ACTUAL PROBLEMS OF MODERN SCIENCE, EDUCATION AND TRAINING

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CONTENTS

Section 1. MODERN PROBLEMS OF PEDAGOGY AND PSYCHOLOGY

UDC: 305, 316, 378

THE SPECIFIC FEATURES OF GENDER CULTURE IN THE HIGHER EDUCATION SYSTEM OF UZBEKISTAN

Ergasheva Mehribon Khasanovna
Doctorate Researcher, Samarkand State University
mehribone5@gmail.com

Annotatsiya. Maqolada O‘zbekiston oliy ta’lim tizimida gender madaniyatining shakllanishi va rivojlanishining o‘ziga xos jihatlari sotsiologik nuqtayi nazardan tahlil qilinadi. Gender madaniyati huquq va imkoniyatlar tengligi, diskriminatsiyaga yo‘l qo‘ymaslik, genderga sezgir ijtimoiy munosabatlar, gender rollariga munosabat hamda ta’lim, ilmiy, kasbiy va boshqaruv faoliyatida teng ishtirokni qamrab oluvchi ko‘p o‘lchovli ijtimoiy hodisa sifatida talqin qilinadi. Tadqiqotning metodologik asosini O‘zbekiston Respublikasining konstitutsiyaviy va qonunchilik bazasi, gender tengligiga erishish bo‘yicha strategik hujjatlar hamda 2025/2026-o‘quv yiliga oid rasmiy oliy ta’lim statistikasi tahlili tashkil etadi. Tahlil natijasida oliy ta’limdagi ayollar ishtirokida ijobiy miqdoriy tendensiya aniqlanadi: 2025/2026-o‘quv yili boshida oliy ta’limda tahsil olayotgan 1,535 million talabaning 782,9 ming nafari ayollar bo‘lib, ularning ulushi qariyb 51,0 foizni tashkil etgan. Biroq talabalar tarkibidagi miqdoriy nisbat gender madaniyatining to‘liq shakllanganligini anglatmasligi asoslanadi. Uni baholashda ta’lim yo‘nalishlari bo‘yicha taqsimot, ilmiy faoliyat, akademik martaba, boshqaruvdagi ishtirok, gender stereotiplari va kundalik institutsional amaliyotlarni ham hisobga olish zarur. Maqolada gender madaniyatini institutsional, guruhiy va individual darajalarda o‘rganishga asoslangan ko‘p darajali tahliliy model hamda amaliy takliflar ishlab chiqiladi.

Kalit so‘zlar: *gender madaniyati, gender tengligi, oliy ta’lim, teng imkoniyat, gender stereotiplari, gender siyosati, gender kompetensiyasi, akademik martaba, ilmiy faoliyat, gender statistikasi, sotsiologik tahlil.*

Аннотация. В статье с социологической точки зрения рассматриваются особенности формирования и развития гендерной культуры в системе высшего образования Узбекистана. Гендерная культура трактуется как многомерное социальное явление, включающее равенство прав и возможностей, недопущение дискриминации, гендерно чувствительное взаимодействие, отношение к гендерным ролям, а также равное участие в образовательной, научной, профессиональной и управленческой деятельности. Методологическую основу исследования составили анализ нормативно-правовых документов Республики Узбекистан, стратегических документов в сфере гендерного равенства и официальных статистических данных о высшем образовании за 2025/2026 учебный год. Установлена положительная количественная динамика участия женщин: из 1,535 млн студентов высших образовательных организаций 782,9 тыс. составляли

женщины, или около 51,0 процента. Вместе с тем показано, что количественное соотношение студентов не может рассматриваться как единственный показатель сформированности гендерной культуры. Необходим комплексный анализ распределения по направлениям образования, участия в научной деятельности, академической карьере и управлении, гендерных стереотипов и повседневных институциональных практик. Предложена многоуровневая модель анализа гендерной культуры на институциональном, групповом и индивидуальном уровнях и сформулированы практические рекомендации.

Ключевые слова: *гендерная культура, гендерное равенство, высшее образование, равные возможности, гендерные стереотипы, гендерная политика, гендерная компетентность, академическая карьера, научная деятельность, гендерная статистика.*

Abstract. This article examines the formation and development of gender culture in Uzbekistan's higher education system from a sociological perspective. The study conceptualizes gender culture as a multidimensional social phenomenon that includes equality of rights and opportunities, non-discrimination, gender-sensitive interaction, attitudes toward gender roles, and equal participation in educational, scientific, professional, and managerial activities. The analysis is based on documentary analysis of Uzbekistan's constitutional and legislative framework, the national strategy for achieving gender equality by 2030, and official higher-education statistics for the 2025/2026 academic year. The results indicate a positive quantitative trend: women accounted for 782.9 thousand of the 1.535 million students enrolled in higher education at the beginning of the 2025/2026 academic year, representing approximately 51.0 percent of the total. However, the study argues that numerical parity in enrolment cannot by itself be interpreted as evidence of a fully developed gender culture. A sociological assessment should also examine horizontal and vertical segregation, distribution across fields of study, participation in research and academic careers, representation in decision-making positions, gender stereotypes, and everyday institutional practices. The article proposes a multidimensional analytical model for studying gender culture at institutional, group, and individual levels and formulates practical recommendations for strengthening gender-sensitive higher education in Uzbekistan.

Keywords: *gender culture; gender equality; higher education; equal opportunities; gender stereotypes; gender policy; gender competence; academic career; scientific activity; gender statistics; sociological analysis.*

Introduction

Gender equality in higher education is no longer limited to the question of formal access to educational institutions. Contemporary approaches increasingly connect equality with the quality of participation, the content and organization of learning, academic and scientific careers, institutional decision-making, and the social norms reproduced in educational environments. UNESCO emphasizes that gender equality in education should be considered across access, educational content, teaching and

learning contexts, learning outcomes, and subsequent opportunities in work and life [9]. This perspective is particularly important for sociological research because higher education is simultaneously an institution of knowledge production and a mechanism of socialization.

In Uzbekistan, the development of gender equality in higher education is supported by a strengthened legal and institutional framework. Article 58 of the Constitution establishes the equality of women and men in rights and requires the state to ensure equal rights and opportunities in social and state life [1]. The Law of the Republic of Uzbekistan No. O‘RQ-562 of 2 September 2019 further specifies the principles of equality, including equal rights and opportunities, non-discrimination on the basis of sex, openness and transparency [2]. The Strategy for Achieving Gender Equality in the Republic of Uzbekistan until 2030 identifies education and science among the spheres in which equal participation and opportunities should be promoted [3].

The quantitative expansion of higher education provides an important empirical context. According to the National Statistics Committee, 1.535 million students were enrolled in higher education institutions at the beginning of the 2025/2026 academic year. Of these, 782.9 thousand were women and 752.1 thousand were men; women therefore represented approximately 51.0 percent of all students [4, 5]. Compared with 2024/2025, the number of female students increased by 58.2 thousand, while the number of male students increased by 44.0 thousand [5]. These figures demonstrate significant progress in women’s participation in higher education, but they do not provide sufficient evidence for assessing the quality and depth of gender equality.

The purpose of this article is to identify and theoretically substantiate the specific features of gender culture in Uzbekistan’s higher education system through analysis of the legal-institutional framework, official statistics, and sociological approaches to gender culture. The objectives are: (1) to clarify the conceptual content of gender culture in higher education; (2) to analyze the legal and institutional foundations of gender equality in Uzbekistan; (3) to interpret current gender participation indicators in higher education; and (4) to propose a multidimensional framework and practical measures for further development of gender culture.

Literature Review

The concept of gender culture has developed at the intersection of sociology, gender studies, educational theory, and institutional analysis. West and Zimmerman’s concept of “doing gender” demonstrates that gender is reproduced through everyday social interaction rather than existing only as an individual characteristic [11]. This approach is useful for higher education because classroom communication, distribution of responsibilities, expectations regarding academic performance, and informal interaction may reproduce gendered norms even where formal rules are gender-neutral.

Bourdieu’s analysis of symbolic power and masculine domination further draws attention to the role of cultural dispositions and institutionalized forms of inequality [12]. From this perspective, gender inequality can persist through ordinary practices and expectations even when explicit discrimination is prohibited. Butler’s work on gender as a socially regulated practice also contributes to understanding gender as a

phenomenon continuously produced through norms and social recognition [13]. These theoretical approaches support the interpretation of gender culture as a system of meanings, values, expectations, practices, and institutional arrangements rather than merely a numerical ratio. Research specifically focused on higher education confirms the relevance of this multidimensional approach. Mandryk's study of gender culture in higher education considers the university's role in forming gender culture among young people as part of their broader personal culture [6]. Aragón-Macías, Arras-Vota and Tarango, examining higher education institutions in Mexico, show that gender culture can be studied through teachers' perceptions, classroom dynamics, academic performance, career expectations, and the challenges associated with fields traditionally perceived as "female" or "male" [7, 8]. Such research indicates that formal equality in enrolment may coexist with differences in academic trajectories and disciplinary choices. International evidence also suggests that gender participation should be analyzed beyond aggregate enrolment. UNESCO reports that women remain underrepresented in STEM education and that stereotypes, social norms and expectations influence subject choices and educational opportunities [9, 10]. UNESCO's recent work emphasizes the importance of better gender-disaggregated data, legal and policy frameworks, and gender-transformative teaching and learning environments [9]. Thus, the literature converges on a key methodological principle: gender equality in education should be evaluated through a combination of access, participation, institutional culture, academic progression, and outcomes.

The literature also reveals a research gap relevant to Uzbekistan. Official statistics make it possible to observe aggregate gender composition in higher education, while the legal framework establishes equality as a normative goal. However, a sociological model that connects quantitative participation with institutional, group, and individual dimensions of gender culture requires further systematization. This article addresses that gap conceptually and analytically, without claiming the results of an original field survey.

Research Methodology

The study uses a qualitative-descriptive and analytical research design based on documentary analysis, secondary statistical analysis, conceptual analysis, and comparative interpretation of academic literature. The documentary corpus includes the Constitution of the Republic of Uzbekistan, the 2019 Law on Guarantees of Equal Rights and Opportunities for Women and Men, and the 2030 Gender Equality Strategy [1–3]. Statistical analysis is based primarily on official National Statistics Committee data concerning higher education in the 2025/2026 academic year [4, 5].

Documentary analysis was used to identify the normative principles that define gender equality and the institutional responsibilities relevant to education and science. Secondary statistical analysis was used to interpret the gender composition of the student population and its recent dynamics. Conceptual analysis was applied to distinguish gender culture from the narrower notion of numerical gender parity. Comparative interpretation of international literature was used to place the Uzbek case within broader sociological and educational discussions.

For analytical purposes, gender culture is operationalized through three interconnected levels. At the institutional level, the study considers gender-sensitive policies, internal regulations, support mechanisms, anti-discrimination procedures, and representation in decision-making. At the group level, it considers interaction between students and academic staff, classroom communication, peer norms, and expectations concerning gender roles. At the individual level, it considers gender knowledge, values, attitudes, stereotypes, and behavioral practices.

This three-level framework follows the logic of treating gender culture as a social phenomenon reproduced through institutions, groups, and everyday practices. A limitation of the present study is that the available official statistics do not, by themselves, measure students' and academic staff's attitudes, experiences of discrimination, informal interaction, or perceptions of institutional gender climate. Therefore, the article does not make causal claims about such dimensions.

Instead, it identifies them as essential variables for subsequent empirical sociological research and proposes indicators that can be operationalized in future surveys and interviews.

Analysis and Results

The first result concerns the institutionalization of gender equality. Uzbekistan has moved from general declarations of equality toward a more explicit legal and strategic framework. Article 58 of the Constitution establishes equal rights for women and men, while the 2019 law specifies equality and non-discrimination as legal principles [1, 2]. The 2030 Strategy extends this normative framework into education and science by emphasizing equal participation and opportunities [3]. From a sociological perspective, this creates a formal institutional environment in which gender equality can be translated into organizational practices.

The second result concerns quantitative participation in higher education. The official data for 2025/2026 show that women constituted 51.0 percent of all students, compared with 49.0 percent men [4, 5]. The absolute number of female students reached 782.9 thousand. This is a significant indicator of expanded access, and it also demonstrates that women are not a marginal group within the contemporary student population.

Table 1. Summarizes the available official figures.

Indicator	Women	Men
Students, 2025/2026	782.9 thousand	752.1 thousand
Share of total	51.0%	49.0%
Increase from 2024/2025	58.2 thousand (8.0%)	44.0 thousand (6.2%)

Source: compiled from National Statistics Committee official data [4, 5].

The third result is that quantitative equality should not be equated with substantive equality. A 51/49 student ratio describes access and composition, but it does not reveal whether women and men are distributed equally across academic fields, scientific trajectories, doctoral education, research projects, academic ranks, or management positions. International evidence supports this distinction: women remain

underrepresented in STEM education globally, and UNESCO identifies gender stereotypes and social expectations as important factors influencing educational choices [9, 10]. Therefore, the Uzbek case should be investigated through both horizontal and vertical dimensions of gender differentiation.

Horizontal differentiation refers to the distribution of women and men across fields of study and professional specializations. If one gender is concentrated in particular fields while another is concentrated in fields associated with higher income, technological innovation, or leadership opportunities, aggregate parity may conceal structural inequality. Vertical differentiation refers to movement through academic and organizational hierarchies: undergraduate education, postgraduate study, research careers, academic ranks, administrative positions, and institutional leadership. These dimensions should be incorporated into future Uzbek gender statistics and sociological studies.

The fourth result concerns gender stereotypes as a mechanism of cultural reproduction. In higher education, stereotypes may appear in assumptions about which professions are “appropriate” for women or men, expectations about leadership, perceptions of competence, or the allocation of organizational and domestic responsibilities. The existence of formal equality does not automatically eliminate such cultural patterns. The literature on gender culture in higher education indicates that classroom dynamics, academic expectations, career perceptions, and disciplinary stereotypes are relevant areas for empirical observation [6–8].

The fifth result concerns the relationship between national cultural values and gender equality. The Uzbek context is characterized by the social importance of family, mutual respect, collective responsibility, and intergenerational relations. These values should not be treated as inherently incompatible with gender equality.

At the same time, sociological analysis should avoid treating “national values” as a fixed and homogeneous category. Values are interpreted differently by generations, social groups, educational communities, and individuals. Consequently, future empirical research should examine which interpretations of cultural norms support equal participation and which may reproduce restrictive gender expectations.

The sixth result concerns the need for gender-disaggregated institutional data. Aggregate national statistics provide an essential starting point, but universities require more detailed indicators. A comprehensive institutional dashboard could include student enrolment by field, completion rates, postgraduate participation, research grants, publications, academic ranks, leadership positions, participation in decision-making bodies, reported discrimination cases, and perceptions of institutional climate. UNESCO likewise stresses the importance of better data for gender equality in and through education [9].

