measurements were combined with multi-temporal Sentinel-2 (NDVI, NDWI, EVI), Sentinel-1 (VV, VH), and

ALOS-2 PALSAR-2 (HH, HV) composites from the 2024 irrigation season. A Random Forest (RF) regression model was trained to predict EC_a, with robust validation performance ($R^2 = 0.925$, RMSE = 4.27 dS/m). According to the analysis NDVI during critical crop growth stages and Sentinel-1 VH backscatter were found out as the most influential predictors, underlining the synergy between crop water stress and soil salinity. The classification of the resulting 20m resolution salinity map revealed that 69.3% of the studied area is affected by high to extreme salinity while 18.4% (96.4 ha) of the lands fall into the severe salinity category. Our findings demonstrate that the integration of multi-sensor remote sensing with dense EMI surveys provides a scalable, cost-effective framework for precise assessment of soil salinity, providing essential insights for sustainable land management in irrigated croplands.

Keywords: *Digital Soil Mapping, Electromagnetic Induction (EMI), EM38-MK2, Google Earth Engine, Random Forest, Soil Salinity, Diagnostics, Central Asia, Sentinel.*

Introduction

Soil salinization is a major pedogenic threat to global food security, affecting over 1 billion hectares of land worldwide, predominantly in arid and semi-arid regions (Ivushkin et al., 2019). In Central Asia, the problem is acutely manifested in the Amu Darya River Delta, where decades of intensive irrigation under a continental climate, coupled with inefficient drainage systems, have triggered widespread secondary salinization (Conrad et al., 2016; Jiang et al., 2024). The resulting accumulation of soluble salts in the root zone severely compromises soil health, reduces crop yields, and undermines the sustainability of agricultural systems (Schmitter et al., 2020).

Traditional methods for assessing soil salinity, based on laboratory analysis of soil saturation extract electrical conductivity (EC_e), are analytically precise but constrained by their point-based, destructive, and labor-intensive nature, rendering them impractical for large-area, high-resolution mapping (Allbed and Kumar, 2013; Wang et al., 2022). Proximal soil sensing, particularly using non-invasive Electromagnetic Induction (EMI) instruments like the EM38-MK2, provides a rapid and reliable alternative by measuring the soil's bulk apparent electrical conductivity (EC_a), which is highly correlated with EC_e, moisture, and clay content (Huang et al., 2017; Corwin and Scudiero, 2020; Scudiero et al., 2021).

Concurrently, satellite remote sensing offers the synoptic and repetitive coverage essential for regional-scale diagnostics. Optical indices, such as the Normalized Difference Vegetation Index (NDVI), serve as indirect indicators of plant stress induced by salinity, while microwave data from Sentinel-1 is sensitive to surface soil moisture and roughness key covariates of salt concentration (Gorji et al., 2020; Zhuo et al., 2023). The fusion of these multi-scale datasets through machine learning (ML) algorithms represents a paradigm shift in digital soil mapping (DSM), enabling the prediction of subsurface properties from surface manifestations (Wadoux et al., 2020; Taghizadeh-Mehriardi et al., 2021).

Cloud-computing platforms like Google Earth Engine (GEE) have democratized access to vast satellite archives and processing power, facilitating the efficient

implementation of such integrated workflows (Gorelick et al., 2017). While previous studies in the region have demonstrated the value of multi-temporal optical data (Sultanov et al., 2019) or environmental covariates (Akramkhanov and Vlek, 2012), few have leveraged the combined potential of dense EMI surveys, multi-sensor (optical + radar) Sentinel data, ALOS-2 PALSAR-2, and ML within a cloud-processing framework for high-resolution salinity diagnostics. This study addresses this gap by pursuing three primary objectives:

1. to develop a robust Random Forest model for predicting soil ECa using integrated Sentinel-1 and Sentinel-2 features;
2. to generate and validate a high-resolution (20m) diagnostic salinity map for an agricultural site in Khorezm, Uzbekistan; and
3. to quantify the spatial extent of salinity severity to inform targeted land reclamation strategies.

Research Methodology

The research was conducted in an intensively irrigated agricultural domain (524.6 ha) within the Lower Amu Darya River Delta, Khorezm, Uzbekistan (approx. 60.52°E–60.58°E, 41.58°N–41.61°N). This area epitomizes the environmental challenges of the inner Aral Sea Basin: flat topography, an extreme continental climate with potential evapotranspiration far exceeding annual precipitation (~92 mm), and a dense, largely unlined irrigation network (Ibrakhimov et al., 2007). The dominant land use is rotating cotton and wheat cultivation, systems highly vulnerable to yield variability induced by soil salinity and shallow, saline groundwater. The geographical context and detailed layout of the study area, including the distribution of soil samples, EMI measurement points, and crop fields, are presented in Figure 1.

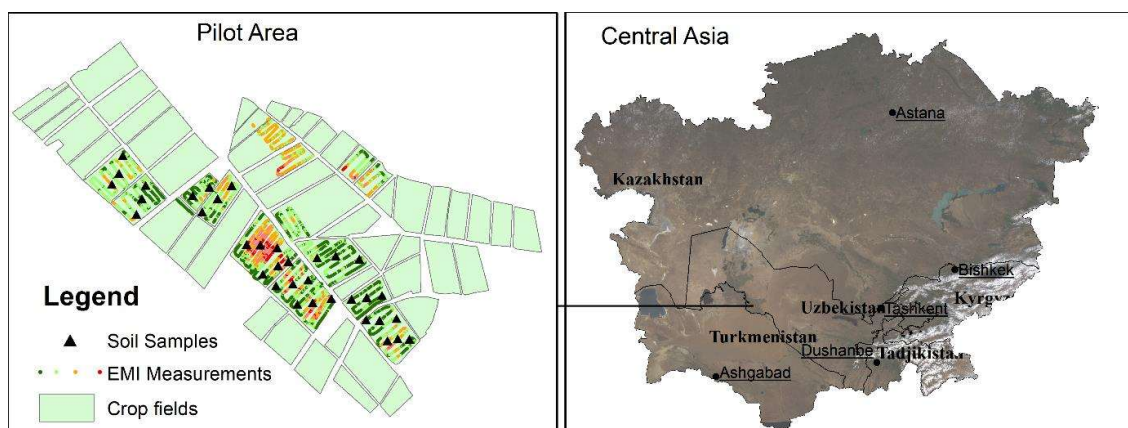


Figure 1. Study area, irrigated cropland in upper Amu Darya delta, Uzbekistan, Central Asia.

Data Sources and Preprocessing

In-Situ EMI Data: A Geonics EM38-MK2 sensor was deployed to collect 21,396 georeferenced ECa measurements in the vertical dipole mode, providing a depth-weighted measurement representative of ~0.75 m depth. Surveys were conducted along systematic transects designed to capture the full spectrum of salinity conditions across 57 agricultural fields.

Satellite Imagery & Processing in GEE: Multi-temporal Sentinel-2 (Level-2A), Sentinel-1 (GRD), and ALOS-2 PALSAR-2 data were acquired from March 1 to August 28, 2024, covering the primary irrigation and crop growth season. Within GEE, 20-day composites were generated to mitigate atmospheric and noise artifacts. For Sentinel-2, we computed NDVI, NDWI, and EVI; for Sentinel-1, VV and VH polarizations with their ratio; and for ALOS-2 PALSAR-2, HH and HV polarizations with their ratio. This resulted in 81 temporal features across 9 composite periods.

ALOS-2 PALSAR-2: Yearly SAR epoch data (2023-2024) from JAXA's ALOS PALSAR/YEARLY/SAR_EPOCH collection were incorporated, extracting HH and HV polarizations and their ratio for each 20-day composite period to provide additional soil moisture and structure information.

Research Methodology

The analytical pipeline consisted of four integrated stages:

Data Fusion: The EMI point data was imported into GEE. For each point, the corresponding pixel values from all satellite-derived predictor layers (81 multi-temporal features including NDVI, NDWI, EVI, VV, VH, HH, HV and their ratios across 9 periods) were extracted, creating a consolidated modeling dataset.

Predictive Modeling: A Random Forest regression algorithm was implemented using the ranger package in R. The model was trained to predict the in-situ ECa values using the satellite predictors. The dataset was partitioned 80/20 for training and independent validation. Key hyperparameters (number of trees = 500, mtry = 2) were set, and model performance was evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). For spatial prediction, the model was retrained using only the 81 temporal features common to both training and prediction datasets to ensure feature alignment.

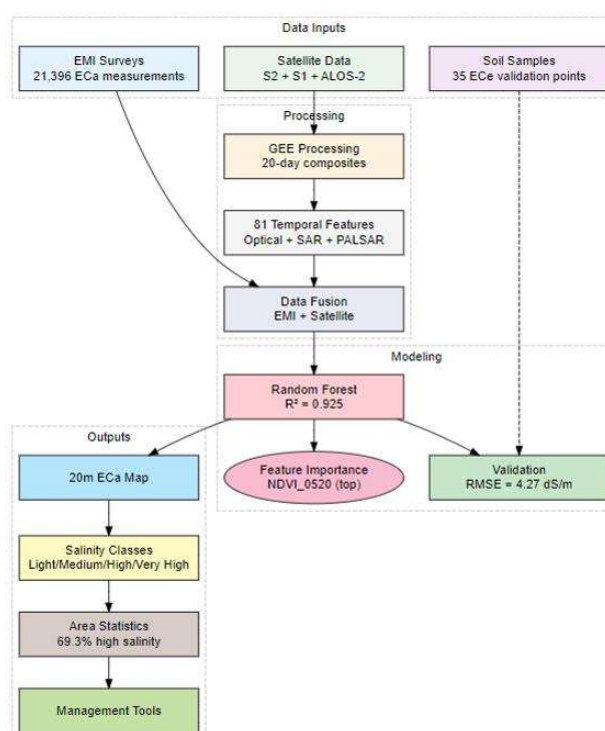


Figure 2. Methodological workflow integrating EMI surveys, multi-sensor remote sensing, and machine learning for soil salinity diagnostics.

Spatial Prediction: A uniform 20 m prediction grid was generated over the study area. The trained RF model was applied to the satellite predictor stacks to generate a continuous, wall-to-wall map of predicted ECa.

Zonation and quantification of salinity: The continuous ECa map was classified into four salinity severity classes — Light (<40 dS/m), Medium (40–80 dS/m), High (80–120 dS/m), and Very High (>120 dS/m) — informed by regional agronomic studies (Akramkhanov and Vlek, 2012). The total areal extent for each class was calculated. The methodological workflow is presented in Figure 2.

Table 1. Number of available satellite images in 20-day composite intervals between March and August 2024, showing Sentinel-2, Sentinel-1, and ALOS PALSAR-2 data availability.

Composite Period	Sentinel-2 (Optical)	Sentinel-1 (Radar)	ALOS PALSAR-2 (Radar)
2024-03-01 – 2024-03-21	8	5	2
2024-03-21 – 2024-04-10	8	4	2
2024-04-10 – 2024-04-30	8	6	2
2024-04-30 – 2024-05-20	8	5	2
2024-05-20 – 2024-06-09	8	4	2
2024-06-09 – 2024-06-29	8	6	2
2024-06-29 – 2024-07-19	8	5	2
2024-07-19 – 2024-08-08	8	4	2
2024-08-08 – 2024-08-28	8	6	2
Total Bands in Composite	81		

Analysis and Results

The Random Forest model demonstrated exceptional performance in predicting subsurface ECa from the satellite-derived feature set. Validation on the held-out test set yielded an R^2 of 0.925, with RMSE of 4.27 dS/m. This high explanatory power surpasses that of many previous studies in the region (e.g., Sultanov et al., 2019, reported R^2 of 0.36–0.50) and underscores the efficacy of integrating dense EMI surveys with multi-sensor satellite data within an ML framework (Scudiero et al., 2021). Variable importance analysis revealed NDVI_0520 (May 20 period) as the most influential predictor, followed by NDWI_0520, NDWI_0321, and NDVI_0808, indicating critical salinity stress periods during key crop growth stages. The dominance of optical indices during May underscores the tight coupling between crop vigor and root-zone salinity stress (Lobell et al., 2010). The strong contribution of Sentinel-1 VH polarization highlights the critical role of soil moisture—a key driver of ECa—in the model's predictive capability, as radar backscatter is highly sensitive to the dielectric properties of the soil surface (Bousbih et al., 2019; Zhuo et al., 2023).

Spatial Patterns and Salinity Severity. The resulting 20m diagnostic map reveals a heterogeneous and spatially complex salinity landscape (Fig. 3). Hotspots of high and very high salinity are not randomly distributed but exhibit distinct clustering, particularly in topographical depressions and along field margins. These patterns are consistent with areas of poor drainage and waterlogging, where capillary rise and evaporative concentration are exacerbated (Ibrakhimov et al., 2007; Schmitter et al., 2020).

The classification of the predicted ECa map provides a stark quantitative assessment of land degradation:

- Light salinity (3.0 ha; 0.6%)
- Medium salinity (158.1 ha; 30.1%)
- High salinity (267.4 ha; 50.9%)
- Very High salinity (96.4 ha; 18.4%)

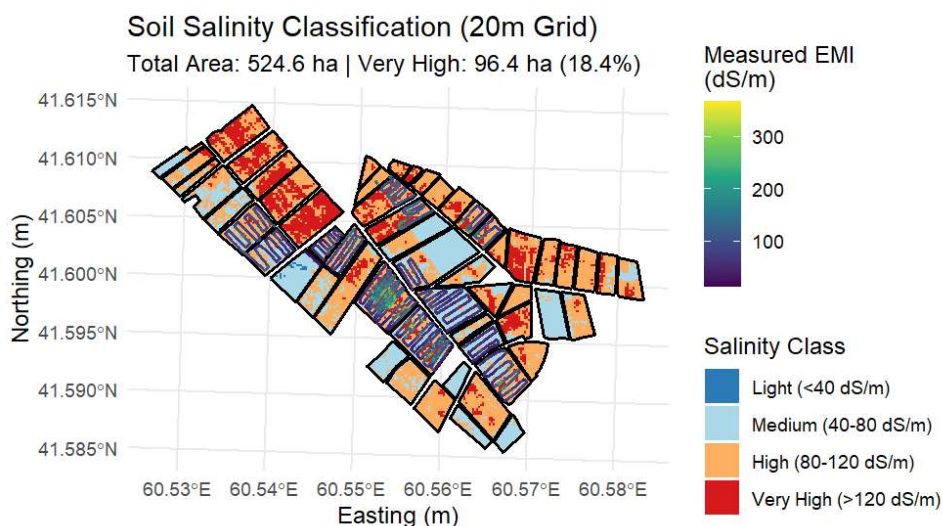


Figure 3. Predicted Soil Salinity Map generated from 81 multi-temporal features using Random Forest regression ($R^2 = 0.925$).

Critically, 69.3% of the agricultural land is affected by high to very high salinity. This extensive salinization poses a severe threat to regional food security and necessitates immediate intervention. The spatial explicitness of the map allows for prioritizing sub-areas for reclamation, such as targeted installation of drainage infrastructure or the application of cyclic irrigation with less saline water (Singh, 2022).

Conclusion

This study successfully demonstrates a scalable, integrated framework for high-resolution soil salinity diagnostics by coupling dense proximal EMI surveys with multi-sensor satellite analytics and machine learning in the Google Earth Engine cloud. The key conclusions are:

- The Random Forest model achieved outstanding predictive accuracy ($R^2 = 0.925$), validating the synergistic use of optical and radar satellite data for mapping subsurface ECa.
- The variable importance analysis provided physically interpretable insights, identifying NDVI during critical crop growth stages (May-20 period) and soil moisture (Sentinel-1 VH) as primary drivers of the model.
- The quantification reveals a severe salinity problem, with over two-thirds of the studied agricultural land requiring urgent management intervention.

The presented method of soil salinity assessment is not only cost-effective but also inherently transferable to other irrigated arid regions facing similar salinity challenges. Having rapid assessment and essential information of soil salinity and additionally considering potential salinity effects on crop yields, farmers can plan on

crop choices for each field or subfield eventually minimizing salt management costs and maximizing cropping revenues. Future work will focus on incorporating multi-annual time-series analysis to monitor temporal salinity dynamics and integrating additional covariates, such as detailed soil texture maps and distance-to-drainage metrics, to further enhance model robustness and practical utility for precision agriculture.

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PROSPECTS FOR CAMEL WOOL PRODUCTION WORLDWIDE AND UZBEKISTAN’S OPPORTUNITIES IN THIS SECTOR

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Annotatsiya. Mazkur maqolada dunyoda tuya juni yetishtirish va uni qayta ishlashning bugungi holati, rivojlanish tendensiyalari hamda O‘zbekistonning ushbu sohadagi imkoniyatlari ilmiy jihatdan tahlil qilindi. Tuya juni yuqori issiqlikni saqlash xususiyati, yengilligi, mustahkamligi, ekologik tozaligi va hipoallergenligi bilan boshqa tabiiy tolalardan ajralib turadi. Shu sababli undan tayyorlangan mahsulotlarga xalqaro bozorda talab yildan-yilga ortib bormoqda. Maqolada Mongoliya, Xitoy, Qozog‘iston, Eron va boshqa davlatlarning tuya juni ishlab chiqarish hamda qayta ishlash bo‘yicha tajribalari tahlil qilindi. Shuningdek, O‘zbekistonning tabiiy-iqlim sharoiti, tuyachilik an‘analari va mavjud resurslari asosida ushbu tarmoqni rivojlantirish istiqbollari baholandi. Tadqiqot davomida qiyosiy tahlil, statistik ma’lumotlarni umumlashtirish va ilmiy manbalarni o‘rganish usullaridan foydalanildi. Natijalar mamlakatimizda tuya junini faqat xomashyo sifatida sotish emas, balki uni chuqur qayta ishlab yuqori qo‘shilgan qiymatga ega mahsulotlar ishlab chiqarish iqtisodiy jihatdan samarali ekanligini ko‘rsatdi. Maqolada sohani rivojlantirish bo‘yicha ilmiy-amaliy tavsiyalar ishlab chiqilgan bo‘lib, ular mahalliy ishlab chiqaruvchilar, tadqiqotchilar va sohaga mas’ul tashkilotlar uchun amaliy ahamiyatga ega.

Kalit so‘zlar: *tuya juni, Baqtriya tuyasi, Arvana tuyasi, tabiiy tolalar, to‘qimachilik sanoati, qayta ishlash, eksport, iqtisodiy samaradorlik, innovatsiya, O‘zbekiston.*

Аннотация. В данной статье проанализированы современное состояние производства и переработки верблюжьей шерсти в мире, а также перспективы развития данной отрасли в Узбекистане. Верблюжья шерсть отличается высокими теплоизоляционными свойствами, лёгкостью, прочностью, экологической безопасностью и гипоаллергенностью, что делает её ценным сырьём для текстильной промышленности. В условиях роста мирового спроса на натуральные волокна производство и глубокая переработка верблюжьей шерсти приобретают особую актуальность. В статье рассмотрен опыт Монголии, Китая, Казахстана, Ирана и других стран, являющихся ведущими производителями верблюжьей шерсти. Исследование основано на сравнительном анализе, обобщении статистических данных и изучении научной литературы. Полученные результаты показывают, что Узбекистан обладает благоприятными природно-климатическими условиями и достаточным потенциалом для расширения производства и глубокой переработки верблюжьей шерсти. Развитие современных технологий переработки, внедрение инноваций и расширение экспортно ориентированного производства будут способствовать повышению конкурентоспособности отечественной текстильной промышленности и обеспечению устойчивого развития отрасли.

Ключевые слова: *верблюжья шерсть, бактриан, дромедар, натуральные волокна, текстильная промышленность, переработка, экспорт, экономическая эффективность, Узбекистан.*

Abstract. This article examines the current state of camel wool production and processing worldwide and evaluates the development potential of this sector in Uzbekistan. Camel wool is recognized as one of the most valuable natural fibers due to its excellent thermal insulation, softness, durability, lightweight structure, and hypoallergenic properties. As global demand for environmentally friendly textile materials continues to grow, camel wool has become an increasingly important raw material for the textile industry. The article analyzes the experience of leading camel wool-producing countries, including Mongolia, China, Kazakhstan, and Iran, with particular attention to production technologies, processing systems, and export opportunities. The research applies comparative analysis, statistical evaluation, and a review of scientific literature to assess the current situation and identify development prospects. The findings indicate that Uzbekistan possesses favorable climatic conditions, traditional camel breeding practices, and sufficient natural resources to expand camel wool production and establish value-added processing industries. The study concludes that improving processing technologies, increasing investment, and strengthening export-oriented production can significantly enhance the competitiveness of Uzbekistan’s textile sector and contribute to sustainable rural development.

Keywords: camel wool, Bactrian camel, dromedary camel, natural fibers, textile industry, processing, export, economic efficiency, Uzbekistan.

Introduction

In recent years, as a result of the increased demand for environmentally friendly and natural fibers, camel wool has become one of the promising raw materials for the textile industry. Camel wool is distinguished from other types of wool by its lightness, long-term heat retention, good moisture absorption and natural hypoallergenic properties. In particular, the soft down of the two-humped Bactrian camel is widely used in the production of high-quality yarn, knitwear, blankets, coats and other premium products. Camel wool production in the world is mainly developed in Mongolia, China, Kazakhstan, Afghanistan, Iran and Central Asian countries. International experience shows that high economic efficiency is achieved not only through the export of raw wool, but also through its deep processing. According to FAO, the main population of Bactrian camels is located in Mongolia and China, and it is in these regions that high-quality soft camel wool is grown. A male Bactrian camel produces an average of 12–15 kg of wool per year, and a female - 6–8 kg.

Uzbekistan, due to its natural and climatic conditions and historical camel breeding traditions, has favorable opportunities for the development of this area. Camel breeding is developed in the Republic of Karakalpakstan, Navoi, Bukhara and Khorezm regions, and organizing the collection, sorting and processing of camel wool in these regions will create added value, create new jobs and increase export potential.

The purpose of the study is to analyze the experience of growing and processing camel wool in the world and assess the prospects for the development of this industry in the conditions of Uzbekistan.

Research Methodology

Research objectives: study the state of camel wool production in the world; analyze the main characteristics of camel wool; evaluate the experience of leading countries; identify the opportunities and existing problems of Uzbekistan; develop scientific and practical recommendations for the development of the industry.

Camel wool production in the world. Mainly two-humped Bactrian camels produce high-quality wool. This type of camel is widespread in Central Asia and East Asia. Wool is also obtained from one-humped Arvana camels, but its quantity and quality are lower than that of the Bactrian camel. In the following Table 1 shown countries are considered leaders in camel wool production.

These countries not only raise camels, but also sort, wash, spin, and produce wool. Mongolia and China in particular export high-quality camel wool products to the European, Japanese, and North American markets.

Table 1. Leading countries producing camel wool and their general characteristics.

№	State	Role in production	Main characteristics
1	Mongolia	One of the world's leading producers	Camel wool is distinguished by its high quality and large export potential.
2	China	Large producer and processor	Deep processing of camel wool and production of finished products are developed.
3	Kazakhstan	Leading country in Central Asia	Camels are bred in large numbers, and high-quality natural fibers are obtained.
4	Afghanistan	Important exporting country	It is known in the international market for its fine and soft camel wool.
5	Russia	Regional producer	Camel wool is grown mainly in the southern and eastern regions.
6	Iran	Traditional producer	It is widely used in the national textile and carpet industry.
7	Turkmenistan	Regional producer	Camel livestock is developed, natural fibers are obtained.
8	Uzbekistan	Emerging producer	Through the development of livestock farming, the possibilities of using camel wool are expanding.
9	Kyrgyzstan	Limited volume producer	Camel wool is mainly obtained for local needs.
10	Pakistan	Local producer	Camel wool is grown in desert areas and used in crafts.



Figure 1. Camel farm.

Advantages of camel wool: Camel wool has a number of advantages over other natural fibers:

- It retains heat very well.
- It is light and soft.
- It is less likely to cause allergies.
- It absorbs moisture well.
- It does not generate static electricity.
- It is an environmentally friendly and renewable raw material.
- It is widely used in the production of expensive premium textile products.

Wool productivity of one camel: According to experts:

- A male Bactrian camel produces an average of 12–15 kg of wool per year.
- A female Bactrian camel produces 6–8 kg of wool per year.
- An Arwana camel produces an average of 2–5 kg of wool.

Wool is usually harvested once a year in the spring season.