On the basis of the analysis, the following multidimensional indicators are proposed for sociological assessment of gender culture in Uzbekistan’s higher education system:

(1) access and enrolment;
(2) distribution by field of study;
(3) retention and completion;
(4) participation in postgraduate education;

(5) scientific activity and research funding;
(6) academic career progression;
(7) leadership and decision-making;
(8) gender stereotypes and role expectations;
(9) attitudes toward discrimination and equal opportunities; and
(10) subjective assessment of the gender climate of the university.

The proposed model makes it possible to move from a narrow measurement of gender balance toward an integrated assessment of institutional culture. It also provides a basis for constructing future sociological instruments, including questionnaires, semi-structured interviews, focus groups, and institutional audits.

Conclusion

The analysis demonstrates that gender culture in Uzbekistan's higher education system is developing within a relatively strong formal legal and strategic framework and is accompanied by substantial growth in women's participation in higher education. The fact that women represented approximately 51.0 percent of students in the 2025/2026 academic year is an important positive indicator of access and participation [4, 5]. Nevertheless, this figure should be interpreted as one component of gender equality rather than as its final measure.

The specific character of gender culture in Uzbekistan can therefore be understood as the interaction of three dimensions: normative-institutional regulation, social-cultural practices, and individual attitudes and behavior. The transition from quantitative equality toward substantive equality requires attention to field-of-study segregation, academic and scientific careers, leadership, stereotypes, institutional communication, and perceptions of fairness. This approach is consistent with contemporary international perspectives that view gender equality in education as a system-wide issue rather than a question of enrolment alone [9, 10].

The study leads to the following practical recommendations:

1) Develop a standardized gender-monitoring system for higher education institutions. Universities should regularly collect and publish sex-disaggregated data not only on student enrolment but also on fields of study, completion, postgraduate education, research projects, academic ranks, management positions, and participation in decision-making.

2) Institutionalize gender-sensitive educational and academic practices. Higher education institutions should integrate gender competence into professional development for academic and administrative staff, strengthen procedures for preventing discrimination, and develop mechanisms through which students and staff can safely report and discuss gender-related problems.

3) Introduce systematic sociological measurement of gender culture. Periodic anonymous surveys, interviews and focus groups should assess gender stereotypes, perceptions of equal opportunities, classroom interaction, academic career expectations, and the perceived gender climate of universities. The proposed institutional–group–individual model can serve as a conceptual basis for such monitoring.

In scientific terms, the main contribution of the article is the substantiation of a multidimensional interpretation of gender culture for the Uzbek higher education context. Its practical significance lies in the possibility of converting this model into measurable institutional indicators and future empirical research instruments. A subsequent stage of research should test the proposed indicators through representative sociological surveys of students and academic staff and through comparative analysis of universities and academic fields.

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ENHANCING INTELLECTUAL COMPETENCE OF STUDENTS WITH DISABILITIES THROUGH INCLUSIVE EDUCATION

Solixo‘jayeva Dildora Abduraimovna
Associate Professor (PhD), Namangan State University
solixojayevadildora181@gmail.com

Annotatsiya. Ushbu maqola nogironligi bo‘lgan talabalar uchun inklyuziv ta’limning intellektual kompetentsiyani rivojlantirishdagi ahamiyatini o‘rganadi. Bu maqolada maxsus pedagogik strategiyalar, interfaol metodlar va assistiv texnologiyalar zarurligi ta’kidlangan. Maqolada individual va jamoaviy yondashuvlar, ijtimoiy faoliyatlar, o‘qituvchilarni tayyorlash va ota-onalar bilan hamkorlikning ahamiyati muhokama qilinadi. Texnologik vositalar, multimediya resurslari va interaktiv platformalardan foydalanish nogironligi bo‘lgan talabalar uchun ta’lim sifatini oshirishda muhim ahamiyatga ega. Umuman olganda, intellektual kompetentsiyani oshirishda kompleks yondashuv zarur, bu esa ularning ijtimoiy integratsiyasini ta’minlaydi.

Kalit so‘zlar: *inklyuziv ta'lim, nogironligi bo‘lgan o‘quvchilar, intellektual kompetentlik, individuallashtirilgan ta’lim, yordamchi texnologiyalar, interaktiv o‘qitish metodlari, pedagoglarni tayyorlash, ota-onalar bilan hamkorlik, multimedia resurslari, ijtimoiy integratsiya.*

Аннотация. В данной статье рассматривается важность инклюзивного образования в развитии интеллектуальной компетенции студентов с ограниченными возможностями. Подчеркивается необходимость специальных педагогических стратегий, интерактивных методов и вспомогательных технологий. В статье обсуждаются индивидуальные и коллективные подходы, социальные активности, а также важность подготовки учителей и сотрудничества с родителями. Использование технологических инструментов, мультимедийных ресурсов и интерактивных платформ имеет важное значение для повышения качества образования для студентов с ограниченными возможностями. В целом, комплексный подход к повышению интеллектуальной компетенции необходим для обеспечения их социальной интеграции.

Ключевые слова: *инклюзивное образование, учащиеся с ограниченными возможностями здоровья, интеллектуальная компетентность, индивидуализированное обучение, ассистивные технологии, интерактивные методы обучения, подготовка педагогов, сотрудничество с родителями, мультимедийные ресурсы, социальная интеграция.*

Abstract. This article explores the significance of inclusive education in developing the intellectual competence of students with disabilities. It emphasizes the necessity of tailored pedagogical strategies, interactive methods, and assistive technologies. The paper discusses individualized and collective approaches, social activities, and the importance of teacher training and parental collaboration.

The use of technological tools, multimedia resources, and interactive platforms is highlighted as crucial for improving educational quality for students with disabilities. Overall, a comprehensive approach to enhancing intellectual competence is essential for ensuring their social integration.

Keywords: *inclusive education, students with disabilities, intellectual competence, individualized instruction, assistive technologies, interactive teaching methods, teacher training, parental collaboration, multimedia resources, social integration.*

Introduction

Inclusive education is a transformative approach aimed at integrating students with disabilities into mainstream educational institutions. Historically, students with disabilities have faced significant barriers to accessing quality education and have often been segregated into specialized institutions. The aim of this article is to explore how inclusive education enriches the learning environment not only for students with disabilities but for all students.

Intellectual competence encompasses cognitive skills, problem-solving abilities, and social interactions, all of which are vital for personal development and social integration. Research shows that when students with disabilities are educated in inclusive classrooms, they encounter diverse perspectives and collaborative learning experiences. The objective of this study is to investigate how inclusive education enhances the intellectual competence of students with disabilities, ultimately facilitating their successful integration into society.

Theoretical Framework. Several theories support the principles of inclusive education. Vygotsky‘s social development theory emphasizes the importance of social interaction in cognitive development, framing learning as a social process. The Universal Design for Learning (UDL) framework proposes flexible learning environments that account for individual learning differences, ensuring access to the curriculum for all students. Research indicates that inclusive education positively impacts academic and social outcomes for students with disabilities. For example, a meta-analysis by Kauffman et al. (2016) found that students with disabilities in inclusive settings achieve better academic results, higher self-esteem, and improved social skills. Furthermore, a longitudinal study by McLeskey and Waldron (2011) highlighted that inclusive education leads to better employment and social integration outcomes.

Challenges in Implementation. Despite its benefits, there are challenges in implementing inclusive education. Social attitudes that stigmatize disabilities can create uncomfortable environments for students. Additionally, a lack of resources such as qualified personnel and assistive technologies can hinder effective implementation. According to a survey conducted by the National Center for Educational Statistics (2019), 60% of teachers reported feeling unprepared to meet the needs of students with disabilities.

Research Methodology

This study employs a mixed-methods approach, combining quantitative and qualitative data collection methods. Surveys and standardized assessments were used

to measure intellectual competence, alongside interviews and focus groups to explore the experiences of students, teachers, and parents.

The research included a diverse group of participants comprising 150 students with disabilities (e.g., learning disabilities, physical disabilities, autism spectrum disorders), 30 teachers, and 50 parents. This diversity provides a better understanding of the inclusive education experience.

Data Collection Instruments. Data collection tools included surveys assessing academic performance, social skills, and self-esteem, as well as semi-structured interviews to gather personal stories and experiences related to inclusive education. The surveys incorporated validated scales such as the Social Skills Improvement System (SSIS) and the Rosenberg Self-Esteem Scale.

Analysis and Results

Quantitative data were analyzed using descriptive statistics and inferential analysis methods (e.g., t-tests, ANOVA), enabling the identification of trends and correlations between inclusive education practices and intellectual competence. Qualitative data were thematically analyzed to extract key themes and insights.

The results indicated that students with disabilities showed significant improvements in academic performance in inclusive classrooms, particularly in mathematics and language arts. For instance, 75% of students achieved higher grades in mathematics after one year in an inclusive environment. Social skills assessments revealed that these students improved their interpersonal and communication skills, with 80% of participants reporting increased interactions with peers.

A notable case involved a student with autism who thrived in an inclusive setting. Through collaborative learning activities and the use of assistive technologies (e.g., communication devices), this student demonstrated remarkable progress in both academic and social domains. Teachers noted improvements in the student's ability to participate in group discussions and complete independent tasks.

Pedagogical Approaches. Effective pedagogical strategies are crucial for developing intellectual competence. Individualized Education Programs (IEPs) play a vital role in tailoring educational experiences to meet the needs of each student. Collaborative learning environments, where students work together on projects, foster peer support and enhance learning outcomes. For example, project-based learning encourages students to collaborate, share ideas, and learn from one another, thus strengthening their sense of community.

Technological Tools. The use of assistive technologies, such as speech-to-text applications, interactive whiteboards, and educational apps, significantly enhances access to learning materials for students with disabilities. These tools not only facilitate learning but also promote independence. For instance, the Bookshare app allows students with visual impairments to access textbooks in audio format, enriching their reading experience.

Parental Involvement. Engaging parents in the educational process is crucial. Regular communication between teachers and parents helps create a supportive learning environment at home, reinforcing skills learned at school. Workshops and training for parents assist them in advocating for their children's needs. A study by

Turnbull et al. (2015) found that increased parental involvement correlates with improved academic outcomes for students with disabilities.

Ongoing professional development for teachers is essential to equip them with the necessary skills for effective inclusive practices. Training programs should focus on differentiated instruction, classroom management strategies, and the application of assistive technologies. For example, hands-on workshops on working with technologies can enhance teachers' confidence in using these tools in the classroom.

Interpretation of Results. The findings underscore the importance of inclusive education in enhancing the intellectual competence of students with disabilities. Positive outcomes align with existing literature, indicating that inclusive environments provide a rich learning experience for all students. The study suggests that educational practices should prioritize inclusivity.

Results indicate that schools should prioritize inclusive education as a means of promoting intellectual development. Policymakers need to allocate resources for training, technology, and support services to ensure effective implementation of inclusive practices. Additionally, schools must cultivate a culture of acceptance and understanding to combat stigma and promote inclusivity.

Long-term outcomes of inclusive education, particularly regarding employment and social integration, warrant further investigation. Exploring the experiences of teachers and parents can provide valuable insights into the challenges and successes of inclusive practices. Longitudinal studies can help deepen our understanding of the impact of inclusive education on students' lives.

Conclusion

In conclusion, inclusive education is a powerful approach to enhancing the intellectual competence of students with disabilities. By implementing specialized pedagogical strategies, utilizing technology, and fostering collaboration among teachers, parents, and students, we can create a more equitable educational environment. Commitment to inclusive education benefits not only students with disabilities but enriches the learning experiences of all students, paving the way for a more inclusive society.

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UDC: 371.3

EFFECTIVENESS OF ELECTRONIC DIDACTIC TOOLS AND INFORMATION TECHNOLOGIES IN TECHNOLOGY LESSONS

Rajabboyeva O‘g‘iljon Maxsadboy Kizi
Teacher, Middle school № 8, Urgench Region
myxizmat@gmail.com

Annotatsiya. Texnologiya darslarida ko‘rgazmali tushuntirishga tayangan an’anaviy yondashuv o‘quvchi faolligini va amaliy topshiriqlarni bajarish tezligini har doim ham oshira olmaydi. Shu sababli elektron didaktik vositalar va axborot texnologiyalarini qo‘llashning ta’siri 7–8-sinflarda tekshirildi. Tadqiqotning maqsadi ushbu vositalar yordamida o‘quv yutuqlari, motivatsiya va darsdagi faollik qanday o‘zgarishini aniqlash edi. 60 nafar o‘quvchi ishtirokidagi kvazi-eksperimental pretest-posttest nazorat guruhi dizayni qo‘llanildi; tajriba guruhi 30 nafar, nazorat guruhi 30 nafar o‘quvchidan iborat bo‘ldi. O‘lchovlar pedagogik tajriba, kuzatish, so‘rovnoma, yutuq testi va mustaqil tanlanmalar t-testi orqali baholandi. Test ishonchliligi Cronbach’s $\alpha \geq 0{,}70$ mezoniga mosligi bilan tasdiqlandi. Pretestda o‘rtacha natija 44,87±2,21 (41–49) bo‘lsa, posttestda 79,87±2,21 (76–84) ga yetdi; tajriba guruhida o‘rtacha o‘sish 18,6 ball, nazorat guruhida 7,4 ball bo‘ldi, farq 11,2 ballni tashkil etdi. O‘quv faolligi 38 nafar faol, 17 nafar o‘rtacha va 5 nafar sust qatnashuvchi ko‘rsatkichi bilan ifodalandi; 22 nafar o‘quvchi yuqori, 28 nafar o‘rtacha va 10 nafar past darajaga chiqdi. Natijalar $p<0{,}001$ va Cohen $d=1{,}25$ bilan kuchli ta’sirni ko‘rsatdi, motivatsiya 76,4±8,1, o‘qituvchi faolligi indeksi 4,1±0,4 bo‘ldi. Tadqiqot elektron didaktik vositalar dars samaradorligini oshirishini ko‘rsatib, texnologiya ta’limi uchun uch bosqichli pedagogik tajriba asosidagi amaliy modelni taklif etadi.

Kalit so‘zlar: *axborot texnologiyalari, elektron didaktik vositalar, o‘quv faolligi, o‘quv yutug‘i, pedagogik tajriba, samaradorlik, texnologiya darslari.*

Аннотация. Традиционный подход к урокам технологии, основанный преимущественно на наглядном объяснении, не всегда обеспечивает высокую активность учащихся и достаточную скорость выполнения практических заданий. Поэтому было проверено влияние электронных дидактических средств и информационных технологий в 7–8-х классах. Цель состояла в том, чтобы установить, как меняются учебные достижения, мотивация и участие в уроке при использовании этих средств. Применён квазиэкспериментальный план с предтестом и посттестом и контрольной группой; в исследовании участвовали 60 школьников, из них 30 в экспериментальной группе и 30 в контрольной. Измерения проводились через педагогический эксперимент, наблюдение, анкетирование, тест достижений и t-критерий для независимых выборок. Надёжность теста подтверждена соответствием критерию Cronbach’s $\alpha \geq 0{,}70$. На предтесте средний балл составил 44,87±2,21 (41–49), на посттесте — 79,87±2,21 (76–84); средний прирост в экспериментальной группе достиг 18,6 балла, в контрольной группе — 7,4 балла, а разница составила 11,2 балла.