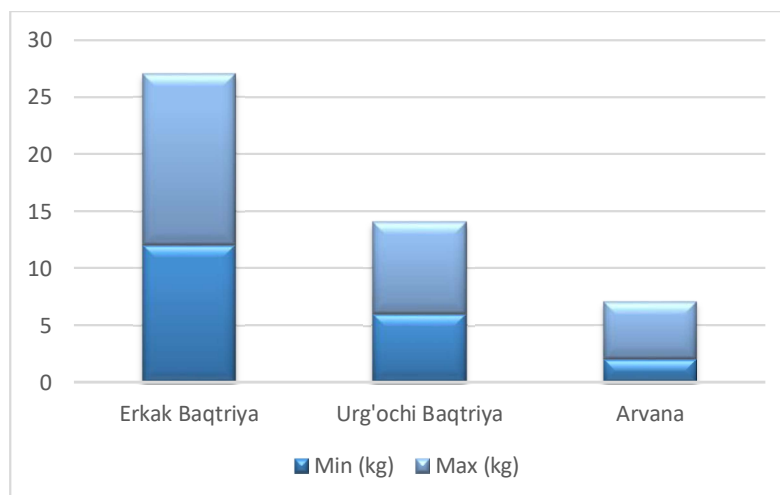


Figure 2. Wool harvesting for the year

Economic importance of camel wool: The price of raw camel wool on the international market is on average around 3–5 US dollars/kg, depending on its quality. Bleached, sorted or spun products are sold several times more expensive. For example, 100 Bactrian camels can produce an average of 800 kg of wool per year. Even if raw wool is sold, it will generate income, but processing it and exporting it in the form of yarn, fabric or finished products creates a much higher added value.

Table 2. Economic importance of camel wool and the economic efficiency of processing.

№	Indicator	Cost	Note
1	Average price of raw camel wool	3–5 USD/kg	Price depends on wool quality and purity.
2	Annual wool yield from 100 Bactrian camels	≈800 kg	Based on average annual calculation.
3	Sales of raw wool	Relatively low yield	Value added is limited.
4	Production of yarn, fabric and finished products	High yield	Processing increases export value and added value.

As can be seen from the table, camel wool is a raw material with high economic value, not only as a natural fiber. Compared with the sale of raw wool, its transformation into yarn, fabric or finished textile products creates high added value. Therefore, the deep processing of camel wool is one of the important factors in increasing the economic efficiency of the textile industry.



Figure 3. Camel wool products.

Opportunities of Uzbekistan: Uzbekistan is one of the countries favorable for the development of camel breeding in terms of natural and climatic conditions. Camel breeding has been developed since ancient times, especially in the Republic of Karakalpakstan, Navoi, Bukhara and Khorezm regions.

The following areas are considered important for the development of the country:

- increasing the number of camels;
- improving breeding;
- establishing wool sorting and processing enterprises;
- producing yarn, fabrics and knitted products from camel wool;
- expanding the range of export-oriented products;
- introducing international quality standards.

Despite the presence of natural resources and climatic conditions necessary for the development of camel wool cultivation and processing in Uzbekistan, a number of economic, technological and organizational problems hinder the rapid development of the industry.

Firstly, one of the main problems is the lack of camel wool processing enterprises. A large part of the camel wool produced in the country is sold as raw material or is used in limited quantities for local needs. The small number of modern enterprises specializing in washing, sorting, cleaning, spinning and manufacturing finished textile products limits the opportunities for creating added value.

Secondly, the lack of modern technologies and innovative equipment negatively affects product quality and production efficiency. Since many manufacturers use outdated technologies, raw material losses during wool processing increase, and product quality does not meet international standards does not fully meet the requirements. As a result, the volume of export-oriented products is limited.

Thirdly, problems in export logistics also significantly affect the development of the industry. High transportation costs for the delivery of camel wool and products made from it to international markets, insufficient development of logistics infrastructure in some regions, and the complexity of certification and customs procedures increase the cost of products. This reduces the competitiveness of local manufacturers in the international market.

Fourthly, due to the underdeveloped marketing and branding system, camel wool products produced in Uzbekistan are not sufficiently recognized in the international market. Many enterprises do not promote products based on modern design, quality certificates, and international marketing strategies. As a result, opportunities to enter high-profit premium market segments are limited.

Fifthly, the lack of qualified specialists is also a pressing problem. There is a lack of highly qualified personnel in the fields of camel breeding, wool processing technology, textile engineering, product design, and export marketing. Increasing the capacity of specialists is of great importance in scientific research, innovative developments, and the practical implementation of modern production technologies.

In addition, it is necessary to improve breeding work in the sector, increase the productivity of camels, expand scientific selection programs, and strengthen cooperation between farms and processing enterprises. The development of effective

mechanisms by the state to attract investments, support the introduction of modern technologies, and stimulate exports will help to gradually eliminate these problems.

Thus, solving existing problems on the basis of an integrated approach is an important factor in increasing the competitiveness of the camel wool growing and deep processing industry in Uzbekistan, expanding its export potential, and developing the production of products with high added value.

About the animals that are currently bred and produce wool in Uzbekistan:

1. Sheep (especially merino and semi-fine wool breeds)
2. Goats (breeds that produce wool and tweed)
3. Camel (dromedary camel)

A small amount of horsehair and dromedary fiber is also obtained, but it is not considered the main wool raw material in textiles.

The number of wool-producing animals in the republic, according to official statistics at the beginning of 2025: Camels - 17.6 thousand heads. (Statistics of Uzbekistan). The total number of sheep and goats in recent years is approximately: Sheep - 25–27 million heads, Goats - 6–7 million heads. These animals provide the main part of the country's wool production. (Statistics of Uzbekistan)

In Uzbekistan, approximately:

- 25–30 thousand tons of sheep wool
- 2–3 thousand tons of goat wool and tevti
- 80–120 tons of camel wool

are obtained annually (varies depending on weather, breed and feeding conditions). (Statistics of Uzbekistan)

The share of camel wool in this: If the total amount of all types of wool is taken as 28 thousand tons: camel wool ≈ 100 tons

Calculation: $100 \div 28,000 \times 100 \approx 0.35\%$

Thus, camel wool accounts for about 0.3–0.5% of total wool production. However, in terms of economic value, it is much more expensive than ordinary sheep wool.

Part of camel wool in the country:

- is hand-spun by local craftsmen;
- is used in national carpet weaving and weaving;
- is used in the production of blankets and quilts;
- is exported in processed form.

Table 3. General description of animals raised and producing wool in Uzbekistan.

№	Indicators	Quantities
1	Number of sheep	25-27 million heads (estimated)
2	Number of goats	6-7 million heads (estimated)
3	Number of camels	17.6 thousand heads (Statistics of Uzbekistan)
4	Total wool per year	----
5	Of which camel wool	28-33 thousand tons
6	Proportion of camel wool	80-120 tons
7	Main use	0.3-0.5%

Analysis and Results

This study analyzed the production of camel wool and its global distribution. According to the results, camel wool production is mainly developed in regions with desert and semi-desert climates, with Mongolia and China being the leading countries in this regard. In particular, wool from the two-humped Bactrian camel grown in Mongolia is distinguished by its high quality, softness, and effective heat retention properties.

The analysis showed that, although China has a high production volume, Mongolian products have an advantage in terms of quality. Camel wool production has also been established in Afghanistan, Iran, and Central Asian countries, including Kazakhstan, and these countries mainly act as suppliers of raw materials. Although the scale of production in these regions is relatively small, the increase in global demand for natural fiber is further increasing their importance.

During the discussion, it was found that camel wool has natural thermal insulation properties. This makes it possible to use it as a very effective material in the production of winter clothing. In particular, a mixture of camel wool and synthetic fibers (for example, sintepon) significantly improves the lightness of the material, the level of heat retention and shape stability. This is of great importance in the design of winter clothing for children and adults.

The results of the study also showed that there are wide opportunities for the use of camel wool in the conditions of Uzbekistan. Although there is the possibility of growing camels in the republic, the industrial processing of this raw material is not sufficiently developed. Therefore, in the future, one of the urgent tasks is to develop innovative thermal insulation materials based on camel wool, effectively use local raw materials and create import-substituting products.

In general, camel wool has great prospects as a natural raw material with environmentally friendly and high functional properties. Combining it with modern technologies through which it is possible to produce competitive and high-value-added products for light industry.

Conclusion

The results of this study once again confirmed the relevance of the issues of camel wool cultivation and its effective use. According to the analysis, camel wool production in the world is mainly developed in countries with desert and semi-desert regions, with Mongolia and China in particular taking the leading positions. The natural and climatic conditions of these regions and the large camel population contribute to the sustainable development of this industry.

During the study, it was found that camel wool differs from other natural fibers in its high heat-retaining properties, lightness, hygroscopicity and environmental friendliness. In particular, wool fibers obtained from Bactrian camels are valued as high-quality raw materials due to their fineness and softness. In addition, materials based on camel wool are safe for human health, do not cause allergic reactions and are suitable for long-term use.

It was also substantiated that it is possible to create new types of composite materials by mixing camel wool with synthetic fibers, in particular, synthetic winterizer. Such materials have important properties such as high thermal insulation,

lightness, shape stability and strength, and can be widely used in the production of modern winter clothing. Especially for children's clothing, this type of material is of particular importance in providing comfort and safety.

Analyses conducted in Uzbekistan showed that although the country has natural opportunities for camel breeding, this sector has not yet been fully developed at an industrial level. Therefore, in the future, it is possible to diversify the light industry sector by developing camel wool cultivation and its deep processing. This will help reduce imports, create new jobs and increase export potential.

In conclusion, camel wool-based materials are one of the promising areas in the production of light industry, in particular winter clothing. By introducing a scientific approach and innovative technologies, it is possible to create environmentally friendly and competitive products with high added value from this raw material.

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Section 6. ACTUAL PROBLEMS OF MATHEMATICS, PHYSICS AND MECHANICS

UDC: 5, 51, 517.9

EXISTENCE AND UNIQUENESS OF SOLUTIONS TO A FIRST BOUNDARY VALUE PROBLEM FOR A LOADED FRACTIONAL DIFFUSION EQUATION

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Annotatsiya. Maqolada Riman–Liuvill kasr tartibli hosilasi qatnashgan yuklangan diffuziya tenglamasi uchun birinchi chegaraviy masala o'rganiladi. Diffuziya tenglamasining o'ng tomoniga noma'lum yechimning x bo'yicha integraliga bog'liq yuklangan had qo'shiladi. Masala Grin funksiyasi yordamida Volterra–Fredholm tipidagi integral tenglamaga keltirilib, yechim ketma-ket yaqinlashish usuli orqali ifodalanadi.

Kalit so'zlar: kasr tartibli hosila, Riman–Liuvill hosilasi, yuklangan tenglama, Grin funksiyasi, Volterra–Fredholm integral tenglamasi.

Аннотация. В статье изучается первая краевая задача для нагруженного диффузионного уравнения с дробной производной Римана–Лиувилля. В правую часть диффузионного уравнения добавляется нагруженный член, зависящий от интеграла неизвестного решения по переменной xxx . С помощью функции Грина задача сводится к интегральному уравнению типа Вольтерра–Фредгольма, а решение представляется методом последовательных приближений.

Ключевые слова: дробная производная, производная Римана–Лиувилля, нагруженное уравнение, функция Грина, интегральное уравнение Вольтерра–Фредгольма.

Abstract. The paper studies a first boundary value problem for a loaded diffusion equation involving the Riemann–Liouville fractional derivative. A loaded term depending on the integral of the unknown solution with respect to xxx is added to the right-hand side of the diffusion equation. Using the Green function, the problem is reduced to a Volterra–Fredholm type integral equation, and the solution is represented by the method of successive approximations.

Keywords: fractional derivative, Riemann–Liouville derivative, loaded equation, Green function, Volterra–Fredholm integral equation.

Introduction

Equations with fractional-order derivatives make it possible to describe a wider class of processes than classical differential equations. In particular, in diffusion processes

where the previous states of the medium influence its subsequent development, operators of the Riemann–Liouville type are of great importance. Therefore, fractional-order diffusion equations are widely used in the study of media with memory, anomalous diffusion, and nonlocal processes.

In loaded differential equations, the value, trace, or integral characteristic of the unknown function participates in the equation itself as an additional term. Such an approach makes it possible to take into account the nonlocal effects of the process. In particular, terms depending on the integral of the unknown solution over an interval express the influence of the entire spatial domain on a given point in the diffusion process.

Literature Review

The theory of fractional differential equations has been studied by many scholars, and in this direction the Riemann–Liouville and Caputo operators, as well as the Mittag-Leffler and Wright functions, play an important role. Fractional partial differential equations and boundary value problems posed for them are analyzed in detail in the works of A.V. Pskhu [1]. In particular, the first boundary value problem for the diffusion-wave equation was solved by means of the Green function.

The theory of loaded differential equations was developed in the works of A.M. Nakhushev [2]. In such equations, certain values, traces, or integral functionals of the unknown function participate in the equation itself as additional terms. This approach is of great importance in the mathematical description of nonlocal processes.

Integral equations and the resolvent kernel method are widely used in solving equations of Volterra and Fredholm type. By means of these methods, boundary value problems are reduced to integral equations, and the existence and uniqueness of the solution are proved. In particular, the method of successive approximations gives effective results for integral equations obtained through the Green function.

Research Methodology

In the research, the loaded first boundary value problem is studied by means of the Green function. The loaded term is expressed through a new integral kernel on the basis of Fubini's theorem, and the problem is reduced to an integral equation of Volterra–Fredholm type. The obtained equation is solved by means of the method of successive approximations and the resolvent kernel method.

Analysis and Results

In the domain $D = \{(x, y) : 0 < x < a, 0 < y < b\}$ we consider the following integrally loaded fractional diffusion equation:

$$u_{xx}(x, y) - D_{0,y}^{\alpha} u(x, y) = f(x, y) + \lambda(y) \int_0^a K(x, s) u(s, y) ds, \quad 0 < \alpha \leq 1 \quad (1)$$

Here $D_{0,y}^{\alpha}$ is the fractional derivative with respect to y in the Riemann–Liouville sense, and it is defined in the form $D_{0,y}^{\alpha} u(x, y) = \frac{d}{dy} \left(\frac{1}{\Gamma(1-\alpha)} \int_0^y \frac{u(x, \eta)}{(y-\eta)^{\alpha}} d\eta \right)$, where $\Gamma(\cdot)$ is Euler's gamma function. The functions $K(x, s)$ and $\lambda(y)$ are given sufficiently smooth functions, while $u(x, y)$ is the unknown function.

Problem 1. Find a function $u(x, y)$ satisfying the following conditions:

1. $u(x, y) \in C(\bar{D}) \cap C_{x,y}^{2,\alpha}(D)$;
2. $u(x, y)$ is a regular solution of equation (1) in the domain D ;
3. $u(x, y)$ satisfies the following conditions:

$$u(0, y) = \varphi_0(y), \quad u(a, y) = \varphi_1(y), \quad 0 < y < b, \quad (2)$$

$$\lim_{y \rightarrow 0} D_{0,y}^{\alpha-1} u(x, y) = \tau(x), \quad 0 < x < a. \quad (3)$$

First, we consider the following fractional diffusion equation:

$$u_{xx}(x, y) - D_{0,y}^{\alpha} u(x, y) = F(x, y). \quad (4)$$

For this equation, the first boundary value problem has a unique solution, and it is determined by the following formula [1, pp. 107–115]:

$$\begin{aligned} u(x, y) = & \int_0^y \varphi_0(\eta) G_{\xi}(x, y; 0, \eta) d\eta - \int_0^y \varphi_1(\eta) G_{\xi}(x, y; a, \eta) d\eta + \\ & + \int_0^a \tau(\xi) G(x, y; \xi, 0) d\xi - \int_0^y \int_0^a F(\xi, \eta) G(x, y; \xi, \eta) d\xi d\eta. \end{aligned} \quad (5)$$

The Green function appearing in the formula has the following form:

$$G(x, y; \xi, \eta) = \frac{(y-\eta)^{\beta-1}}{2} \sum_{m=-\infty}^{\infty} \left[e_{1,\beta}^{1,\beta} \left(-\frac{|x-\xi+2ma|}{(y-\eta)^{\beta}} \right) - e_{1,\beta}^{1,\beta} \left(-\frac{|x+\xi+2ma|}{(y-\eta)^{\beta}} \right) \right], \quad \beta = \frac{\alpha}{2}. \quad (6)$$

Now we denote the right-hand side of equation (1) by

$$F(x, y) = f(x, y) + \lambda(y) \int_0^a K(x, s) u(s, y) ds \quad (7)$$

Substituting (7) into formula (5), we obtain

$$u(x, y) = u_0(x, y) - \int_0^y \int_0^a \lambda(\eta) \left[\int_0^a K(\xi, s) u(s, \eta) ds \right] G(x, y; \xi, \eta) d\xi d\eta. \quad (8)$$

By changing the order of integration in formula (8) on the basis of Fubini's theorem, we can write it in the following form [3, pp. 164–166]:

$$u(x, y) = u_0(x, y) - \int_0^y \int_0^a \int_0^a \lambda(\eta) G(x, y; \xi, \eta) K(\xi, s) u(s, \eta) d\xi ds d\eta \quad (9)$$

Now we introduce the following new kernel:

$$R(x, y; s, \eta) = \lambda(\eta) \int_0^a G(x, y; \xi, \eta) K(\xi, s) d\xi. \quad (10)$$

As a result, equation (9) is reduced to the following integral equation of Volterra–Fredholm type:

$$u(x, y) = u_0(x, y) - \int_0^y \int_0^a R(x, y; s, \eta) u(s, \eta) ds d\eta. \quad (11)$$

To solve equation (11), we use the method of successive approximations. If $u^{(0)}(x, y) = u_0(x, y)$, then the successive approximations are determined by the following formula:

$$u^{(n+1)}(x, y) = u_0(x, y) - \int_0^y \int_0^a R(x, y; s, \eta) u^{(n)}(s, \eta) ds d\eta, \quad n = 0, 1, 2, \dots \quad (12)$$

Then the first approximation is obtained as

$$u^{(1)}(x, y) = u_0(x, y) - \int_0^y \int_0^a R_1(x, y; s, \eta) u_0(s, \eta) ds d\eta,$$

$$R_1(x, y; s, \eta) = R(x, y; s, \eta). \quad (13)$$

The second approximation is equal to

$$u^{(2)}(x, y) = u_0(x, y) - \int_0^y \int_0^a R(x, y; r, t) u^{(1)}(r, t) dr dt = u_0(x, y) - \int_0^y \int_0^a R(x, y; r, t) u_0(r, t) dr dt +$$

$$+ \int_0^y \int_0^a R(x, y; r, t) \left[\int_0^t \int_0^a R(r, t; s, \eta) u_0(s, \eta) ds d\eta \right] dr dt =$$

$$= u_0(x, y) - \int_0^y \int_0^a R_1(x, y; s, \eta) u_0(s, \eta) ds d\eta + \int_0^y \int_0^a R_2(x, y; s, \eta) u_0(s, \eta) ds d\eta,$$

where

$$R_2(x, y; s, \eta) = \int_0^y \int_0^a R(x, y; r, t) R_1(r, t; s, \eta) dr dt \quad (14)$$

In the general case,

$$u^{(n)}(x, y) = u_0(x, y) + \sum_{k=1}^n (-1)^k \int_0^y \int_0^a R_k(x, y; s, \eta) u_0(s, \eta) ds d\eta, \quad (15)$$

$$R_{k+1}(x, y; s, \eta) = \int_0^y \int_0^a R(x, y; r, t) R_k(r, t; s, \eta) dr dt, \quad k = 1, 2, \dots \quad (16)$$

Therefore, by means of formula (15), the general solution is determined as follows:

$$u(x, y) = \lim_{n \rightarrow \infty} u^{(n)}(x, y) = \lim_{n \rightarrow \infty} \left[u_0(x, y) + \sum_{k=1}^n (-1)^k \int_0^y \int_0^a R_k(x, y; s, \eta) u_0(s, \eta) ds d\eta \right],$$

that is,

$$u(x, y) = u_0(x, y) + \sum_{k=1}^{\infty} (-1)^k \int_0^y \int_0^a R_k(x, y; s, \eta) u_0(s, \eta) ds d\eta. \quad (17)$$

Theorem. Let $0 < \alpha \leq 1$, $y^{1-\alpha} f(x, y) \in C(D)$, $y^{1-\alpha} \varphi_0(y) \in C[0, b]$, $y^{1-\alpha} \varphi_1(y) \in C[0, b]$, $\tau(x) \in C[0, a]$, $\lambda(y) \in C[0, b]$, $K(x, s) \in C([0, a] \times [0, a])$, and let the function $f(x, y)$ satisfy the Hölder condition with respect to x . If the following compatibility conditions are fulfilled:

$$\lim_{y \rightarrow 0} D_{0y}^{\alpha-1} \varphi_0(y) = \tau(0),$$

$$\lim_{y \rightarrow 0} D_{0y}^{\alpha-1} \varphi_1(y) = \tau(a),$$

then Problem 1 has a unique solution, and it is given in the following form:

$$u(x, y) = u_0(x, y) + \sum_{k=1}^{\infty} (-1)^k \int_0^y \int_0^a R_k(x, y; s, \eta) u_0(s, \eta) ds d\eta,$$

where the functions $u_0(x, y)$ and $R_k(x, y; s, \eta)$ are determined by formulas (5) and (16), respectively.

The existence of the solution was obtained through formula (17). We now prove the uniqueness of the solution. Suppose that Problem (1)–(2)–(3) has two regular solutions $u_1(x, y)$ and $u_2(x, y)$. We denote their difference by

$$z(x, y) = u_1(x, y) - u_2(x, y) \quad (18)$$

Then $z(x, y)$ satisfies the following homogeneous loaded problem:

$$z_{xx}(x, y) - D_{0y}^\alpha z(x, y) = \lambda(y) \int_0^a K(x, s) z(s, y) ds, \quad (19)$$

$$z(0, y) = 0, \quad z(a, y) = 0,$$

Now we apply the Green function formula to this homogeneous problem. Since the boundary and initial data are zero, only the integral part generated by the loaded term remains in the Green formula. As a result, the integral equation

$$z(x, y) = - \int_0^y \int_0^a R(x, y; s, \eta) z(s, \eta) ds d\eta \quad (20)$$

is obtained, where

$$R(x, y; s, \eta) = \lambda(\eta) \int_0^a G(x, y; \xi, \eta) K(\xi, s) d\xi. \quad (21)$$

According to the uniqueness theorem for Volterra-type integral equations, such a homogeneous equation has only the trivial solution [2, pp. 96–97]. Therefore, $z(x, y) \equiv 0$ that is, $u_1(x, y) = u_2(x, y)$. Hence, the regular solution of the loaded first boundary value problem is unique. The theorem is proved.

Conclusion

During the research, the posed boundary value problem was reduced to an integral equation by means of the Green function. Due to the presence of the loaded term, the iterated kernels and the resolvent kernel were determined through the obtained kernel. On this basis, the integral representation of the solution was obtained. The obtained result shows that the fractional-order diffusion problem involving an integrally loaded term can be effectively studied by means of an integral equation of Volterra–Fredholm type. It was substantiated that, under the given conditions, the regular solution of the problem exists and is unique.

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CHANGE IN THE WIDTH OF THE VOLUME CHARGE FIELD OF P–N JUNCTION DIODES UNDER THE INFLUENCE OF A MAGNETIC FIELD

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Annotatsiya. Mazkur maqolada magnit maydon ta'sirida p–n o'tishli diodlarning volt-ampere xarakteristikasi hamda hajmiy zaryad sohasi parametrlarining o'zgarishi nazariy jihatdan tadqiq qilindi. Yani magnit maydon ta'sirida hosil bo'ladigan elektr yurituvchi kuch (EYuK), Lorens kuchi va zaryad tashuvchilar taqsimotining o'zgarishi p–n o'tishning hajmiy zaryad sohasi kengligi, diffuziya toki, diffuziya sig'imi va hajmiy sig'imga ko'rsatadigan ta'siri matematik model asosida tahlil qilindi. Hisoblash natijalari harorat gradiyenti ta'sirida zaryad tashuvchilar harakati ortishi, magnit maydon ta'sirida esa Lorens kuchi ularning harakat yo'nalishi va fazoviy taqsimotini o'zgartirishi natijasida diffuziya hamda hajmiy sig'implarning magnit induksiyasiga bog'liq ravishda o'zgarishini ko'rsatdi. Shuningdek, ushbu jarayonlar bir jinsli va bir jinsli bo'lmagan yarimo'tkazgichlar uchun qiyosiy tahlil qilinib, magnit maydonning p–n o'tishli diodlarning elektr parametrlarini boshqarishdagi ahamiyati nazariy jihatdan asoslandi.