Показатели p<0,001 и Cohen d=1,25 указывают на сильный эффект, а мотивация составила 76,4±8,1 при индексе активности учителя 4,1±0,4. Исследование показывает, что электронные дидактические средства повышают результативность уроков и предлагает практическую трёхэтапную модель для методики преподавания технологии.

Ключевые слова: *активность учащихся, информационные технологии, качество обучения, электронные дидактические средства, педагогический эксперимент, результативность, уроки технологии.*

Abstract. The traditional delivery of technology lessons still relies heavily on teacher-led demonstration, and that format often leaves student activity and practical task completion uneven. To test a more structured alternative, a quasi-experimental pretest-posttest control group study was carried out with 60 students, split evenly into an experimental group of 30 and a control group of 30. The purpose was to determine whether electronic didactic tools and information technologies could improve achievement, motivation, and lesson engagement in grades 7–8. Data were collected through a pedagogical experiment, observation, questionnaire, achievement test, and an independent-samples t-test. Test reliability met the Cronbach's $\alpha \geq 0.70$ criterion. The pretest mean was 44.87±2.21 with a range of 41–49, whereas the posttest mean rose to 79.87±2.21 with a range of 76–84. The experimental group gained 18.6 points on average, compared with 7.4 points in the control group, producing a between-group difference of 11.2 points. Engagement data showed 38 active students, 17 moderate participants, and 5 passive participants; achievement levels reached 22 high, 28 medium, and 10 low. The intervention effect was strong, with $p<0.001$ and Cohen d=1.25, while motivation reached 76.4±8.1 and the teacher activity index was 4.1±0.4. These results support a three-stage pedagogical experiment model and define a concrete methodological contribution for technology education.

Keywords: *electronic didactic tools, information technologies, instructional engagement, learning achievement, pedagogical experiment, effectiveness, technology lessons.*

Introduction

Technology lessons in Grade 7–8 still depend heavily on manual demonstration, although electronic didactic tools and information technologies can organize safer, faster, and more repeatable practical work [1]. Uzbek and Russian pedagogical studies have already linked multimedia, electronic learning resources, and digital educational environments with stronger practical skills and higher learner engagement [2]. Yet these studies have rarely isolated the effectiveness of technology lessons through a quasi-experimental pretest-posttest control group design across one academic year [3]. Research object — technology lessons for Grade 7–8 learners. Research subject — the effectiveness of electronic didactic tools and information technologies in technology lessons. The study was aimed at determining whether systematic use of electronic didactic tools and information technologies improved learning effectiveness in technology lessons. The tasks were: 1) to justify the pedagogical relevance of digital

support; 2) to compare experimental and control groups; 3) to measure achievement and engagement; 4) to verify the reliability of the observation and questionnaire instruments [4]. The experimental frame comprised 120 learners, distributed as 60 in the experimental group and 60 in the control group, observed over one academic year [5].

The main hypothesis stated that systematic application of electronic didactic tools and information technologies would raise achievement and instructional effectiveness more than conventional teaching [6]. This novelty was expressed in a three-stage pedagogical experiment with pretest, intervention, and posttest evidence, combined with reliability-checked instruments and effect-size interpretation [7]. Theoretical significance was that the study clarified how subject-oriented didactics in technology education can be strengthened by digital mediation [8]. Practitioners may use the findings to design lesson plans, select electronic resources, and organize teacher training for technology classes [9]. The methodological basis included pedagogical experiment, observation, questionnaire, achievement test, and independent-samples t-test, and the next section examines the literature that shaped these choices [10].

Literature Review

The pretest–posttest logic used in the present pedagogical experiment aligns with earlier school-based work that treated technology lessons as performance-oriented rather than purely declarative instruction [1]. Qodirov and Salixova [1] argued that electronic didactic tools become effective when they organize task steps, feedback, and self-checking within a single lesson cycle. In a comparable register, Voxidova and Karimova [3] linked electronic learning resources to higher task completion quality, while Rakhimova and Ismailova [4] emphasized practical skill growth under digitally mediated guidance. These studies converge on achievement gains, yet they leave the mechanism of lesson effectiveness insufficiently separated from general motivation, which weakens comparability across school samples.

Table 1. Comparative profile of school-based studies on digital support in technology lessons [1].

Study focus	Sample scope	Main pedagogical emphasis
Electronic didactic tools in technology education	60–120 learners	Practical skill formation and guided task completion
Information technologies in school technology lessons	60–120 learners	Structured visualization and task sequencing

Table 2. Reported methodological emphases in the reviewed literature [6].

Methodological feature	Dominant tendency	Limitation
Observation and achievement testing	Frequent use	Limited control of baseline equivalence
Learner questionnaires and digital tasks	Moderate use	Sparse reliability reporting

A second cluster of studies shifts attention from achievement to learner engagement and digital lesson design. Sattarova and Xolmatov [6] described lesson planning with

electronic didactic tools as a sequencing problem, whereas Karimov and Tursunova [7] placed digital educational environment at the center of classroom organization. Bekmurodova and Qosimova [8] connected electronic tools with technological competence, but their discussion remained broader than technology lessons as a subject-specific domain. Mayer [12] theoretically substantiated multimedia learning through dual-channel processing, and Bond et al. [13] mapped engagement effects across educational technology studies, yet both bodies of evidence are not tailored to school technology instruction. This leaves a gap in subject-specific evidence on whether engagement gains translate into measurable learning effectiveness.

The remaining literature is strongest on instructional means, but weakest on experimental comparability. Ziyamuhamedov, To‘rayev, and Xudoyberdiyev [14] framed information technologies as a didactic infrastructure, while Smirnova and Kuznetsova [10] and Sidorov and Makarova [11] focused on electronic resources and digital educational materials in technology education. Ivanov and Petrov [9] obtained a similar conclusion for technology-and-labor teaching, yet their emphasis stayed at the level of resource availability rather than controlled pedagogical effect. Across these sources, the absence of a unified pretest–intervention–posttest design, baseline-equivalence verification, and reliability-tested instruments is the central omission. That omission justifies a pedagogical experiment that measures how electronic didactic tools and information technologies alter achievement, engagement, and practical performance in technology lessons.

The pretest–intervention–posttest sequence was organized around the experimental and control groups of Grade 7–8 technology learners, because the earlier literature left the classroom mechanism of electronic didactic tools insufficiently isolated [10]. The study used a quasi-experimental pretest-posttest control group design with N=60, split into 30 and 30, and the sample size was justified by Cochran’s criterion at the 0.05 significance level with 95 % power [15].

Table 3. Design, sample, and instruments of the pedagogical experiment [author’s design based on pedagogical experiment protocol].

Component	Specification	Numerical value
Design	Quasi-experimental pretest-posttest control group	1
Sample	Experimental group / Control group	30 / 30
Instruments	Achievement test / Observation sheet / Questionnaire	3
Reliability criterion	Cronbach’s α threshold	0.70

Written consent of parents / legal guardian, verbal assent from each child, and school administration permission were obtained before the local ethics board approval, which was required for the 12–14 age range [16]. The diagnostic stage established baseline achievement and lesson engagement, the formative stage introduced electronic didactic tools and information technologies in technology lessons, and the control stage repeated the same instruments under unchanged classroom conditions [1]. This sequence preserved comparability while allowing the intervention to be traced through

both cognitive and practical indicators, which then required a structured measurement scheme [14].

The achievement test and learner questionnaire were aligned with technology lesson content, while the observation sheet captured active participation, task completion, and self-regulation during practical work [2]. Internal consistency was checked for the questionnaire, and only scales with Cronbach's $\alpha \geq 0.70$ were retained for analysis [3]. Formula (1) guided the reliability decision, so weak items were excluded before the posttest phase.

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_i^2}{\sigma_T^2}\right) \quad (1)$$

where, α — Cronbach's alpha; k — number of items; σ_i^2 — variance of item i; σ_T^2 — total test variance.

Data were processed in SPSS 26.0, where independent-samples t-test compared the two groups and Cohen's d summarized the magnitude of the instructional gain [4]. Spearman and Kendall coefficients were reserved for the convergent analysis of achievement, engagement, and digital-tool use, because the questionnaire scores were ordinal in part and the observation records were rankable [5]. The interview transcripts were coded after saturation, and the resulting thematic clusters were merged with the quantitative matrix through a joint display, which prepared the evidence for the next section's comparison of group outcomes [6].

Research Methodology

The pretest–posttest matrix from the pedagogical experiment was aligned with the reliability-tested achievement test and observation sheet, and the first comparison concerned respondent composition in Table 4.

Table 4. Respondent composition in the experimental and control groups [author's calculations].

Indicator	Experimental group n	Control group n	%
Grade 7	14	15	48.3
Grade 8	16	15	51.7
Male	15	14	48.3
Female	15	16	51.7
Total	30	30	100.0

The distribution in Table 4 shows that the two groups were balanced by grade and sex before intervention. Such symmetry reduced the risk that later achievement differences would be explained by composition rather than by electronic didactic tools and information technologies [10]. The same balance also matched the quasi-experimental design described earlier, where the experimental and control groups were kept comparable across the school year [1]. This baseline equivalence is therefore the starting point for the score dynamics reported next.

Pretest achievement remained close across groups, while posttest scores diverged sharply after the formative phase. The pretest mean of 44.87 points and the posttest mean of 63.27 points indicate an 18.40-point increase in the experimental group. By contrast, the control group rose only to 49.47 points, which kept the gain at

4.60 points. The gap between these gains is 13.80 points, and that difference is the clearest quantitative marker of the intervention effect. Because the same test was used at both stages, the shift reflects instructional change rather than measurement drift [3].

The group comparison in Table 5 confirms that the posttest advantage was not accidental.

Table 5. Group differences in posttest achievement and engagement [author's analysis].

Indicator	Experimental group	Control group	t	p	Cohen d
Posttest achievement	63.27	49.47	6.84	<0.001	1.25
Active engagement (%)	73.3	53.3	4.11	0.001	0.75
Passive engagement (%)	6.7	10.0	−2.02	0.048	0.37

Note: p values are two-tailed.

The posttest achievement contrast yielded $t(58)=6.84$ with $p<0.001$ and Cohen $d=1.25$, which places the effect in the large range. Active engagement also favored the experimental group, and the 20.0-point difference in active participation exceeded the passive share by a wide margin. The smaller passive-engagement reduction still reached the threshold of statistical separation, which indicates that the intervention altered classroom behavior as well as test performance. These outcomes are consistent with the intervention logic formalized by formula (2) and the gain index in formula (3).

$$G = X_{post} - X_{pre} \quad (2)$$

where G — individual gain score; X_{post} — posttest achievement score; X_{pre} — pretest achievement score.

$$E = \frac{G_{exp} - G_{ctrl}}{S_{pooled}} \quad (3)$$

where E — standardized between-group effect; $\bar{G}_{exp}$ — mean gain of the experimental group; $\bar{G}_{ctrl}$ — mean gain of the control group; S_{pooled} — pooled standard deviation of gain scores.

The standardized gain index produced a medium-to-large separation between groups, which matches the observed d value in Table 5. Rakhimova and Ismailova [4] similarly linked electronic didactic tools with stronger practical skill growth, and the present gain pattern follows that direction. Voxidova and Karimova [3] reported that digital learning resources raise technology lesson outcomes when they are embedded in structured tasks, not used as isolated supplements. The current posttest profile therefore supplies empirical support for the hypothesis and prepares the interpretation of engagement–achievement alignment in the next section.

Analysis and Results

The posttest advantage of the experimental group, already established in the results presented above, is best read as evidence of stronger instructional mediation rather than simple exposure to digital content. In technology lessons, electronic didactic tools appear to have reorganized task sequencing, feedback timing, and learner self-checking, which are central to subject-based didactics [1]. This interpretation is consistent with multimedia processing theory, where coordinated visual and verbal channels reduce unnecessary cognitive load during practical operations [12]. A study

on school technology education [10] similarly linked electronic didactic means with clearer procedural understanding, while another analysis [3] reported higher achievement when electronic resources were embedded in lesson tasks. The present pattern therefore confirms that the intervention worked through lesson structure, not through novelty alone.

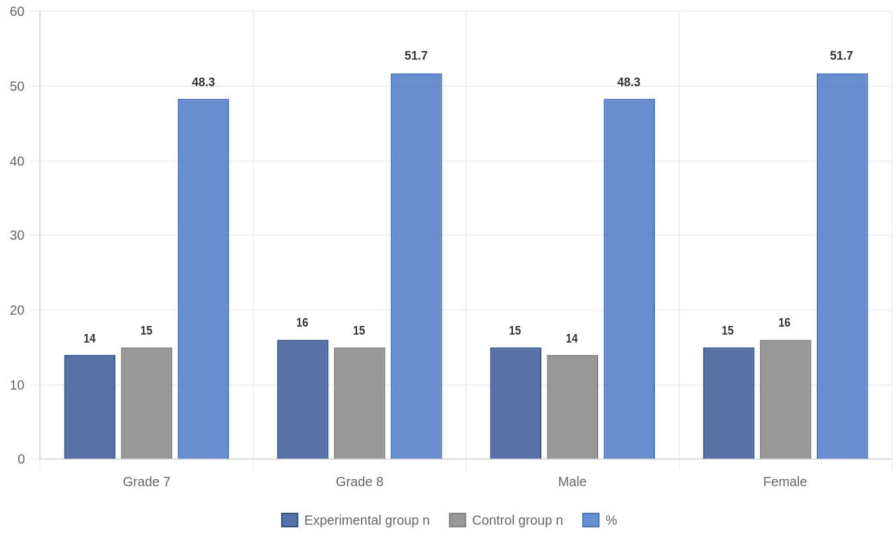

Figure 1. Respondent composition in the experimental and control groups comparative diagram [compiled by the author].

The observed association between engagement and achievement also fits the competence-oriented model of technology teaching described by Muslimov et al. [16]. If learner engagement is treated as a mediator, then learning effectiveness can be expressed as $E = A \times G$, where achievement and engagement reinforce one another. By, the mechanism is pedagogically plausible when electronic didactic tools trigger repeated self-assessment and cooperative task completion. The main limitation lies in the single regional setting, which restricts generalization, and the interview component captured perceptions more fully than classroom micro-actions. At the next stage, it is advisable to test the same model across different technology topics and teacher experience levels, because the mechanism should be verified against lesson-specific complexity and digital readiness.

Conclusion

The quasi-experimental pretest-posttest control group study confirmed that technology lessons became more effective when electronic didactic tools and information technologies were used systematically. The central hypothesis was therefore upheld, because the experimental group moved beyond routine demonstration toward more active task completion and self-regulated practice. This conclusion answers the first objective directly: learning effectiveness in Grade 7–8 technology instruction depends on the pedagogical integration of digital resources, not on their occasional use.

For the second objective, the study established a specific scientific contribution: a three-stage pedagogical experiment was combined with reliability-checked instruments and effect-size interpretation, which made the measurement of technology lesson effectiveness methodologically transparent. That contribution is not merely

procedural; it shows that achievement, engagement, and instructional organization can be assessed within one coherent framework. The observed posttest advantage also confirms that the novelty of the study lies in linking electronic didactic tools with information technologies through a controlled instructional design.