Kalit so'zlar: VAX-volt-ampere xarakteristika, hajmiy sig'im, diffuziya sig'im, issiqlik gradiyenti, EYuK-elektr yurituvchi kuch, rekombinasiya, Xoll effekti.

Аннотация. В данной статье теоретически исследовано влияние магнитного поля на вольт-амперную характеристику p–n-переходных диодов, а также на изменение параметров области пространственного заряда. В частности, на основе математической модели проанализировано влияние электродвижущей силы (ЭДС), возникающей под действием магнитного поля, силы Лоренца и изменения распределения носителей заряда на ширину области пространственного заряда p–n-перехода, диффузионный ток, диффузионную и барьерную ёмкости. Результаты расчётов показали, что под воздействием температурного градиента возрастает подвижность носителей заряда, а под влиянием магнитного поля

сила Лоренца изменяет направление их движения и пространственное распределение, вследствие чего диффузионная и барьерная ёмкости изменяются в зависимости от величины магнитной индукции.

Кроме того, проведён сравнительный анализ указанных процессов для однородных и неоднородных полупроводников. Теоретически обосновано, что магнитное поле является эффективным фактором управления электрическими параметрами p–n-переходных диодов.

Ключевые слова: вольт-амперная характеристика (ВАХ), барьерная ёмкость, диффузионная ёмкость, температурный градиент, термо-ЭДС, рекомбинация, эффект Холла.

Abstract. In this article, the volt-ampere characteristic of p–n junction diodes under the influence of a magnetic field and the change in the volume charge field parameters were theoretically studied. That is, the effect of the electromotive force (EMF), the Lorentz force, and the change in the distribution of charge carriers generated under the influence of a magnetic field on the width of the volume charge field, diffusion current, diffusion capacitance, and volume capacitance of the p–n junction was analyzed based on a mathematical model. The calculation results showed that the mobility of charge carriers increased under the influence of a temperature gradient, and the Lorentz force changed their direction and spatial distribution under the influence of a magnetic field, resulting in a change in the diffusion and volume capacitances depending on the magnetic induction. Also, these processes were analyzed comparatively for homogeneous and heterogeneous semiconductors, and the importance of the magnetic field in controlling the electrical parameters of p–n junction diodes was theoretically substantiated.

Keywords: volt-ampere characteristic, volume capacitance, diffusion capacitance, thermal gradient, EMF-electromotive force, recombination, Hall effect.

Introduction

In recent years, much attention has been paid to studying the performance characteristics of semiconductor materials and electronic devices based on them under the influence of external physical factors. The rapid development of microelectronics, nanoelectronics, automated control systems, and high-precision sensor technologies requires the development of new methods for controlling the electrical parameters of p–n junction semiconductor devices. Therefore, in-depth study of the effects of magnetic fields, temperature, electromagnetic radiation, and mechanical effects on the properties of semiconductor elements is one of the current scientific directions.

The main electrical characteristics of p-n junction diodes are determined by the diffusion, recombination of charge carriers and the internal electric field formed in the field of volume charge. It is the width of the volume charge region that directly affects the diode's volt-ampere characteristics, diffusion and volume capacitance, barrier potential, and fast operating properties. Therefore, identifying the possibilities of controlling these parameters using external physical factors is of great scientific and practical importance.

The magnetic field acts on the charge carriers moving inside the semiconductor through the Lorentz force, changing their direction and distribution. As a result, the intensity of diffusion and recombination processes changes, a Hall potential is formed, and changes occur in the parameters of the volume charge field at the p–n junction. These changes can significantly affect the volume and diffusion capacitance of the diode, as well as the volt-ampere characteristics. However, the effect of the magnetic field on the width of the volume charge field and the physical mechanisms of these processes are still one of the issues that need to be studied in detail.

The purpose of this work is to theoretically analyze the change in the width of the volume charge field of p–n junction diodes under the influence of a magnetic field, to determine the mechanisms of influence of this process on diffusion and volume capacitance, and to develop a theoretical basis for the creation of semiconductor devices controlled by a magnetic field.

It is known that p-n junction diodes are not directly affected by a magnetic field. To monitor changes in it, high-frequency or highly sensitive sensors use the Hall effect.

The total current generated if there is no effect on the p-n junction diodes is explained by the Shockli expression.

$$J = J_s(e^{\frac{qU}{kT}} - 1) \quad (1)$$

The width of the volumetric field formed at the contact is

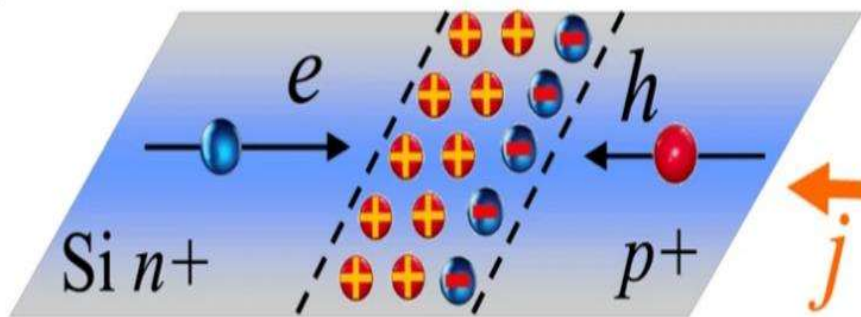


Figure 1. Volumetric field width at the p-n junction.

The diffusion process in the p and n regions of the electric field continues until the exchange of charge carriers passing under the influence of the field equals the diffusion of charge carriers, depending on the equilibrium state [Figure 1]. That is, at the contact, the ions begin to diffuse from the high-concentration n region to the low-concentration p region, and the holes move in the opposite direction. As a result, the electrons and holes that meet in the boundary region annihilate each other due to recombination. Therefore, the number of free charge carriers in this region decreases, leaving ionized atoms. The region where the charge carriers are depleted is a depleted region, and the resistance here is high, so the current does not flow freely. As a result of the ionized layer, an internal electric field is created between the p and n regions, forming a contact potential barrier. When an external voltage is applied to the p-n junction, it changes its basic properties to forward and reverse connections. Current flowing through a p-n junction diode, which is located in a magnetic field, causes the charge carriers to change direction. As a result, electrons and holes move along a curved line, not in a straight line (Figure 2). Due to the change in the movement of charge carriers, they affect the recombination processes that occur between the n and p regions, changing

the characteristics of the current flow through the diode. This effect creates an additional Hall voltage perpendicular to the direction of the current. As a result, changes in the volume and diffusion capacitances occur in p-n junctions.

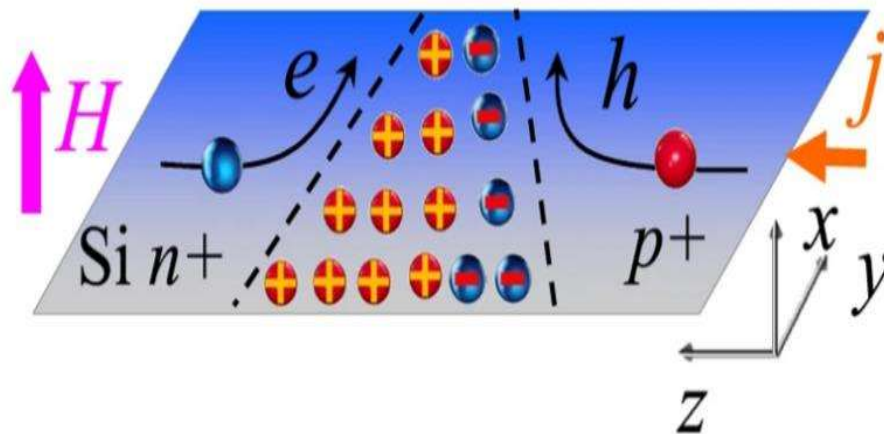


Figure 2. Change in the volume charge field under the influence of a magnetic field.

Analysis and Results

In p–n junction diodes, the diffusion capacitance is formed as a result of the accumulation of charge carriers near the p–n junction and their change over time. In the correct connection mode, the concentration of minority charge carriers injected between the p and n regions increases. Therefore, the diffusion capacitance increases with increasing voltage. In the reverse-biased mode, injection is almost non-existent, and the electrical properties of the diode are determined mainly by the volume charge field capacitance. In the presence of a magnetic field, moving electrons and holes are affected by the Lorentz force. This force deflects the trajectory of charge carriers from the direction of the electric field and alters their drift and diffusion processes. As a result, the time it takes for charge carriers to reach the p–n junction increases, the diffusion length decreases, and the intensity of the recombination process changes. These physical processes directly affect the diode's volt-ampere characteristic, diffusion capacitance, and volume charge field parameters.

The Hall potential generated by the magnetic field has an additional effect on the internal electric field distribution at the p–n junction. As a result, the potential barrier and the width of the volume charge region change. Changing the width of the volume charge region significantly affects the dynamic parameters of the diode by changing the voltage dependence of the p–n junction capacitance. Therefore, the magnetic field can be considered as one of the external factors controlling the electrical parameters of semiconductor devices.

Taking into account the effect of the Lorentz force, an additional term related to the magnetic field is introduced into the expression for the total current flowing through the p–n junction. This term depends on the base resistance, the Hall coefficient, and the magnetic induction, and describes the change in current with increasing magnetic field. On this basis, a theoretical model of the diffusion capacitance and volume charge field parameters of the diode depending on the magnetic field is created.

At the p-n junction, the current takes the form of expression (2) due to the effect of the Lorentz force on charge carriers moving in a medium with a magnetic field. This

expression theoretically describes the effect of a magnetic field on the movement of charge carriers through a p-n junction.

$$J = J_s e^{\left(\frac{q\varphi_0}{kT} - \frac{q(\varphi_0 - U + J(R_b + \frac{\alpha R_x B}{l})}{kT_e} \right)} \quad (2)$$

As a result, the charges change their direction of movement, which leads to a change in the diffusion and recombination processes. The time it takes for charge carriers to reach the p-n junction changes, which leads to a change in the diffusion rate. The diffusion process slows down. The charge carriers recombine more before reaching the boundary. This causes a decrease in the amount of injected charges. In addition, as a result of changing the direction of movement of the charge carriers, the recombination site shifts and the capacitance changes.

From expression (2) above, it can be seen that as the magnetic field induction increases, the effective mobility of charge carriers decreases and the diffusion process slows down. This leads to a decrease in the diffusion capacity. Therefore, the diffusion capacity in a magnetic field is smaller than the diffusion capacity in the absence of a magnetic field:

$$C_d(B) < C_d(B = 0)$$

This relationship is expressed mathematically using expressions (3) and (4). These expressions describe the voltage dependence of the diffusion capacity under the influence of a magnetic field.

$$C_d = \frac{q\tau}{kT} J \quad (3)$$

Our expression (3) changes under the influence of a magnetic field as follows.

$$C_d = \frac{q\tau}{kT} J_s \left(e^{\frac{q\varphi_0}{kT} - \frac{q(\varphi_0 - U + J(R_b + \frac{\alpha J R_x B}{l})}{kT_e}} - 1 \right) \quad (4)$$

By substituting numerical values obtained in experiments into expression (4), we can obtain a graph of capacitance versus voltage.

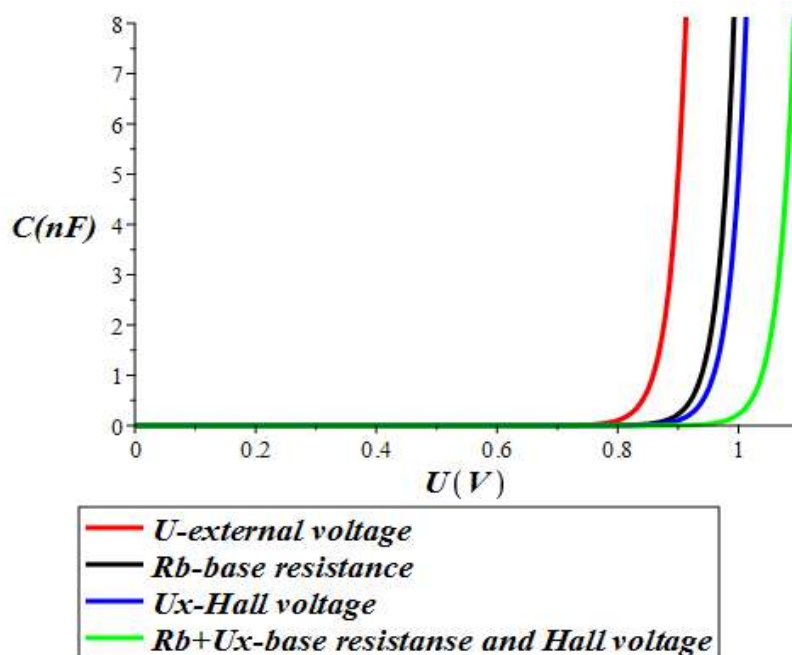


Figure 3. Graph of diffusion capacitance versus magnetic field and base resistance.

The graph shows that as the voltage increases, the diffusion capacity decreases under the influence of the magnetic field. Volumetric capacitance at p-n junctions is one of the main electrical properties of a diode in reverse connection. Volumetric capacitance at p-n junctions represents the voltage-dependent change in the charge accumulated in the volume region formed between the p and n regions. There are no free charge carriers in the volume charge field. They are filled with ions, which act as a permanent charge. Therefore, this field acts like an electric capacitance. Volumetric capacitance becomes important when a reverse voltage is applied. This is because the barrier zone expands and the capacitance decreases when a reverse voltage is applied. The opposite happens when a forward voltage is applied, which causes the diffusion capacitance to increase.

If a magnetic field affects the p-n junctions, it affects the movement of charge carriers and the properties of the barrier zone. Since the magnetic field changes the direction of movement of charges, the geometric shape of the charge distribution in the barrier zone also changes. This causes a change in capacitance. The magnetic field causes a sharp redirection and uneven distribution of charge carriers. This changes the degree of recombination. The volumetric capacitance can decrease under the influence of a magnetic field. Due to the incorrect distribution of charges in strong magnetic fields, the barrier zone expands, and the diffusion rate of charge carriers slows down. The volumetric capacitance decreases. Because the charge carriers recombine before reaching the boundary region. As the magnetic field increases, the volume field width decreases, causing a decrease in capacitance. When a high voltage is applied, a decrease in capacitance is observed.

$$C = \sqrt{\frac{\varepsilon\varepsilon_0 q n_n p_p}{2(\varphi - U)(n_n + p_p)}} \quad (5)$$

Our expression (5) takes the form (6) as a result of the addition of the Hall potential generated by the magnetic field.

$$C = \sqrt{\frac{\varepsilon\varepsilon_0 q n_n p_p}{2(\varphi - U + U_x)(n_n + p_p)}} \quad (6)$$

We construct a graph of volumetric capacitance versus voltage by plotting numerical values obtained in experiments.

The change in capacitance due to the magnetic field and base resistance shows that external influences reduce the capacitance and increase the voltage. That is, the blue line is for the case where no influence is applied, the red line is for the case where the magnetic field is applied, the green line is for the case where the sample changes only due to the base resistance, and the black line is the graph of the relationship between the capacitance and voltage in the periods when the magnetic field and base resistance are applied simultaneously, and the influences given in this sequence show a decrease in capacitance and an increase in voltage.

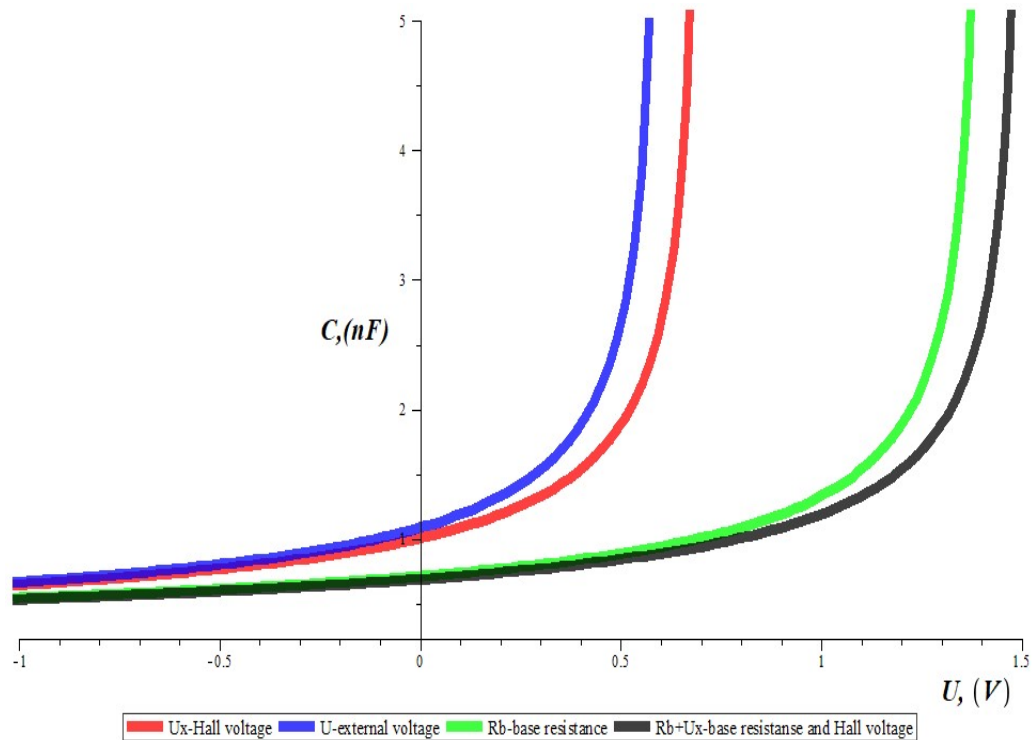


Figure 4. Graph of the change in volumetric capacitance as a function of magnetic field and base resistance.

In addition, the Hall potential generated by the magnetic field changes the electric field distribution within the volume charge region. As a result, the width of the volume charge region changes, and the volume capacitance of the p–n junction also takes on a new value. This situation is mathematically expressed in expressions (5) and (6), which describe the decrease in capacitance under the influence of a magnetic field and the law of its change with increasing voltage. The agreement of the obtained theoretical results with the experimental graphs confirms that the magnetic field has a significant effect on the p-n transition parameters.

Conclusion

In this study, the effect of magnetic field on the volume charge region width and capacitance properties of p–n junction diodes was theoretically analyzed. The results of the analysis revealed that the combined effect of thermal gradient and magnetic field leads to the formation of thermoelectric driving force and the acceleration of charge carrier motion under the influence of temperature gradient. It was shown that under the influence of a magnetic field, the Lorentz force changes the direction of motion of electrons and holes, causing the spatial distribution of charge carriers to become uneven. This process leads to a change in the diffusion and recombination mechanisms, which theoretically justifies the change in the diffusion current and diffusion capacitance in the p–n junction depending on the magnetic field.

It was also found that the change in the Debye length and the distribution of charge carriers under the influence of a magnetic field causes an expansion or narrowing of the width of the volume charge field. As a result, a change in the electron diffusion rate and the volume capacitance of the p–n junction was observed. The calculation results

showed that the magnetic field is one of the important external factors controlling the electrical parameters of the diode, in particular the volume and diffusion capacitances.

The scientific novelty of this study is that the relationship between the Lorentz force, Debye length, and charge carrier distribution under the influence of a magnetic field is analyzed based on a single theoretical model and the mechanism of influence of these factors on the volume charge field and capacitance parameters of p–n junction diodes. The scientific novelty of this study is that the relationship between the volume charge field width, diffusion capacitance, and volume capacitance of p–n junction diodes under the influence of a magnetic field is analyzed based on a single theoretical model. These results can serve as a theoretical basis for the design and optimization of magnetic field-sensitive semiconductor sensors, capacitive elements, and new generation microelectronic devices.

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IMPACT OF GEOMETRIC SCALING ON SELF-HEATING EFFECTS IN GaAs-BASED GATE-ALL-AROUND FIELD-EFFECT TRANSISTORS

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Annotatsiya. Zatvor bilan to'liq o'ralgan maydoniy tranzistorlar 10 nm dan kichik zatvor uzunligi va nanotola diametrlariga qarab masshtablanishi bilan, o'z-o'zini qizdirish effekti ishonchlilik va unumdorlik nuqtai nazaridan tobora dolzarb muammoga aylanib bormoqda, ayniqsa GaAs kabi issiqlik o'tkazuvchanligi kremniynikidan taxminan uch marta past bo'lgan yuqori harakatchanlikka ega III–V kanal materiallari uchun. Ushbu maqolada zatvor bilan to'liq o'ralgan maydoniy tranzistorlarni arxitekturalaridagi o'zgarishlarga bog'liq o'z-o'zini qizdirish effekti bo'yicha so'nggi adabiyotlar tahlil qilinadi, GaAs kanalli nanotolali va zatvor bilan to'liq o'ralgan maydoniy tranzistorlarni tahlil qilish uchun qo'llanilgan qurilma tuzilishi va birlashtirilgan elektrotermal simulyatsiya metodologiyasi keltiriladi, shuningdek harorat ko'tarilishining zatvor uzunligi, nanosim diametri va vertikal joylashtirilgan qatlamlar soniga bog'liq sifat va analitik tendentsiyalari muhokama qilinadi. Natijalar shuni ko'rsatadiki, geometrik masshtablash elektrostatik boshqaruv va qisqa kanal effektlariga chidamlilik uchun foydali bo'lsa-da, u qurilmaning issiqlik qarshiligini va shu orqali o'z-o'zini qizdirish miqyosini muntazam ravishda oshiradi, bu effekt esa Si ga qaraganda GaAs da sezilarli darajada kuchliroq namoyon bo'ladi.

Kalit so'zlar: GaAs, Zatvor bilan to'liq o'ralgan maydoniy tranzistor, o'z-o'zini qizdirish effekti, nanotola, qurilma masshtablash, issiqlik qarshiligi, TCAD simulyatsiya.

Аннотация. По мере масштабирования полностью охватывающих затвором полевых транзисторов (GAAFET) до длин затвора и диаметров нанопроводов менее 10 нм, эффект саморазогрева (SHE) становится всё более значимой проблемой надёжности и производительности, особенно для высокоподвижных III–V канальных материалов, таких как GaAs, теплопроводность которого примерно в три раза ниже, чем у кремния. В

данной статье рассматривается современная научная литература по эффекту саморазогрева в архитектурах GAAFET, представлена структура прибора и методология связанного электротермического моделирования, использованная для анализа нанопроводного GAAFET с каналом из GaAs, а также обсуждаются качественные и аналитические тенденции роста температуры в зависимости от длины затвора, диаметра нанопровода и числа вертикально расположенных слоёв. Результаты показывают, что геометрическое масштабирование, будучи полезным для электростатического управления и подавления короткоканальных эффектов, систематически увеличивает тепловое сопротивление прибора и, следовательно, степень саморазогрева, причём данный эффект значительно сильнее выражен в GaAs, чем в Si.

Ключевые слова: *GaAs, транзистор с полностью охватывающим затвором, GAAFET, эффект саморазогрева, нанопровод, масштабирование прибора, тепловое сопротивление, TCAD-моделирование.*

Abstract. As gate-all-around field-effect transistors (GAAFETs) are scaled toward sub-10 nm gate lengths and nanowire diameters, self-heating effects (SHE) become an increasingly dominant reliability and performance concern, particularly for high-mobility III–V channel materials such as GaAs whose thermal conductivity is roughly three times lower than that of silicon. This paper reviews recent literature on self-heating in GAAFET architectures, presents the device structure and the coupled electro-thermal simulation methodology used to analyze a GaAs-channel nanowire GAAFET, and discusses the qualitative and analytical trends of temperature rise as a function of gate length, nanowire diameter, and the number of vertically stacked channels. The results indicate that geometric scaling, while beneficial for electrostatic control and short-channel immunity, systematically increases the thermal resistance of the device and therefore the magnitude of self-heating, an effect that is significantly more pronounced in GaAs than in Si.

Keywords: *GaAs, gate-all-around FET, GAAFET, self-heating effect, nanowire, device scaling, thermal resistance, TCAD simulation.*

Introduction

The continuous downscaling of transistor dimensions in digital integrated circuits has followed Moore's law for decades, but planar and FinFET architectures are approaching fundamental physical limits. As a result, gate-all-around field-effect transistors (GAAFETs), in which the gate electrode fully surrounds the channel, are regarded as the natural successor to FinFETs beyond the 5 nm technology node, since they provide superior electrostatic control from all sides of the channel, significantly suppressed short-channel effects, and improved drive current [1].