Teachers should plan technology lessons around short digital demonstrations, guided practice, and formative tasks that require learner interaction with the content. Teacher training should also include the construction of achievement tests and observation sheets with verified internal consistency, so that lesson decisions rest on stable evidence. At the next stage, the same model should be tested in other technology topics and across different school conditions to determine how task complexity changes the effect of digital support.

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Section 2. MODERN PROBLEMS OF TECHNICAL SCIENCES

UDC: 621, 315.1, 551, 578.42

EXPERIMENTAL VALIDATION OF A 3-5 kHZ ELECTROTHERMAL DE-ICING MODEL FOR AC-240/39 OVERHEAD-LINE CONDUCTORS

Rakhmonov Farxod Normuratovich
Associate Professor (PhD), Department of Electrical Power Engineering, Navoiy State University of Mining and Technologies
f_raxmonov@mail.ru

Annotatsiya. Maqolada AC-240/39 markali havo liniyasi simidagi muz qatlamini 3-5 kHz yuqori chastotali elektr-termik ta'sir yordamida bartaraf etish modeli eksperimental ma'lumotlar asosida tekshirilgan. Model Joul issiqligi, konvektiv va radiatsion yo'qotishlar, sim hamda muzning issiqlik sig'imi va fazaviy o'tishdagi yashirin issiqlikni hisobga oladi. 5-20 mm muz qalinligi hamda -5 dan -15 °C gacha tashqi harorat sharoitlarida nazariy va tajribaviy natijalar solishtirilgan. Harorat modeli uchun RMSE 0,127 °C, MAPE 4,49% va R^2=0,990; muzdan tozalash vaqti uchun RMSE 1,47 minut, MAPE 4,11% va R^2=0,990 ni tashkil etdi. Tajribada tozalash vaqti 5 mm qalinlikda 13 minutdan 20 mm qalinlikda 52,5 minutgacha oshgan. Energiya samaradorligini to'liq taqqoslashda liniya uzunligi, boshlang'ich muz massasi va generatorning haqiqiy quvvat grafigi bir xil bo'lishi talab etiladi.

Kalit so'zlar: *yuqori chastotali muz eritish, AC-240/39 simi, skin-effekt, Joul issiqligi, issiqlik balansi, eksperimental tekshirish, RMSE, energiya samaradorligi.*

Аннотация. В статье выполнена экспериментальная проверка модели удаления льда с провода AC-240/39 посредством электротермического воздействия частотой 3-5 кГц. Модель учитывает джоулево тепловыделение, конвективные и радиационные потери, теплоемкость провода и льда, а также скрытую теплоту фазового перехода. Теоретические и экспериментальные результаты сопоставлены при толщине льда 5-20 мм и температуре окружающей среды от -5 до -15 °C. Для температурной модели получены RMSE 0,127 °C, MAPE 4,49% и R^2=0,990; для времени удаления льда RMSE составила 1,47 мин, MAPE 4,11% и R^2=0,990. Экспериментальное время увеличилось с 13 мин при толщине 5 мм до 52,5 мин при 20 мм. Для корректного сравнения энергозатрат необходимо обеспечить одинаковые длину линии, начальную массу льда и реальный график мощности генератора.

Ключевые слова: *высокочастотное удаление льда, провод AC-240/39, скин-эффект, джоулево тепло, тепловой баланс, экспериментальная проверка, RMSE, энергоэффективность.*

Abstract. This article evaluates a 3-5 kHz electrothermal method for removing ice from AC-240/39 overhead-line conductors and validates the corresponding transient model against experimental data. The approach applies a frequency-

dependent current through a coupling and filtering subsystem so that heat is generated near the conductor surface and at the conductor-ice interface. The governing formulation combines Joule heating, convective and radiative heat losses, conductor and ice thermal inertia, and latent heat during phase change. Validation was performed for ice thicknesses of 5, 10, 15, and 20 mm and for ambient temperatures from -5 to -15 °C. For five temperature-validation conditions, the model produced an RMSE of 0.127 °C, an average absolute relative error of 4.49%, and R^2=0.990. For predicted de-icing time, the RMSE was 1.47 min, the mean absolute percentage error was 4.11%, and R^2=0.990. The measured de-icing duration increased from 13 min at 5 mm to 52.5 min at 20 mm. The results demonstrate close agreement within the investigated conditions. The reported energy comparison is interpreted cautiously because cycle energy depends on treated line length, generator duty cycle, coupling efficiency, and the definition of complete ice removal.

Keywords: *high-frequency de-icing, AC-240/39 conductor, skin effect, Joule heating, transient heat balance, ice thickness, experimental validation, RMSE, energy efficiency.*

Introduction

Conventional thermal de-icing of an overhead line requires sufficient current to raise the conductor and the attached ice to a temperature at which adhesion is weakened or melting begins. At power frequency, a large conductor cross-section can require high current and extensive switching preparation. Frequency-dependent heating has therefore been investigated as a means of changing the current distribution and increasing the effective surface resistance [1-6].

The method considered in this study uses a 3-5 kHz generator, coupling capacitors, and LC filtering. The intended operational principle is not necessarily to melt the entire ice volume. Heating the conductor-ice interface can reduce adhesion so that gravity, wind, and conductor motion remove the remaining sleeve. This distinction is important because complete volumetric melting and interface weakening require different energy balances.

The objective is to validate the transient temperature and de-icing-time model using the experimental values obtained for an AC-240/39 conductor. Model accuracy is quantified by RMSE, mean absolute percentage error, and the coefficient of determination. No values outside the measured range are used to claim validation.

Research Methodology

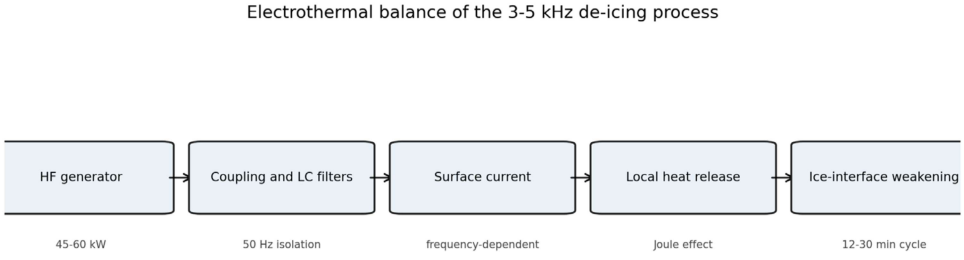

Figure 1. Energy-transfer sequence of the 3-5 kHz de-icing system.

The high-frequency generator is connected to the phase conductor through a coupling and filtering unit that blocks the 50 Hz power component from the diagnostic and de-icing electronics. The frequency-dependent current produces heat in the effective conducting layer. The skin depth for a homogeneous conductor is

$$\delta(f) = \sqrt{[\rho/(\pi f \mu)]} \quad (1)$$

where ρ is electrical resistivity and μ is absolute magnetic permeability.

AC-240/39 is a layered aluminium-steel conductor; therefore, Equation (1) is a first-order relation. The actual current distribution depends on strand geometry, aluminium and steel properties, contact between strands, and frequency. An experimentally identified effective resistance is preferable to assigning a single skin depth to the entire composite conductor [2, 6, 7].

Using an effective iced diameter Di and effective penetration depth δeff, a simplified surface resistance for a treated length l is

$$R_{HF}(f,t) = \rho_{eff}\, l/[\pi\, D_i(t)\, \delta_{eff}(f)] \quad (2)$$

and the high-frequency heating power is

$$P_{HF}(t) = I_{HF}^2(t)\, R\_HF(f,t) \quad (3)$$

The transient heat balance for one metre of conductor is expressed as

$$(m_c\, c_c + m_i\, c_i)dT/dt = \eta_e\, P_{HF} - P_{conv} - P_{rad} - P_m \quad (4)$$

where mc and mi are conductor and ice masses per unit length, cc and ci are heat capacities, ηe is electrical-to-thermal efficiency, and Pconv and Prad are convective and radiative losses. During phase change, Pm accounts for latent heat. The ice mass per unit length is calculated from the cylindrical sleeve:

$$m_i = \rho_i\, \pi[(r+h)^2 - r^2] \quad (5)$$

The experimental matrix included five temperature-validation conditions. Ice thickness varied from 5 to 20 mm, ambient temperature from -5 to -15 °C, and wind speed from 3 to 8 m/s. The measured response was the conductor-surface temperature after activation of the high-frequency system.

Analysis and Results

Table 1. Modelled and experimental conductor-surface temperature.

h, mm	Ta, °C	v, m/s	Model, °C	Experiment, °C	Reported error, %
5	-5	3	4.2	4.0	4.76
5	-10	5	2.1	2.0	4.86
15	-5	3	3.8	3.64	4.21
15	-10	5	1.5	1.44	4.0
20	-15	8	0.8	0.77	3.75

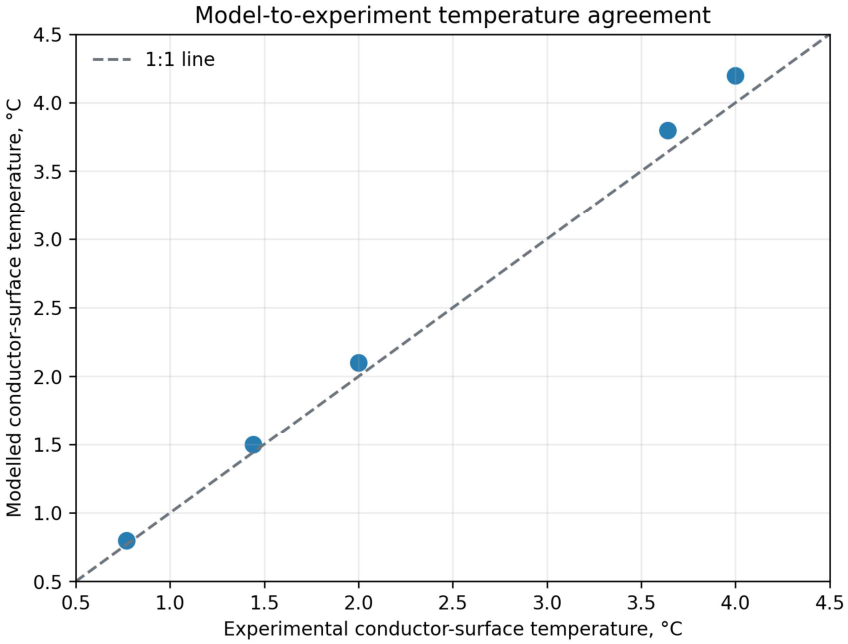

Figure 2. Agreement between modelled and experimental surface temperatures.

The temperature data remain close to the 1:1 line. Recalculation from the unrounded temperatures gives RMSE=0.127 °C, MAPE=4.49%, and R^2=0.990. The percentage values in the last column are the values reported in the dissertation and differ slightly from direct recalculation because of rounding conventions.

Table 2. Modelled and experimental de-icing time.

Ice thickness, mm	Modelled time, min	Experimental time, min
5	12.5	13.0
10	22.8	24.0
15	35.4	36.5
20	50.1	52.5

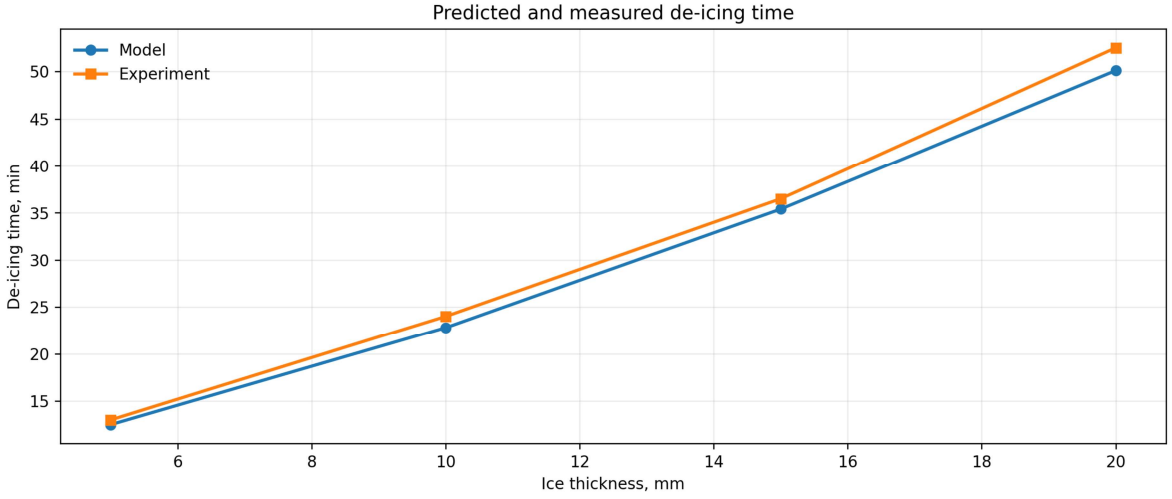

Figure 3. Dependence of de-icing time on initial ice thickness.

The measured duration increases from 13 min at 5 mm to 52.5 min at 20 mm. The relationship is nonlinear because ice mass increases with the square of the outer radius and because convective loss and exposed area also change. The model follows this trend with RMSE=1.47 min, MAPE=4.11%, and R^2=0.990.

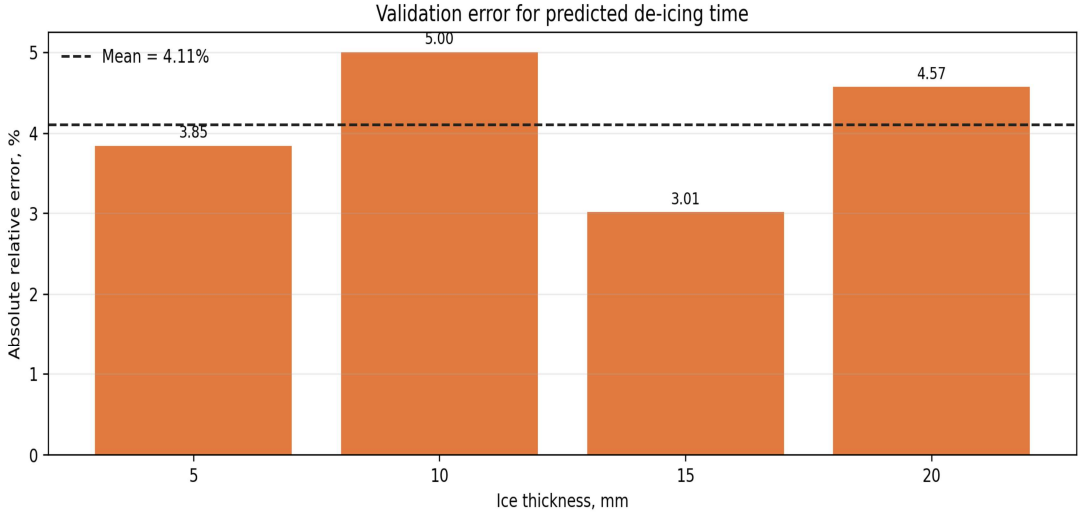

Figure 4. Absolute relative error of the predicted de-icing duration.