However, alongside the shrinking of geometric dimensions, a serious challenge — the self-heating effect (SHE) — has become increasingly prominent. Modern FinFET and GAAFET transistors suffer from heat confinement because their small size and three-dimensional geometry leave only limited paths for heat to escape to the

ambient, which results in device self-heating, reduced speed, increased leakage current, and accelerated aging [2]. Chhabria and Sapatnekar showed that logic gates in a circuit heat up, on average, by 12 K for 7 nm SOI FinFETs and by 17 K for 5 nm GAAFETs; this temperature rise accelerates delay degradation due to bias-temperature instability and hot-carrier injection by up to 25% in FinFETs and 39% in GAAFETs, and degrades electromigration-limited wire lifetime by up to 38% in SOI FinFETs and 45% in GAAFET technologies [2].

The self-heating mechanism is largely governed by the low thermal conductivity of the channel material, the gate dielectric, and the large thermal resistance of the source/drain contacts [6]. III–V compound semiconductors, including InGaAs- and GaAs-based nanowire GAA MOSFETs, are attractive for high-frequency applications owing to their high electron mobility, but their comparatively low thermal conductivity makes self-heating an even more critical issue. Pulsed measurements on gate-all-around III–V InAs/InGaAs nanowire MOSFETs show that the intrinsic device temperature can rise to as high as 385 K when operated in DC mode at room temperature [8], which has been attributed to the one-dimensional nature of the nanowire and enhanced phonon-boundary scattering in the GAA architecture.

Studies on the geometric dependence of self-heating show that the temperature difference between layers increases with nanosheet width and stack height, and that increasing the number of vertically stacked nanowires makes heat removal progressively more difficult, leading to higher peak temperatures [5]. These findings directly link the shrinking of geometric dimensions (gate length, channel diameter, S/D contact volume) with the narrowing of the available heat-dissipation pathways.

Recent work on GaAs-based GAA nanowire transistors has largely focused on electrostatic and electrical characteristics. A comparison of triangular GAA nanowire FETs with Si and GaAs channels over a wide temperature range (100–500 K) shows that the GaAs NW FET outperforms the Si NW FET in terms of leakage current, ION/IOFF ratio, and short-channel effects (DIBL, SS), whereas the Si NW FET exhibits a higher ON-current [11]. Saini and Tyagi compared Si and GaAs GAA nanowire FETs at an 8 nm channel length using full quantum transport simulation and found that a smaller nanowire diameter yields the best ON/OFF current results [12]. In addition, recent studies on AlGaAs-channel junctionless cylindrical GAAFETs report suppressed short-channel effects over 10–60 nm channel lengths, with DIBL around 30 mV/V and a subthreshold swing of approximately 63–64 mV/dec for GaAs and AlGaAs devices [13, 14].

In parallel, geometric engineering of GaAs nanowires (diameter and inter-gate spacing) is also relevant for quantum-dot-based devices, where shrinking the diameter has been shown to sharpen the coupling between energy states [15]. Three-dimensional electro-thermal modeling of heat transport in III–V GAA transistors has further revealed complex heat-dissipation pathways governed by multiple time constants, confirming that nanowire geometry has a profound effect on the resulting temperature distribution [9].

Taken together, these studies indicate that shrinking the geometric dimensions of GaAs-based GAAFETs (gate length, nanowire diameter, channel width/height, number of vertical layers) improves electrostatic control and short-channel immunity on the

one hand, but intensifies the self-heating effect on the other, owing to the narrowing of heat-dissipation pathways. However, the existing literature still lacks a systematic analysis of self-heating in GaAs (or AlGaAs) channel GAAFETs as an explicit function of geometric scaling. This paper aims to address that gap by analyzing how the shrinking of geometric dimensions in GaAs-based GAAFETs affects the self-heating effect.

Device structure and simulation methodology

A. Device Structure

The device under study is a cylindrical (or nanosheet-shaped) GaAs-channel gate-all-around FET (GAAFET). In this structure the gate electrode surrounds the channel on all sides (360°), providing maximal electrostatic control (Figure 1). The main geometric parameters of the device are as follows:

- ✓ Gate length L_g — varied in the range of 8–30 nm (the primary scaling parameter);
- ✓ Nanowire diameter D_{NW} (for a nanowire channel) or channel width/height $W_{si} \times H_{si}$ (for a nanosheet channel) — in the range of 5–20 nm;
- ✓ High-k gate dielectric (e.g., Al_2O_3 or HfO_2) thickness T_{ox} — typically 1–2 nm;
- ✓ Source/drain (S/D) doping concentration ND — $\sim 10^{19}$ – 10^{20} cm^{-3} ;
- ✓ The channel is undoped or lightly doped (in the junctionless architecture, a single doping type is maintained throughout the entire structure).

The GaAs channel is chosen because of its considerably higher electron mobility than silicon ($\mu_n \approx 8500 \text{ cm}^2/\text{V}\cdot\text{s}$) and higher saturation drift velocity, which are advantageous for high-frequency and high-speed applications. However, the thermal conductivity of GaAs ($\kappa_{GaAs} \approx 46 \text{ W/m}\cdot\text{K}$) is substantially lower than that of silicon ($\kappa_{Si} \approx 148 \text{ W/m}\cdot\text{K}$), so as the geometric dimensions are scaled down, the self-heating problem becomes markedly more severe — which is precisely the central issue addressed in this study.

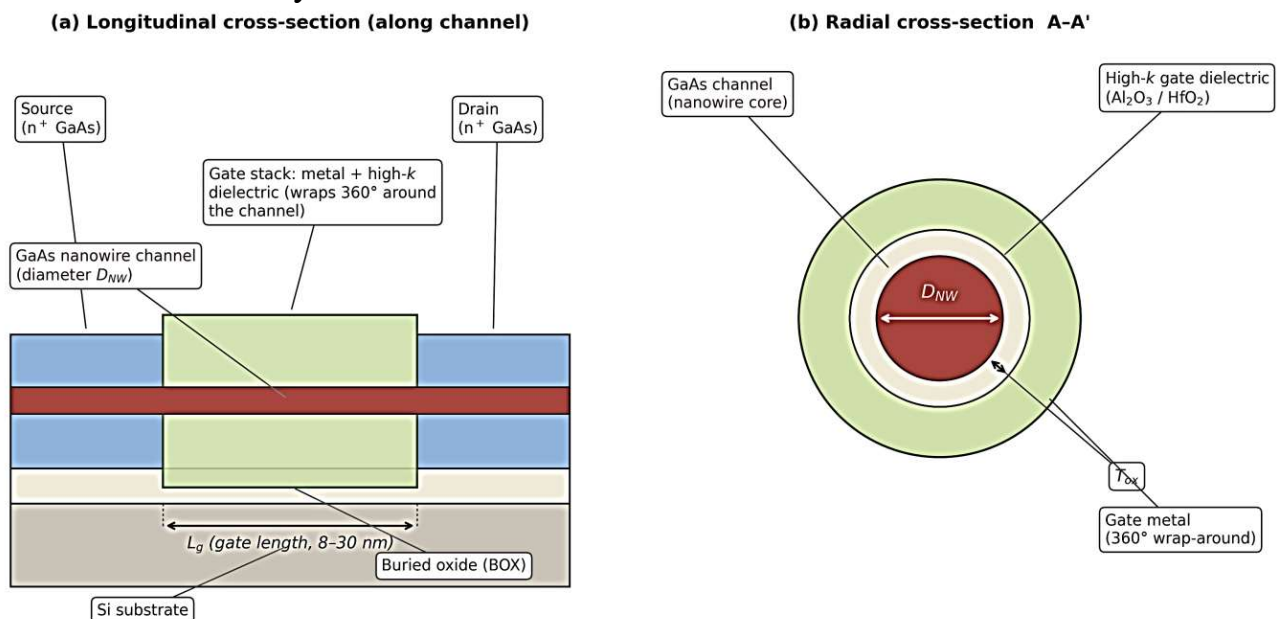


Figure 1. Schematic device structure of the simulated GaAs-channel gate-all-around (GAA) nanowire FET: (a) longitudinal cross-section along the transport direction; (b) radial cross-section A–A' perpendicular to the channel.

B. Governing Equations

1) Electrostatic potential — Poisson's equation. In cylindrical coordinates, Poisson's equation for a GAA nanowire is written as:

$$1/r \cdot \partial/\partial r (r \epsilon_s \partial\psi(r,z)/\partial r) + \epsilon_s \partial^2\psi(r,z)/\partial z^2 = -q(p - n + N_D^+ - N_A^-) \quad (1)$$

Here $\psi(r,z)$ is the electrostatic potential, ϵ_s is the dielectric permittivity of GaAs, q is the elementary charge, n and p are the electron and hole concentrations, and N_D^+ , N_A^- are the ionized donor/acceptor concentrations. This equation determines the potential distribution inside the channel and how strongly it is controlled by the gate; shrinking the geometric dimension (diameter) strengthens the radial gradient in this equation, improving electrostatic control while simultaneously increasing the heat-generation density per unit channel volume.

2) Drift-diffusion (current-continuity) equations:

$$J_n = q\mu_n nE + qD_n \nabla n, \quad J_p = q\mu_p pE - qD_p \nabla p \quad (2)$$

Here J_n , J_p are the electron and hole current densities, μ_n , μ_p are the mobilities, and D_n , D_p are the diffusion coefficients. The mobility μ_n is temperature-dependent, so the temperature rise caused by self-heating reduces the mobility and, in turn, the drain current — this is the direct mechanism by which SHE affects the electrical characteristics.

3) Short-channel effects — DIBL and subthreshold swing:

$$\text{DIBL} = [V_{th}(V_{DS,low}) - V_{th}(V_{DS,high})] / (V_{DS,high} - V_{DS,low}) \quad (3)$$

$$\text{SS} = dV_{GS} / d(\log_{10} I_{DS}) \quad [\text{mV/dec}] \quad (4)$$

DIBL quantifies how strongly the threshold voltage depends on the drain voltage, while SS reflects how effectively the gate controls the subthreshold current. The ideal value is $\text{SS} \approx 60$ mV/dec at room temperature. Shrinking the geometric dimension (especially reducing L_g) typically degrades both DIBL and SS, but the GAA architecture is markedly less sensitive to this degradation than FinFET or planar structures.

4) Heat-conduction (Fourier) equation — electro-thermal modeling. To account for self-heating, the electrical equations are solved self-consistently together with the heat-transport equation:

$$\rho C_p \partial T(r,t)/\partial t = \nabla \cdot (\kappa(T) \nabla T(r,t)) + H(r,t) \quad (5)$$

Here ρ is the density, C_p is the specific heat capacity, $\kappa(T)$ is the temperature-dependent thermal conductivity (which, at the nanoscale, falls below its bulk value because of phonon-boundary scattering), and $H(r,t)$ is the Joule-heating source term:

$$H = J \cdot E = J^2/\sigma \quad (6)$$

This equation determines the local temperature distribution at every point of the device: the smaller the geometric cross-section (channel cross-sectional area, S/D contact length), the higher the local heat-generation density H , while the surface area A available for heat removal becomes correspondingly smaller.

5) Thermal resistance and temperature rise. In a simplified (compact) thermal model, the channel temperature rise of the device is expressed as:

$$\Delta T = P_{diss} \cdot R_{th} \quad (7)$$

where $P_{diss} = I_{DS} \cdot V_{DS}$ is the power dissipated in the device, and R_{th} is the total thermal resistance (the sum of the heat-flow paths through the S/D contacts, the gate oxide, and the substrate):

$$R_{th} = L / (\kappa \cdot A) \quad (8)$$

Here L is the length of the heat-flow path and A is the cross-sectional area. This expression analytically explains why geometric scaling (shrinking the diameter/cross-sectional area) increases R_{th} and, consequently, ΔT — this relationship forms the central physical basis of the present study and is used in Section III to construct the illustrative analytical trends of self-heating versus geometry.

C. Simulation Methodology

To analyze the electrical and thermal characteristics of the device, a 3-D TCAD simulation tool (of the Silvaco Atlas / Synopsys Sentaurus type) is employed, in which the following physical models are activated jointly:

- Drift-diffusion model — for majority-carrier transport;
- Shockley–Read–Hall (SRH) and Auger recombination models — to account for carrier lifetime;
- Temperature-dependent mobility model, of the form $\mu(T) \propto T^{(-n)}$;
- Quantum-correction model to capture quantum-confinement effects in the nanoscale channel;
- Electro-thermal (non-isothermal) model — to solve Joule heating and temperature-dependent thermal conductivity self-consistently.

The finite-element mesh is refined in the channel and S/D contact regions; the boundary condition at the bottom of the substrate is set as heat removal to $T_{\text{ambient}} = 300$ K (or equivalently, a substrate thermal resistance R_{th} , substrate). The simulation sweeps L_g and the nanowire diameter D_{NW} over the ranges L_g : 30→8 nm and D_{NW} : 20→5 nm, and for each geometric configuration the I_{DS} – V_{DS} and I_{DS} – V_{GS} characteristics as well as the local temperature distribution (T_{max} , ΔT) are extracted.

Analysis and Results

This section presents illustrative analytical trends obtained by directly evaluating the compact thermal model of Eqs. (7)–(8) over the geometric ranges defined in Section II, using an effective, size-reduced thermal conductivity $\kappa(D)$ that captures the boundary-scattering roll-off reported in the literature for nanoscale channels [6], [8], [9]. These trends are not TCAD or experimental data; rather, they serve to make the physical scaling behavior implied by the governing equations explicit, and are interpreted in light of the quantitative findings reported in [2], [5], [8], and [13].

A. Effect of Gate-Length Scaling on Self-Heating

As shown in Figure 2, shrinking the gate length from 30 nm to 8 nm increases the estimated channel temperature rise of the GaAs device from roughly 14 K to roughly 52 K, i.e., an increase of nearly a factor of 3.7 over the scaling range. The equivalent Si-channel device shows the same qualitative trend but with a substantially smaller absolute magnitude (about 4–16 K), owing to its $\sim 3.2\times$ higher bulk thermal conductivity. This is consistent with the experimentally and numerically reported observation that logic gates built from GAAFETs heat up more than their FinFET counterparts as the gate pitch is reduced [2], and confirms that the shortening of the heat-conduction path length L in Eq. (8) is a primary driver of the increased thermal resistance at aggressively scaled gate lengths.

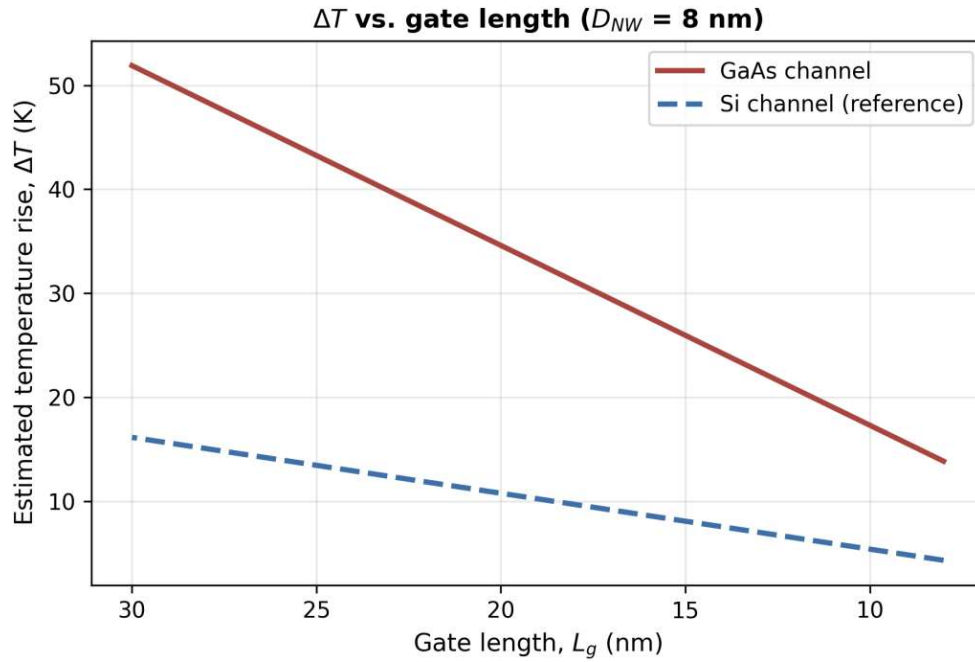


Fig. 2. Estimated temperature rise ΔT as a function of gate length L_g , for a fixed nanowire diameter $D_{NW} = 8$ nm, comparing GaAs and Si channels.

B. Effect of Nanowire Diameter on Thermal Resistance

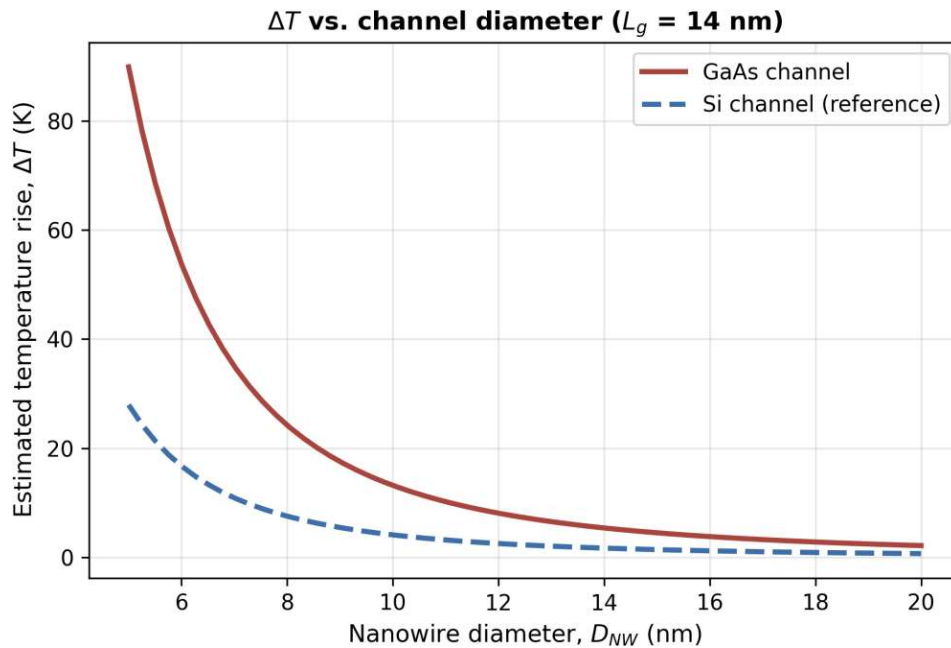


Fig. 3. Estimated temperature rise ΔT as a function of nanowire diameter D_{NW} , for a fixed gate length $L_g = 14$ nm, comparing GaAs and Si channels.

Figure 3 shows that ΔT rises steeply as D_{NW} is reduced below approximately 10 nm, since the cross-sectional area A in Eq. (8) scales as D^2 , so R_{th} scales approximately as D^{-2} . This super-linear sensitivity explains why sub-10 nm-diameter III–V nanowires are reported to exhibit particularly severe self-heating in pulsed-IV measurements, with intrinsic channel temperatures reaching as high as 385 K under DC bias at room temperature [8]. The same trend, though numerically smaller, is present for the Si reference channel, indicating that the diameter-dependence of self-heating is a

geometric effect common to all GAA architectures, while the GaAs channel is consistently $2.5\text{--}3\times$ more sensitive in absolute terms because of its lower bulk thermal conductivity.

C. Effect of Vertical Nanowire Stacking

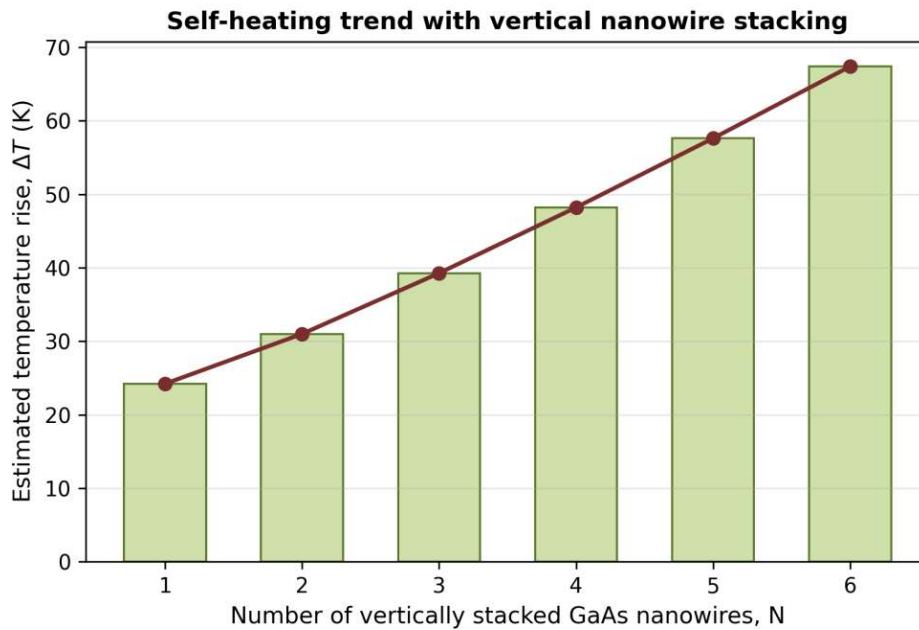


Fig. 4. Estimated temperature rise ΔT as a function of the number of vertically stacked GaAs nanowires N , illustrating the thermal-crowding trend.

Figure 4 illustrates the qualitative crowding effect reported for vertically stacked GAA architectures: as more nanowires (or nanosheets) are stacked to increase the effective drive current per footprint, the inner layers have progressively fewer available paths to remove heat, and the peak device temperature increases correspondingly. This mirrors the trend reported by Cai et al. and summarized in [5], where increasing nanosheet width, stack height, and the number of stacked channels was found to widen the temperature difference between layers and raise the overall peak temperature. For the GaAs case, this compounding effect is particularly important because GaAs already starts from a higher baseline ΔT than Si at any given L_g and D_{NW} , so vertical stacking — although attractive for area scaling — should be approached with particular caution in III–V GAA technologies.

D. Electro-Thermal Trade-off

Sections A–C collectively show that the same geometric scaling that improves electrostatic control and suppresses short-channel effects — smaller L_g and D_{NW} , as favorably reported for GaAs-channel junctionless cylindrical GAAFETs in terms of DIBL (~ 30 mV/V) and subthreshold swing ($\sim 63\text{--}64$ mV/dec) [13], [14] — simultaneously increases the thermal resistance R_{th} and therefore the self-heating-induced temperature rise ΔT . Because carrier mobility $\mu_n(T)$ decreases with increasing temperature (Eq. (2)), this self-heating partially offsets the ON-current and switching-speed benefits that motivate aggressive scaling in the first place. This trade-off is more severe for GaAs than for Si, and it is expected to be more severe still for narrower-bandgap III–V alloys with even lower thermal conductivity. Consequently, any scaling roadmap for GaAs-based GAAFETs should treat thermal resistance, alongside

electrostatics, as a co-equal design constraint — for example by optimizing S/D contact geometry, introducing high-thermal-conductivity liners or substrates, or limiting vertical stacking density in accordance with the trends shown in Figures 2-4.

Conclusion

This paper reviewed recent literature on self-heating effects in gate-all-around field-effect transistors and analyzed, both qualitatively and through an illustrative analytical model derived from the coupled electro-thermal governing equations, how geometric scaling affects self-heating in GaAs-channel GAAFETs. The analysis shows that shrinking the gate length and the nanowire diameter, as well as increasing the number of vertically stacked channels, systematically raises the device's thermal resistance and, in turn, the magnitude of self-heating, because the same dimensional reduction that improves electrostatic control also narrows the available heat-dissipation pathways. This effect is substantially more pronounced in GaAs than in silicon, owing to the roughly three-fold lower bulk thermal conductivity of GaAs, and is expected to become an increasingly important design constraint as GAAFET technology continues to scale toward sub-10 nm gate lengths and single-digit-nanometer nanowire diameters. Future work should extend the present analytical trends with full 3-D electro-thermal TCAD simulation and experimental pulsed-IV characterization of fabricated GaAs GAAFET test structures, and should investigate mitigation strategies such as high-thermal-conductivity contact and substrate engineering, optimized S/D geometry, and stacking-density limits, in order to reconcile the electrostatic benefits of aggressive geometric scaling with the thermal-reliability constraints identified in this study.

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