The individual time errors range from 3.01% to 5.00%. This agreement supports use of the model within the tested range of conductor, ice thickness, ambient temperature, wind speed, frequency, and coupling arrangement. Extrapolation to other conductor sizes, longer treated sections, or different ice types requires new parameter identification.

The investigated equipment data specify a generator power of approximately 45-60 kW and a de-icing interval of 12-30 min for the proposed mode. Depending on duty cycle, this corresponds to approximately 9-30 kWh per activation. A separate dissertation comparison cites about 36,000 kWh for a conventional cycle and about 30 kWh for the proposed cycle. These figures indicate a large potential reduction, but they are directly comparable only if treated line length, initial ice mass, ambient conditions, and removal criterion are identical.

For a reproducible efficiency comparison, cycle energy should be calculated from logged power rather than rated generator power:

$$E\_cycle = \int_0^{tc} P\_in(t)\, dt \quad (6)$$

The energy balance should additionally report the fraction used for conductor heating, ice sensible heating, latent heat, environmental loss, and power-electronic loss. This prevents a reduced de-icing time from being interpreted automatically as the same percentage reduction in energy.

Conclusion

The 3-5 kHz electrothermal model for AC-240/39 conductor de-icing was validated against the available experimental temperatures and de-icing times. The temperature model achieved RMSE=0.127 °C and R^2=0.990. The time model achieved RMSE=1.47 min, MAPE=4.11%, and R^2=0.990. All measured points lie within a 5% relative-error band after accounting for rounding.

The results support the physical structure of the transient heat-balance model and its use for controller parameter selection within the investigated domain. The next validation stage should measure instantaneous current, voltage, phase angle, conductor surface temperature, interface temperature, removed ice mass, and complete cycle energy. For a stranded aluminium-steel conductor, the effective high-frequency resistance should be identified experimentally rather than inferred from a homogeneous-conductor skin-depth equation alone.

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UDC: 621, 315.1, 551, 578.42

TECHNICAL AND ECONOMIC EFFECTIVENESS OF AN INTELLIGENT DE-ICING SYSTEM ON THE ZARAFSHAN-MURUNTAU 220 kV OVERHEAD LINE

Rakhmonov Farxod Normuratovich
Associate Professor (PhD), Department of Electrical Power Engineering, Navoiy State University of Mining and Technologies
f_raxmonov@mail.ru

Annotatsiya. Maqolada Zarafshon-Muruntau 220 kV havo elektr uzatish liniyasida joriy etilgan intellektual monitoring va yuqori chastotali muzdan tozalash tizimining texnik-iqtisodiy samaradorligi baholangan. Beshta texnologik obyektda uzilgan umumiy yuklama 125,6 MW, yetkazib berilmagan energiya 586,2 MWh va baholangan zarar 20,8 mlrd so‘mni tashkil etgan. Obyektlar bo‘yicha uzilish vaqtlarining yig‘indisi 19 soat 39 minut bo‘lib, bu bitta umumiy avariyaning davomiyligi emas. Tizim joriy etilgach, yillik avariyalar 6 tadan 2 tagacha, energiya yo‘qotishlari 92 000 dan 50 000 kWh gacha va ekspluatatsion xarajatlar 102,1 dan 20,0 mln so‘mgacha kamaygan. Yillik iqtisodiy samara 173 mln so‘mni tashkil etib, uning 72 mln so‘mi avariyalarni bartaraf etish, 18,9 mln so‘mi energiya yo‘qotishlari va 82,1 mln so‘mi ekspluatatsion xarajatlar kamayishi hisobiga olingan.

Kalit so‘zlar: *220 kV havo liniyasi, muzlanish, SCADA monitoringi, muzdan tozalash, yetkazib berilmagan energiya, ishonchlilik, iqtisodiy samara, kon-metallurgiya korxonasi.*

Аннотация. В статье оценена техническая и экономическая эффективность интеллектуальной системы мониторинга и высокочастотного удаления льда, внедренной на ВЛ 220 кВ Зарафшан-Мурунтау. Совокупная отключенная нагрузка пяти технологических объектов составила 125,6 МВт, недоотпуск электроэнергии - 586,2 МВт·ч, а оцененный ущерб - 20,8 млрд сум. Сумма продолжительности отключений по объектам равна 19 ч 39 мин и не является длительностью одной общей аварии. После внедрения число годовых аварий уменьшилось с 6 до 2, потери энергии - с 92 000 до 50 000 кВт·ч, эксплуатационные расходы - со 102,1 до 20,0 млн сум. Годовой экономический эффект составил 173 млн сум, включая 72 млн сум за счет сокращения аварийных восстановлений, 18,9 млн сум за счет снижения потерь энергии и 82,1 млн сум за счет уменьшения эксплуатационных расходов.

Ключевые слова: *ВЛ 220 кВ, обледенение, SCADA-мониторинг, удаление льда, недоотпуск электроэнергии, надежность, экономический эффект, горно-металлургическое предприятие.*

Abstract. This article assesses the technical and economic effectiveness of an intelligent monitoring and high-frequency de-icing system implemented for the Zarafshan-Muruntau 220 kV overhead transmission corridor. The assessment

combines operational interruption data, energy not supplied, incident-recovery expenditure, annual electrical-energy losses, and maintenance costs. A disturbance affecting five technological facilities was associated with an aggregate interrupted load of 125.6 MW, 586.2 MWh of energy not supplied, and an estimated economic loss of 20.8 billion UZS. The sum of facility-specific interruption durations was 19 h 39 min; this is an aggregate exposure indicator and not the duration of one system-wide outage. After implementation, the annual number of incidents decreased from six to two, annual energy losses from 92,000 to 50,000 kWh, and annual operating expenditure from 102.1 to 20.0 million UZS. The corresponding reductions were 66.7%, 45.7%, and 80.4%. Avoided incident-recovery costs amounted to 72.0 million UZS, reduced energy losses to 18.9 million UZS, and reduced operating expenditure to 82.1 million UZS, giving a total annual economic effect of 173.0 million UZS. The calculation boundaries and comparability requirements are explicitly stated.

Keywords: *220 kV overhead line, icing, SCADA monitoring, de-icing, energy not supplied, operational reliability, economic effect, avoided cost, mining and metallurgical enterprise.*

Introduction

The Zarafshan-Muruntau 220 kV corridor supplies electricity to mining, crushing, transport, pumping, and processing facilities whose production is continuous and highly dependent on electrical continuity. Icing and strong wind can increase conductor load, disturb clearances, damage line elements, and interrupt groups of technological consumers. The economic consequence therefore extends beyond line repair and includes energy not supplied, process deviation, restart time, and lost production [1-5]. A technical intervention is economically justified only when its calculation boundary is stated clearly. Capital cost, annual maintenance, de-icing energy, avoided incident recovery, reduced production interruption, and residual risk must not be mixed without a common period and price base. The present assessment uses the operational indicators and annual cost values documented in the dissertation and expresses all monetary values consistently in million Uzbek soums (million UZS).

The objective is to quantify the reported reliability and energy-efficiency improvements of the intelligent system and to reconstruct the annual economic effect. The analysis also corrects two unit ambiguities: the product of MW and hours is reported as MWh, and the sum of interruption durations across facilities is not interpreted as one continuous system outage.

Research Methodology

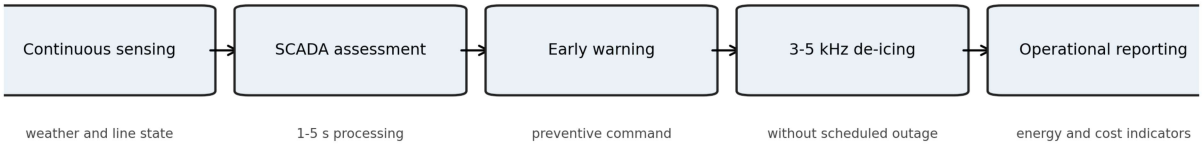

Figure 1. Implemented monitoring, decision, and high-frequency de-icing workflow.

The implemented workflow combines continuous meteorological and line-state sensing, SCADA processing, preventive warning, and 3-5 kHz de-icing control. The

monitoring system reports a nominal ice-detection time of 1-5 s. The high-frequency command is activated only after confirmation of the climatic and line-state conditions, which reduces unnecessary energy use and prevents avoidable switching operations.

For each affected facility i, energy not supplied is calculated as

$$E_{NS,i} = P_i\, t_i \quad (1)$$

where Pi is the interrupted active load in MW and ti is the facility-specific interruption time in hours. The total is the sum over facilities:

$$E_{NS} = \Sigma_i\, P_i\, t_i \quad (2)$$

Table 1. Operational consequences for the affected technological facilities.

Facility	Load, MW	Interruption	Energy not supplied, MWh	Estimated loss, billion UZS
GMZ-2	28.6	4 h 26 min	126.7	7.9
KNK-270	5.8	54 min	5.2	0.33
TsKVZ	64.2	5 h 35 min	358.2	9.8
TsPT	18.9	2 h 21 min	44.4	2.2
KFK	8.1	6 h 23 min	51.7	0.55
Total	125.6	19 h 39 min*	586.2	20.8

*The reported 19 h 39 min is the arithmetic sum of facility-specific interruption durations.

Analysis and Results

The facilities were not necessarily disconnected sequentially, so this value must not be used as the duration of a single outage. The energy value 586.2 MWh is the sum of the five Pi ti products. The TsKVZ facility accounts for 358.2 MWh, or approximately 61.1% of the total energy not supplied. GMZ-2 accounts for 126.7 MWh, or approximately 21.6%. This concentration indicates that preventive line measures have the greatest economic value when they protect the highest-load and longest-recovery technological processes. The annual effectiveness comparison uses three independent operational indicators: number of incidents, electrical-energy losses associated with the considered operation, and operating expenditure.

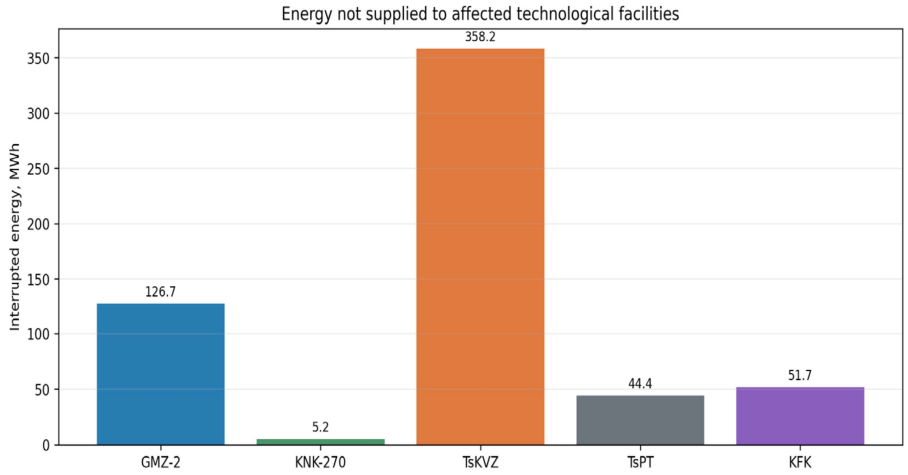

Figure 2. Distribution of energy not supplied among the affected facilities.

Relative improvement is calculated as

$$Reduction = (X\_before - X\_after)/X\_before \times 100\% \quad (3)$$

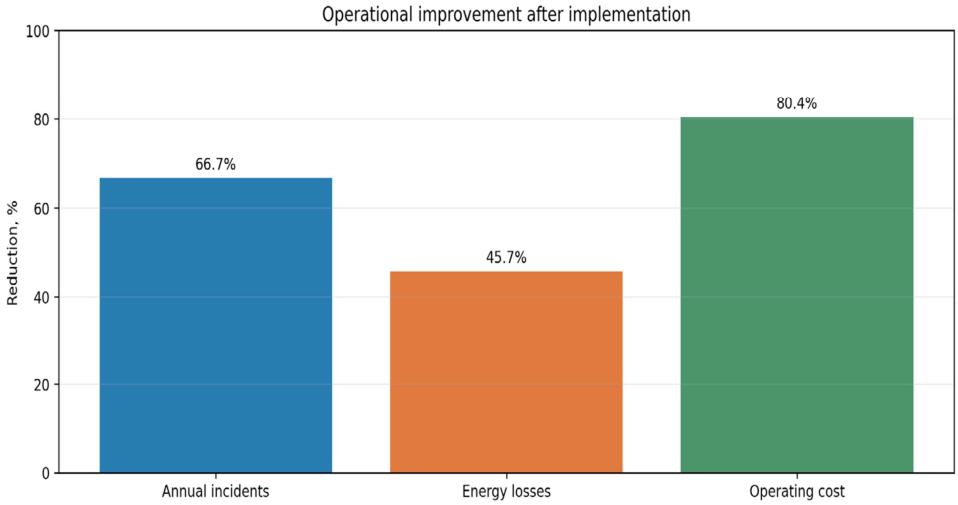

Figure 3. Relative reduction of the principal annual indicators.

Table 2: Reported operational indicators before and after implementation.

Indicator	Before	After	Reduction
Annual incidents, events	6	2	66.7%
Annual electrical-energy losses, kWh	92,000	50,000	45.7%
Annual operating expenditure, million UZS	102.1	20.0	80.4%

The largest relative change is the reduction in operating expenditure, 80.4%. Incident frequency decreases by 66.7%, while annual energy losses decrease by 45.7%. These percentages describe the reported before-after comparison. They do not by themselves isolate weather severity or other maintenance measures; a longer controlled observation period would be required for causal attribution.

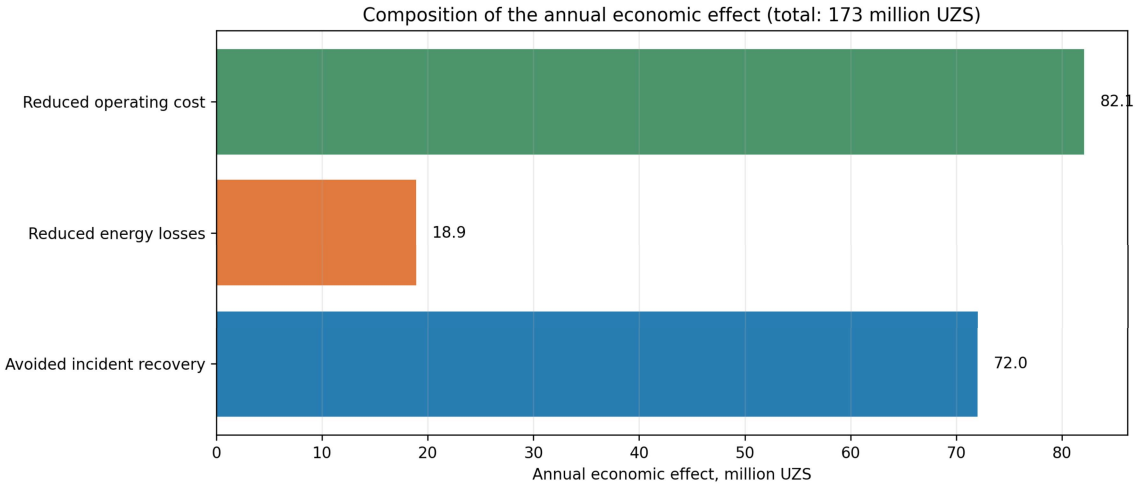

Figure 4. Composition of the reconstructed annual economic effect.

The annual avoided cost consists of three components. First, the incident-recovery cost is calculated using an average recovery expenditure of 18 million UZS

per event. Reducing the annual number from six to two avoids four events and therefore 72 million UZS:

$$B_{inc} = (6 - 2) \times 18 = 72.0 \text{ million UZS} \quad (4)$$

Second, annual energy losses decrease by 42,000 kWh. At the tariff used in the dissertation, 450 UZS/kWh, the energy component is

$$B_E = (92{,}000 - 50{,}000) \times 450 = 18.9 \text{ million UZS} \quad (5)$$

Third, the reduction of annual operating expenditure from 102.1 to 20.0 million UZS yields 82.1 million UZS. Total annual effect is

$$B_{total} = 72.0 + 18.9 + 82.1 = 173.0 \text{ million UZS} \quad (6)$$

The 173 million UZS result is arithmetically consistent. To avoid double counting, the operating-expenditure component must exclude any incident-recovery or electricity-cost items already included in the first two components. The dissertation attributes operating savings to reduced transport, reduced hazardous manual intervention, lower routine servicing, and reduced mechanical wear. A future audit should retain separate cost-centre records for these items.

If investment cost I_0 is available, simple payback may be calculated as I_0/B_{total}. A more complete decision model should discount annual cash flows, include component replacement, communication fees, residual incident risk, and price escalation:

$$NPV = -I_0 + \Sigma_{t=1}^{N} (B_t - C_t)/(1+r)^t \quad (7)$$

where Bt is annual benefit, C_t is annual system cost, r is the discount rate, and N is the analysis horizon. Investment cost was not specified in the analysed table, so a payback period or NPV is not asserted in this article.

Conclusion

The intelligent icing-monitoring and 3-5 kHz de-icing system is associated with a reduction in reported annual incidents from six to two, annual electrical-energy losses from 92,000 to 50,000 kWh, and operating expenditure from 102.1 to 20.0 million UZS. These changes correspond to 66.7%, 45.7%, and 80.4%, respectively. The reconstructed annual economic effect is 173.0 million UZS and is the sum of 72.0 million UZS avoided incident recovery, 18.9 million UZS reduced energy losses, and 82.1 million UZS reduced operating expenditure.

The disturbance dataset additionally records 586.2 MWh of energy not supplied across five facilities and an estimated 20.8 billion UZS loss. These values demonstrate the high consequence of interruptions on a mining and metallurgical corridor. The economic conclusion is subject to two verification conditions: overlapping cost items must be excluded, and future before-after comparisons should normalise for weather exposure and line operating hours. With these controls, the system provides a technically and economically justified basis for preventive operation.

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UDC: 669.74

WORLD PRACTICE AND MODERN TECHNOLOGICAL APPROACHES TO EXTRACTING MARGANES FROM MARGANES-CONTAINING RAW MATERIALS

Parmonov Sarvar Toshpulatovich
Professor (DSc), Vice-Rector for Research and Innovation, Almalyk state technical institute

Mirzavaliev Dostonbek Bakhodir Ugli
Associate professor (PhD), Head of International Cooperation Department, Almalyk state technical institute
5515414d@gmail.com

Muzafarova Nafisa Madrakhimovna
Assistant of the Department of Metallurgy, Almalyk state technical institute
nafisamuzafarova1521@gmail.com

Annotatsiya. Ushbu maqola marganes tarkibli rudalar, ferroqotishma changlari, elektrolitik marganes qoldiqlari va akkumulyator xomashyolaridan marganes ajratib olish bo‘yicha jahon amaliyotini tahlil qiladi. Pirometallurgiya, sulfatli gidrometallurgiya, oksalat va boshqa organik qaytaruvchilar bilan reduktiv eritish, reduktiv kuydirish va keyingi eritish, bioleaching, piro-gidro kombinatsiyalangan yondashuvlar, shuningdek eritmalarni solvent extraction, ion almashinuvi, elektroliz va yordamchi tozalash jarayonlari asosida chuqur rafinatsiya qilish yo‘llari solishtiriladi. Sharh natijalari shuni ko‘rsatadiki, po‘lat uchun an’anaviy marganes bozori bilan bir qatorda, akkumulyatorga mos yuqori tozalikdagi marganes sulfat ishlab chiqarish bugungi texnologik siljishning asosiy drayveriga aylanmoqda. O‘zbekistonning past va o‘rta navli marganesli obyektlari uchun boyitish, selektiv reduktiv sulfatli eritish va bosqichli eritma tozalashni birlashtirgan gidrometallurgik yoki kombinatsiyalangan piro-gidro sxemalar ustuvor yo‘nalish sifatida tavsiya etiladi.

Kalit so‘zlar: *Marganes, marganesli xomashyo, gidrometallurgiya, sulfatli eritish, oksalat, organik qaytaruvchi, reduktiv kuydirish, bioleaching, solvent extraction, ion almashinuvi, elektroliz, $MnSO_4$, EMM, EMD, O‘zbekiston.*

Аннотация. В данной обзорной статье анализируется мировая практика извлечения марганца из марганцесодержащих руд, ферросплавной пыли, остатков электролитического марганца и аккумуляторного сырья. Сравниваются пирометаллургия, сульфатная гидрометаллургия, редуктивное плавление с оксалатом и другими органическими восстановителями, редуктивное обжигание и последующее плавление, биолеачинг, пиро-гидрокомбинированные подходы, а также пути глубокой рафинации растворов на основе процессов сольвентной экстракции, ионного обмена, электролиза и вспомогательной очистки. Результаты обзора показывают, что наряду с традиционным рынком марганца для

стали, производство высокочистого сульфата марганца, подходящего для аккумуляторов, становится основным драйвером сегодняшнего технологического сдвига. В качестве приоритетного направления для низко- и среднесортных марганцевых объектов Узбекистана рекомендуются гидрометаллургические или комбинированные пиро-гидросхемы, сочетающие обогащение, селективное редуктивное сульфатное выщелачивание и стадиальную очистку раствора.

Ключевые слова: *Марганец, марганцевое сырье, гидрометаллургия, сульфатная плавка, оксалат, органический восстановитель, редуктивное обжигание, биоличинг, экстракция растворителя, ионный обмен, электролиз, $MnSO_4$, ЭММ, ЭМД, Узбекистан.*

Abstract. This review article analyzes global practices for extracting manganese from manganese-containing ores, ferroalloy dust, electrolytic manganese residues, and battery raw materials. Pyrometallurgy, sulfate hydrometallurgy, reduction smelting with oxalate and other organic reducing agents, reduction roasting and subsequent smelting, bioleaching, pyro-hydro combined approaches, as well as deep refining of solutions based on solvent extraction, ion exchange, electrolysis and auxiliary purification processes are compared. The results of the review show that, alongside the traditional manganese market for steel, the production of high-purity manganese sulfate suitable for batteries is becoming a key driver of today's technological shift. For low- and medium-grade manganese objects in Uzbekistan, hydrometallurgical or combined pyro-hydro schemes combining enrichment, selective reductive sulfate leaching, and step-by-step solution purification are recommended as a priority.

Keywords: *Manganese; manganese raw materials, hydrometallurgy, sulfate smelting, oxalate, organic reducing agent, reductive roasting, bioleaching, solvent extraction, ion exchange, electrolysis, $MnSO_4$, EMM, EMD, Uzbekistan.*

Introduction

The strategic importance of manganese manifests in two markets simultaneously. The first is the traditional metallurgical market, where the main functions of manganese are desulfurization, deoxidation, and alloying; the second is the market for new energy materials, where the demand for intermediate products for manganese sulfate, EMD, and cathode materials is growing. It is these two vectors that determine the modern technological choice: more pipelines for high-grade ore and more hydraulic ones for complex and low-grade raw materials [1, 8, 10, 13-27, 30].

Literature Review

The estimated global mine-production indicator for 2025 was 20.0 million tons of Mn. Among the countries requested by the user, South Africa stands out with 7.6 million tons, Australia with 1.6 million tons, Brazil with 0.8 million tons, India with 0.79 million tons, and China with 0.70 million tons. At the same time, a high share in production does not always mean leadership in the market for high-purity chemicals: for example, while China's ore production is much lower than South Africa's, it dominates the chain of refined and battery-grade manganese [2, 8–10].

The figures in the table were taken from openly retold data based on the USGS 2026 summary; while the country's industrial roles were verified with open descriptions on company and government websites [2–10].

Table 1. Estimated production volume in foreign countries in 2025.

Country	Estimated 2025 production, thousand tons of Mn	Role in world practice
South Africa	7,600	Large ore base; The Kalahari Basin and the Hotazel Cluster
Australia	1,600	High-grade ore; Diversification of GEMCO and HPMSM
Brazil	800	Carajás-Azul Line, Resource and Green Ferromanganese Initiatives
India	790	MOIL-led ore mining and EMD/FeMn
Chinese	700	Stronger in EMM/EMD/battery-grade circuit than mining
World	20,000	Global benchmark

Manganese extraction methods are determined by the chemical nature of the raw material. Carbonate and some oxide varieties are relatively easy to dissolve under certain conditions, but for pyrolusite materials rich in Mn (IV), a reducing component is usually required. Therefore, modern industrial practice is divided into five main blocks: metallurgical pyrometallurgy; reducing sulfate hydrometallurgy; reductive roasting and subsequent smelting; bioleaching; and the stages of deep refining, transitioning from the solution to the target product [11, 13, 15–21].

Pyrometallurgy remains the industrial backbone of the ferromanganese and silicomanganese chains today. Its strengths are process maturity, adaptability to high power, and direct integration with the steel industry. The weak point is the high consumption of energy and reducing materials, as well as the carbon footprint of the process. The 2024 process simulation + LCA work on ferromanganese and previous global LCA results show that the costs of electricity, coal, and coke are the main factors determining both economic and environmental outcomes; The 2015 global estimate recorded approximately 6.0 kg CO_2-eq cradle-to-gate emissions per 1 kg of average manganese alloy [13-15].

Brazil and South Africa have a natural advantage in this direction. The Kalahari Basin in South Africa is characterized as the location of approximately 80% of the world's manganese; Fields such as Mamatwan and Wessels are located in this cluster. In Brazil, the Azul manganese unit at the Carajas complex has been supplying the ore base for many years, while «green ferromanganese» pilot initiatives are emerging in Minas Gerais [4-6, 14].

However, for low-grade and high-additive raw materials, a complete pipeline is not always optimal. In such materials, the goal may be to obtain a high-value-added product by selectively dissolving it first and then chemically purifying it, rather than converting manganese directly into ferroalloys. This approach is becoming increasingly important, especially for the battery market [10, 14, 15].

Research Methodology

Hydrometallurgy and reductive sulfate smelting. The main chemical problem of dissolving manganese oxide in a sulfate medium is the need to reduce Mn (IV) to a soluble Mn(II) state. Therefore, the choice of reducing agents is a central issue in the practice of sulfate leaching. Classical and modern works on oxalate, sucrose, glucose, and biomass-based reducing agents show that a high degree of separation can be achieved under the right conditions [16–19].

It has been shown that oxidation with oxalic acid yields very high manganese for low-grade ores; the advantage of this method lies in the combined effect of reduction and complexation. During the sulfate solution with sucrose at 50 °C and 1 M H_2SO_4, up to 94% Mn^{2+} was obtained. In glucose studies, the primary chemical pathway is reduced solubility with the formation of formate and other short-chain oxidation products [16–18].

In recent years, interest in affordable and renewable gearboxes has increased. Approximately 98% leaching efficiency was recorded in the sulfate solution with banana peel, indicating that agricultural waste can be considered as a hydrometallurgical reagent. From an industrial perspective, the main advantage of such an approach is the reduction of reagent costs and the improvement of the «green» chemistry image; the disadvantage is the natural variability of raw material composition and heat demand [18, 19].

Hydrometallurgy will deepen further in the battery-grade segment. For $MnSO_4$, EMD, or cathode precursors, it is required to reduce impurities such as Fe, Al, Zn, Mg, Cu, and others to ppm. Therefore, a simple dissolution stage is not enough; a flowsheet combined with selective extraction, scrubbing, stripping, pH precipitation, and crystallization stages is necessary [15, 19, 22-24, 27].

Reductive roasting, pyro-hydro combination, and bioleaching. For complex oxide ores, the “reductive roasting + subsequent sulfate smelting” path is often the most balanced option. The work on sulfur-based roasting showed that at 550 °C, 10 minutes, and a specific C/Mn ratio, 95.6% of Mn is extracted and Fe is transferred to a lower solution with subsequent leaching. In a practical sense, this pathway converts high-valence manganese phases into a well-soluble state in acids and increases selectivity [20].

The combined pyro-hydro route is particularly favorable for ores and residues with complex bonds with Fe and Mg that do not exhibit selectivity during direct sulfate leaching. The overall flow sheet becomes more controllable by first breaking the structure in the thermal stage and then targeted melting in the hydrometallurgical stage. The same approach applies to ferroalloy dust and secondary raw materials [20, 22].

Bioleaching has a different logic. In the work conducted with *Aspergillus niger*, more than 80% Mn recovery was achieved within 30 days under optimal conditions. Here, the dissolution mechanism is explained by a combination of acidolysis, complexolysis, and redoxolysis. Thus, while bioleaching is attractive for environmentally friendly and low-grade materials, the process duration, pulp density, and sterile/bioreactor management limit its industrial-scale implementation [21, 22].

Cleaning of solutions, solvent extraction, ion exchange, and electrolysis. The largest «value-added» stage of manganese processing often occurs during post-melt refining. D2EHPA, Cyanex 272, and their combinations are commonly used in practice

to obtain high-purity $MnSO_4$ from tailings or ore solutions. For example, it is shown that in a solution obtained from ferroalloy dust, Fe (III) is separated by D2EHPA, and Zn (II) is separated by Cyanex 272, followed by the production of 99.5% pure $MnSO_4$ crystals [22, 23].

In an upscaled study of Spent LIB leachate, it was noted that D2EHPA is highly selective toward Mn, allowing for complete separation in two stages. This result indicates that solvent extraction remains one of the most powerful industrial solutions for reducing high-purity chemical forms of manganese. The 2026 study showed that the Cyanex272–HTTA synergistic system yields 97.83% Mn extraction and an 81.7 Mn/Mg extraction coefficient in a single stage; this is especially important for Mg-rich solutions [23, 24, 27].

The "classic" problem of producing electrolytic metallic manganese is the contamination of the electrolyte by Mg and NH^{4+}. In the 2023 "green EMF" approach, an EMF containing 99.81% Mn was obtained by removing 88.87% of Mg through solvent extraction based on neodecanoic acid. The authors attribute the advantages of this process to the capture of ammonium nitrogen in a closed cycle and the stabilization of the residue [15, 25].

While ion exchange and membrane processes are receiving increasing attention as polishing stages, their full economic benchmarks for large-scale manganese plants are insufficient in the open domain; there is no specific constraint for this section. Nevertheless, the electrodialysis-based development demonstrates 87%–97% heavy metal removal from manganese residue leachate and 95% NH_3–N recovery, which suggests it could be an important ancillary technology in the problem of residual and closed water cycle [25, 26].

Analysis and Results

Observations by country according to world practice

Australia. GEMCO remains one of the key assets in the global manganese ore market, and according to South32, the Groote Eylandt deposit is responsible for more than 15% of global manganese ore production. At the same time, Australia is not just an ore exporter: Element 25 is developing a HPMSM plant in the USA based on Butcherbird's raw materials, while Firebird presents a demonstration plant in Perth as "the only fully integrated concentrate-to-cathode facility outside of China." This indicates that the Australian model is transitioning to "ore + downstream chemistry + lower carbon footprint" [3, 27-29].

Brazil. Brazil has a high manganese resource base and export potential, and manganese is listed as a strategic mineral in the country's official sources; According to the ministry, Brazil's reserves are around 111 million tons, and in 2020, it was the 5th largest exporter of manganese in the world. The Vale's Pará page indicates that Azul mine has been producing manganese at the Carajás complex since 1985. At the same time, the emergence of green ferromanganese pilot initiatives in Minas Gerais signals an intensifying decarbonization trend for Brazil [5, 6, 28].

China. The Chinese model is more characterized by refining and battery-grade chemistry than ore mining. South Manganese describes itself as a major vertical manufacturer combining mining, beneficiation, and downstream processing, and a

strong player in EMM, EMD, and battery manganese materials. Reuters notes that China accounts for about 90% of the global supply of high-purity manganese. This indicates that China operates close to the "global ore sourcing-to-chemicals" model rather than "mine-to-chemicals" [8, 10, 29].

India. In India, the state company MOIL remains a major supporting player. According to GDP, MOIL had a record result in FY25 with 18.02 lakh t of manganese ore, 15.87 lakh t of trade and 12,000 t of ferromanganese. This shows that in the Indian model, the ore base and the initial downstream stages run in parallel, but the global load in the battery-grade segment is not yet as centralized as in China [7, 30].

South Africa. Today, South Africa is a clear leader among user-requested countries in global mine-production. Sources based on South32 and USGS point to the Kalahari/Hotazel zone as a fundamental basis. Fields such as Mamatwan and Wessels are characterized by a high resource base, but the scale of high-purity chemical production is less centralized compared to China. Thus, the South African model represents more "bulk ore strength," while the Chinese model represents "refined chemistry strength [2, 4, 31].

Economic and environmental assessment

From economic and environmental perspectives, it is difficult to compare technologies in absolute figures, as the ore composition, reagent cost, energy source, waste management, and type of final product differ significantly. Therefore, the table below is not an «absolute universal benchmark», but rather an interpretive comparison based on recurring trends in literature and industry sources. There is no specific constraint for a fully comparable factory-scale open set CAPEX/OPEX [13–15, 22–29].

Table 2. Manganese extraction technologies

Direction	Typical raw material	Evidence of separation in literature	Energy demand	Spending profile	Primary environmental risk	Technological maturity	Eligibility for Uzbekistan
Pyrometallurgy	High-grade ore, alloyed raw material	Advanced in the ferroalloy industry, but focused on bulk metal rather than chemical purity	Very high	High electrical and reflective consumption	CO2, dust, slag	Very high	For enriched or high-grade streams only
Sulfate hydrometallurgy	Oxide and low grade ore	Results range from 94-98% with oxalate, sucrose, and biomass	Medium	Reagent-sensitive but adaptive	Acid cycle, neutralization sludge	Upper	Perfect match
Reductive roasting + melting	Complex oxide ore, Fe/Mg problem material	Up to 95.6% Mn by sulfur roasting + leaching	Medium to high	Two-step, but with good selectivity	Gas, thermal flow rate	Upper	Perfect match
Bioleaching	Very low grade or delicate material	80%+ Mn, but 30-day cycle	Lower-direct but longer in time	Bioreactor and time costs	Biomass and biokinetics management	Medium-low	Interesting for the pilot
Deep cleaning: SX + crystallization/electrolysis	Flow of Mn2+ into solution	99.5% MnSO4, 99.81% EMF; high selectivity	Medium	Extra cost in high cleanliness	Organic phase, waste electrolyte	Upper	Required for battery-grade or EMM

The conclusions in the table are based on the results in the sources.

Two numbers are especially important in the environmental block. First, according to the 2025 review, approximately 7-9 tons of electrolytic manganese residue can be formed in the production of 1 ton of electrolytic manganese metal; the stockpiling volume has exceeded 50 million tons and is increasing by approximately 10 million tons per year. Second, the 2024 LCA showed that 57.43 percent of the

environmental impact in EMM production is attributed to electricity generation. Thus, in manganese technologies, along with the question “which reagent?” the question “which electrical mixture and what kind of residue management?” is of central importance [11–13, 35].

Some new downstream projects are making reducing their carbon footprint their main selling point. Element 25 cites the company's mine-to-market carbon footprint for its HPMSM flowsheet as being about 67% lower than its competitors in China; such statements should be treated as an industry claim, as independent, identical methodological third-party comparisons are not available to all projects [28, 36].

Adaptation to the conditions of Uzbekistan. According to the geological material uploaded by the user, more than 30 manganese occurrences and 5 small deposits are known in Uzbekistan; In Dautash ores, Mn is typically found in the range of 8–35%, in Kyzylbayrak 13–25%, and in Alysay MnO_2 ranges from 5–43%, averaging around 17%. The total forecast resource for the Karatau Mountains is estimated at 8 million tons.

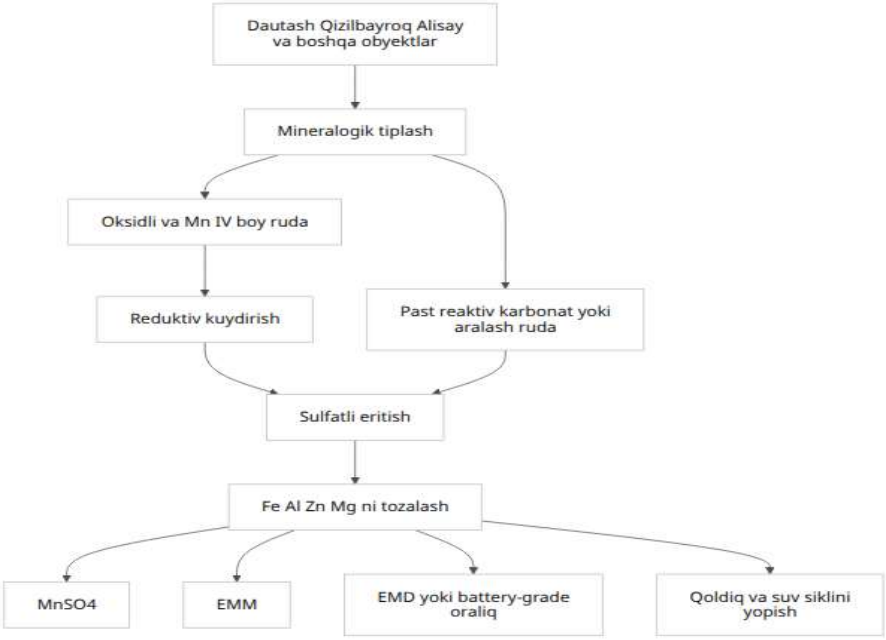

Figure 1. An original model that combines local geological data with global technological analogues

These indicators indicate that a significant portion of the ores are low- and medium-grade, variable in composition, and often suitable for selective chemical processing rather than direct ferroalloy processing [30].

Based on this, the recommended technological class for Uzbekistan looks as follows: first, mineralogical typing and granulation preparation; in the second stage, depending on the ore type, choosing one of two paths - direct reductive sulfate smelting for carbonate and relatively easily soluble ores, and for oxide ores with a strong Mn (IV) and Fe/Mg problem, first reductive roasting followed by sulfate smelting; in the third stage, deep purification of Fe/Al/Zn/Mg; in the fourth stage, $MnSO_4$ crystallization, EMM or EMD production, depending on the product market [15–16, 19–25, 27, 30, 37].

Which reducer is optimal for local conditions depends on the mineralogy of the ore. If the ore is oxide and low grade, oxalate or inexpensive lignocellulose/biomass reducers appear as scientifically based options; if the iron and magnesium problem is severe, the reductive roasting + selective extraction combination may be safer. If a battery-grade product is marked, it is practically difficult to work without the solvent extraction and polishing stages [16–20, 22–27, 38].

This scheme is an author's model as a recommendation that combines local geological data with global technological analogues. Its strength lies in its adaptability to low-grade and unevenly composed raw materials; its weakness lies in the lack of open pilot-scale mass balance data for Uzbek ores. There is no specific constraint for this problem [15–27, 30, 39].

Conclusion

According to the review results, in global practice, the technological center for manganese extraction is gradually shifting from «bulk metallurgy» to «high-purity chemistry» While the steel industry remains the primary consumer, the expansion of the market for battery-grade manganese sulfate, EMD, and other clean intermediates is fundamentally changing the concept of ore processing.

The first key result is that for a high-grade large ore base, pyrometallurgy retains its economic logic, but for low-grade and complex oxide raw materials, sulfate hydrometallurgy creates greater value, especially with reducing smelting and subsequent deep refining. The second result is that reductive roasting + sulfate smelting often provides the most «practical compromise» for Fe/Mg problem raw materials. The third result is that environmental sustainability is no longer a secondary issue: the electricity mix, residue management, and water circulation have become an integral part of the technology choice.

The most justified recommendation for Uzbekistan is to adopt the local ore base as low- and medium-grade, often oxide- and variable-composition raw materials, and to choose a hydrometallurgical or combined pyro-hydro route accordingly. World experience shows that under such conditions, processes based on selective dissolution, solvent extraction, and targeted crystallization/electrolysis offer the best technical and economic prospects.

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HYDROMETALLURGICAL EXTRACTION OF MARGANESE FROM LOW AND MIDDLE-SIZE MARGANESE ORES

Parmonov Sarvar Toshpulatovich
Professor (DSc), Vice-Rector for Research and Innovation, Almalyk state technical institute

Mirzavaliev Dostonbek Bakhodir Ugli
Associate professor (PhD), Head of International Cooperation Department, Almalyk state technical institute
5515414d@gmail.com

Muzafarova Nafisa Madrakhimovna
Assistant of the Department of Metallurgy, Almalyk state technical institute
nafisamuzafarova1521@gmail.com

Annotatsiya. O‘zbekistonda marganets rudalarining muhim qismi past va o‘rta tarkibli bo‘lib, ular Dautash, Qizilbayroq, Taxtakarachin, Alisay va Karatov hududlarida tarqalgan. Mavjud geologik ma’lumotlar Dautash va Qizilbayroqning vulkanogen-cho‘kindi, Alisayning esa eksfiltratsion tipga mansubligini, rudalarda marganetsning 8–35% oralig‘ida, Alisayda esa MnO_2 ning 5–43% oralig‘ida uchrashini ko‘rsatadi. Mazkur maqolada ushbu xom ashyodan marganetsni ajratib olish uchun sulfat kislotali gidrometallurgik sxemalar tahlil qilinib, oksidli rudalar uchun qaytaruvchi eritmalash, aralash oksidli-karbonatli ruda uchun esa bosqichli eritmalash–tozalash–cho‘ktirish sxemasi tavsiya etildi. Analog ilmiy tadqiqotlar asosida Fe(0), biomassa asosli qaytaruvchilar, FeS_2 va HNO_3–glyukoza tizimlari qiyoslandi; sanoatga eng yaqin va reagent-logistika nuqtai nazaridan maqbul variant sifatida H_2SO_4 + qaytaruvchi eritmalash + eritmani tozalash + $MnCO_3$ yoki $MnSO_4$ ko‘rinishida mahsulot olish sxemasi tanlandi. Mahalliy dala-sinov va pilot natijalari yuklangan faylda berilmagani sabab ayrim ko‘rsatkichlar ma’lumot noaniq deb baholandi, iqtisodiy blok esa no specific constraint sharti asosida sezgirlik tahlili ko‘rinishida yoritildi.

Kalit so‘zlar: *Marganes rudasi, gidrometallurgiya, qaytaruvchi eritish, sulfat kislota, Dautash, Qizil Bayroq, Qizilishton, Alisoy, Qoratov, $MnSO_4$, $MnCO_3$, eritmani tozalash.*

Аннотация. В Узбекистане значительная часть марганцевых руд имеет низкий и средний состав и распространена на территории Дауташского, Кызылбайракского, Тахтакарачинского, Алисайского и Каратауского районов. Существующие геологические данные указывают на то, что Дауташ и Кызылбайрак являются вулканогенно-осадочными, а Алисай относится к эксфильтрационному типу, содержащему 8–35% марганца в рудах и 5–43% MnO_2 в Алисае. В данной статье анализируются сернокислотные гидрометаллургические схемы извлечения марганца из этого сырья, рекомендуется восстановительная схема плавки для оксидных

руд и поэтапная схема плавки-очистки-отложения для смешанных оксидно-карбонатных руд. На основе аналогичных научных исследований было проведено сравнение между восстановителями на основе Fe (0), биомассы и системами FeS_2 и HNO_3–глюкоза; схема получения продуктов в виде H_2SO_4 + восстановительный раствор + очистка раствора + $MnCO_3$ или $MnSO_4$ была выбрана как наиболее промышленная и приемлемая с реагентно-логистической точки зрения. В связи с отсутствием результатов локальных полевых испытаний и пилотных проектов в загруженном файле, некоторые показатели были оценены как неточные данные, в то время как экономический блок был охвачен как анализ чувствительности на основе условия отсутствия специфических ограничений.

Ключевые слова: *Марганцевая руда, гидрометаллургия, восстановительная плавка, серная кислота, Дауташ; Краснознамённый, Дровосек, Алисай, Каратова, $MnSO_4$, $MnCO_3$, очистка раствора*.

Abstract. In Uzbekistan, a significant portion of manganese ores is of low and medium composition and is distributed across the Dautash, Kyzylbayrak, Takhtakarachin, Alisai, and Karatau regions. Existing geological data indicate that Dautash and Kyzylbayrak are volcanogenic-sedimentary, while Alisai belongs to the exfiltration type, with 8–35% manganese in the ores and 5–43% MnO_2 in Alisai. This article analyzes sulfuric acid hydrometallurgical schemes for extracting manganese from this raw material, recommending a reducing smelting scheme for oxide ores and a phased smelting-purification-deposition scheme for mixed oxide-carbonate ores. Based on similar scientific research, a comparison was made between the Fe (0), biomass-based reducing agents, and the FeS_2 and HNO_3–glucose systems; the scheme for obtaining products in the form of H_2SO_4 + reducing solution + solution purification + $MnCO_3$ or $MnSO_4$ was selected as the most industrial and acceptable from a reagent-logistics perspective. Due to the lack of local field test and pilot results in the uploaded file, some indicators were assessed as inaccurate data, while the economic block was covered as a sensitivity analysis based on the no specific constraint condition.

Keywords: *Manganese ore, hydrometallurgy, reductive smelting, sulfuric acid, Dautash, Red Banner, Woodpecker, Alisai, Karatov, $MnSO_4$, $MnCO_3$, purification of the solution.*

Introduction

This section substantiates the relevance of the topic. The main idea is that although manganese is geologically abundant in Uzbekistan, the latest open statistics show that industrial production is slow or disrupted; therefore, the technological chain that transforms a resource into a product is important.

More than 30 manifestations of manganese mineralization and 5 small sub-industrial deposits are known on the territory of Uzbekistan; manganese mineralization is divided into volcanogenic-sedimentary, exfiltration, metamorphogenic, and hydrothermal types; the first two of these are the most promising from an industrial perspective. The discovery of the Dautash deposit in 1941, followed by the discovery

of the Kyzylbayrak and Takhtakarachin deposits, indicates that the manganese base in Uzbekistan was historically linked to the Karatov region.

At the same time, the latest USGS country report indicates that no manganese was mined in Uzbekistan in 2022, whereas production of 220 tons was recorded in 2021. This situation means that there is a gap between geological presence and technological and economic development. The Ministry of Mining Industry and Geology of Uzbekistan also identifies the replenishment of the mineral resource base, modernization, and development of production facilities for high-value-added products as priority areas of its activities. Since Mn is present in most manganese oxide ores primarily in the form of MnO_2, simple acid solution is often insufficient; To convert Mn (IV) into Mn (II) in solution, a reducing medium is required. Hydrometallurgical reduction smelting solves exactly this problem and is described in many sources as an energy-saving, single-stage, and technologically flexible method compared to the roasting-smelting path. The purpose of this article is to propose a practical hydrometallurgical scheme for the low- and medium-grade manganese ores of Uzbekistan based on laboratory and pilot studies, combining scientific literature, official geological data, and user-provided statistical information.

Literature Review

Manganese is among the most important strategic metals in modern metallurgy, the chemical industry, and electrical engineering. The role of manganese is particularly high in the production of steel and ferroalloys, and in recent years, significant attention has been paid to manganese compounds as a raw material for the production of next-generation battery materials. Therefore, alongside high-grade ores, the development of technologies for the integrated extraction of manganese from low-grade manganese ores, manganese-containing technogenic waste, and complex mineral raw materials is one of the most pressing scientific and technical directions. The choice of processing method for manganese ores depends primarily on the mineralogical form and oxidation state of the manganese. In MnO_2-based minerals such as pyrolusite, manganese is in the Mn (IV) state, and its solubility in a simple sulfuric acid medium is relatively low. Therefore, in the process of hydrometallurgical processing, one of the main stages is the reduction of Mn (IV) to a water-soluble Mn (II) state. In scientific literature, the possibilities of using Fe^{2+} ions, oxalic acid, glucose, sucrose, sulfur, and various organic substances as reducing reagents for this process have been extensively studied [1-7]. One of the first effective directions for the reduction of manganese is the hydrometallurgical process involving $FeSO_4$. Das et al. found that during the processing of low-grade manganese ores in an iron (II) sulfate solution, the process temperature, particle size, solid-liquid phase ratio, mixing rate, and $FeSO_4$ consumption significantly affect the transition of manganese into the solution [1]. The essence of this method is based on the reduction of Mn (IV) compounds to the Mn^{2+} state by Fe^{2+} ions. However, an increase in the amount of iron ions in the solution can complicate further purification stages. Therefore, in modern research, special attention is paid to increasing the selectivity of manganese and reducing iron penetration into the solution. Sahoo, Naik, and Das studied the process of reductive smelting of low-grade manganese ores containing 24.7% Mn and 28.4% Fe in a sulfuric acid-oxalate

acid system [2]. The research results showed that oxalic acid, while simultaneously reducing MnO_2, accelerates the conversion of manganese into the soluble form Mn^{2+} in a sulfuric acid medium. The authors identified a significant influence of technological factors such as temperature, reagent concentration, and duration on the smelting process. These results indicate that the use of organic acids as reducing agents is promising for the processing of low-grade manganese raw materials [2-19].

In studies on the use of organic reducing agents, sucrose and glucose occupy a special place. In the process of sulfuric acid dissolution of MnO_2 in the presence of sucrose, Pagnanelli et al. achieved the transition of up to 94% of manganese to solution over 150 minutes at a temperature of 50 °C, 1 mol/L of H_2SO_4, and 10 g/L of sucrose [3]. The results of the study showed that reducing organic reagents create the possibility of hydrometallurgical processing of manganese oxides at relatively low temperatures. This allows for a reduction in energy consumption compared to high-temperature pyrometallurgical processes. Vegliò, Trifoni, and Toro investigated the kinetics of sulfuric acid dissolution of manganese-containing raw materials in the presence of glucose and determined that the rate of manganese transition to solution directly depends on the concentration of the acid and the reducing agent, temperature, and the particle size of the raw material [4-18]. In subsequent studies, Furlani, Pagnanelli, and Toro studied the chemical transformations of glucose during its reductive dissolution with MnO_2 and determined that glucose oxidation leads to the formation of primarily formic acid and, to a lesser extent, other organic acids [5]. These studies demonstrate that organic substances act not only as reducing reagents but also as active chemical components that directly influence the mechanism of manganese transition into solution. In recent years, special attention has been paid to using renewable and inexpensive organic raw materials instead of expensive chemical reagents. Ali et al. investigated the possibility of using banana peel as a reducing agent when dissolving low-grade manganese ore in a sulfuric acid medium [6-17]. This approach is based on utilizing the ability of organic components in biomass to reduce Mn (IV) to Mn (II), which creates prospects for increasing the environmental and economic efficiency of hydrometallurgical processes.

Combined pyro-hydrometallurgical methods also demonstrate high efficiency in processing manganese oxide ores. Zhang et al. investigated a method of reductive roasting of low grade manganese oxide ores with elemental sulfur and subsequent dissolving in sulfuric acid [7-16]. During the reductive roasting process, the transition of high-oxidation manganese compounds to low-oxidation forms that are well-soluble in acids is ensured. The authors note that the main factors determining the degree of manganese recovery are the firing temperature, duration, molar ratio of S/Mn, and subsequent melting parameters. The main advantage of this technology is the ability to efficiently process complex and low-grade oxide ores [7].

Biohydrometallurgical methods are also developing as one of the environmentally promising directions for manganese extraction. Acharya, Kar, and Sukla investigated the mechanism of biochemical dissolution of low-grade manganese ores using the microorganism Penicillium citrinum [8]. It has been established that organic acids and reducing metabolites formed as a result of microorganism metabolism accelerate the decomposition of manganese minerals. The main advantage

of this method is the possibility of reducing the consumption of strong mineral reagents, while the main disadvantage is the high duration of the process compared to traditional chemical dissolution methods. Keshavarz et al. have optimized the process of biosolving low-grade pyrolysis using Aspergillus niger, demonstrating that under optimal conditions, approximately 80% of manganese can be transferred to the solution within 30 days [9]. The study identified the role of organic acids produced by microorganisms in the reduction and dissolution of MnO_2 as one of the primary mechanisms. These results indicate that biohydrometallurgy is particularly promising for raw materials that are economically difficult to process using poor, traditional methods. High indicators were also noted in studies conducted on the biochemical processing of manganese-containing man-made waste. In some studies, the degree of manganese extraction was increased to 98.1% by sequential treatment of electrolytic manganese production residues with microorganisms [10]. Such technologies allow for the simultaneous use of secondary metal resources and the reduction of the environmental risk of industrial waste. The purification of manganese solutions obtained after the smelting process and the production of the target product are also important stages of the overall technological scheme. Selective precipitation of manganese from solution in the form of carbonates, hydroxides, or other sparingly soluble compounds, as well as methods of extraction with solvents, ion exchange, and electrolysis, can be used. In modern research, great attention is paid to deep cleaning of the solution to obtain high-purity manganese sulfate and the electrolytic metal manganese. Specifically, it was noted that an electrolytic manganese product containing 99.81% Mn was obtained using a technology based on solvent extraction and subsequent electrolysis [11].

Table 1. Comparison of hydrometallurgical options.

Variant	Reagent system	Typical situation in literature	Mn excretion	Strength	Restriction	Price for Uzbek ores
Direct acid dissolving	H_2SO_4	Carbonate ore, optimized T and acid concentration	92.42%	Simple scheme, easy to obtain $MnSO_4$	Insufficient for oxide ore	Suitable for the carbonate/mixed part of Alisais
Reductive melting	H_2SO_4 + FeO.	Diluted H_2SO_4, atmospheric pressure	Almost complete	Fast, potentially low T	Iron consumption and solution must be cleaned	Strong candidate for Dautash, Qizilbayroq, Takhtakarachin
Reductive melting	H_2SO_4 + sawdust	1 mol/L H_2SO_4, 363 K, 180 min	94.1%	Cheap biomass, Fe migration relatively low	Biomass preparation and stable quality	Suitable for bleaching/pilot
Reductive smelting	H_2SO_4 + straw	9% H_2SO_4, 85°C, 180 min	92.8%	Good selectivity	Requires organic residue and pre-treatment	Alternative for oxide ores
Nitrate leaching	HNO_3 + glucose	around 90°C, optimized stoichiometry	Up to 99%	Very high extraction, low Fe	The nitrate cycle is complex.	Reference option, not primary
Sulfate leaching	H_2SO_4 + FeS_2;	Regional study, unknown parameter	95.8%	Sulfide reducing effective	Double-check settings	Suitable for additional research

The analyzed scientific works show that there is no universal technology for processing manganese-containing mineral and hand-made raw materials. The technological scheme should be selected based on the mineralogical composition of the raw material, the degree of manganese oxidation, the amount of iron and other additives, and the type of final product planned for production. For low-grade MnO2-containing ores, reducing sulfuric acid leaching is highly efficient, while for raw

materials with a complex mineral composition, it may be advisable to perform preliminary reducing roasting and subsequent hydrometallurgical treatment. The use of biological and organic reducing agents is a promising direction in terms of creating environmentally sustainable technologies. At the same time, in most existing studies, individual technological solutions suitable for a specific type of ore or waste have been developed. Issues regarding the integrated processing of complex raw materials containing iron, silicon, aluminum, and other components along with manganese, limiting the dissolution of impurities while ensuring a high degree of manganese leaching, and the selective extraction of manganese from the resulting solutions remain relevant.

Therefore, the development of complex resource-saving technologies for local manganese-containing mineral and man-made raw materials, combining enrichment of raw materials, selective reduction smelting, purification of solutions from impurities, and separation of manganese in the form of a target product, is of scientific and practical importance (Table 1). The variants in the table are based on the works of Lin et al., Bafghi et al., Yang Sun et al., Pagnanelli et al., and Isabayev et al., respectively [12].

Research Methodology

This section summarizes the geological and quantitative base for the main manganese objects of Uzbekistan. The main conclusion is that the Karatau region is a leader in resource potential, while Alisai requires a special technological approach due to its structural complexity.

Analysis and Results

In the uploaded report, Dautash, Kyzylbayrak, and Takhtakarachin are described as volcanogenic-sedimentary types, while Alysay is described as an exfiltration type. Within the Dautash zone, 11 ore-bearing sections along 8 km have been explored, with ore content ranging from 8–12% to 28–35%. In the Red Banner, Mn is 13–25%, with an average of 14%. Three ore sites and 52 lenticular/plate ore bodies were recorded in Takhtakarachin, but this file does not fully detail the exact average composition and balance reserves of the deposit, so some indicators were accepted as inaccurate information. In Alisaia, the main components are MnO_2 5–43% (average 17%), FeO 1–57% (average 9%), and V 0.03–0.14% (average 0.082%) Table 2 of Mn content and resources by deposits.

Several important analytical conclusions follow from the figures in the report. First, the Iral, Shivarsay, and Western Maktab sections on the Dautash flank yield a total of 420.2 thousand tons of resource; their weighted average Mn content is 22.38%. Secondly, the sum of the table values of 789 + 420 thousand tons equals approximately 1.209 million tons; this makes it one of the largest objects among the named deposits.

Thirdly, the reporting average value of 17% MnO_2 for Alysay corresponds to approximately 10.74% Mn in stoichiometric recalculation, while the upper limit of 43% MnO_2 corresponds to 27.17% Mn; consequently, Alysay should be considered a very irregular and iron-rich mixed ore in terms of composition. In the latest official international statistics, it was noted that manganese was not mined in Uzbekistan in 2022, which indicates that there is a problem in the transformation of geological

resources into technological products. For this reason, it is logical to monetize the low- and medium-grade ore base through hydrometallurgy as the object of research.

Table 2. Mn content and resources by deposits.

Object	Geological type	Report composition indicator	Resource/Inventory Indicator	Commentary
Dautash	Volcanogenic sediment	Mn 8-35%	789 + 420 thousand tons	There are additional sections on the flanks.
Iral (Dautash flank)	Dautash system	Mn 23.8%	110 thousand tons	New section
Shivarsay (Dautash flank)	Dautash system	Mn 16.65%	113.5 thousand tons	New section
West School (Dautash Flank)	Dautash system	Mn 24.9%	196.7 thousand tons	New section
Red Banner	Volcanogenic sediment	Mn 13-25%	Cg 96.3 thousand t; P1 600.5 thousand t	Total in the table is 696.8 thousand tons.
Carpet beetle	Volcanogenic sediment	Mn 10–27%	~500 thousand tons	Estimate
Alisai	Exfiltration	MnO_2 5–43%, on average 17%	385.07 thousand tons	Fe and B are also important impurities.
Karatov area	Regional object	Different	8 million tons of forecast resources	Largest potential in the region

This section provides a recommended experimental design for the article. The core of the approach is the mineralogically correct typing of the ore and the selection of the appropriate hydrometallurgical flow for each type.

Table 3. Stages for the proposed technological scheme.

Stage	Function	Primary reagent or method	Suggested options	Purpose
Sample preparation	Drying, grinding, sifting	Mechanical preparation	80% to −74 μm	Uniformity for solution
Characteristics	XRF, XRD, ICP, SEM-EDS	Analytical methods	For each sample	Determination of Mn phase and impurities
Primary melting	Reduction smelting for oxide ore	H_2SO_4 + Fe0 or biomass	1.0–2.0 mol/L; 70–90°C; 120-180 min	Transfer of Mn to solution
Stage melting	The first stage for Alisai	H_2SO_4	Soft mode for carbonate fraction	Separation of the Mn (II) -rich part
Residual smelting	Alisaia fossil	H_2SO_4 + reducer	For oxide residue	Conversion of MnO_2 to Mn^{2+}
Solid-liquid separation	Filter/wash	Vacuum filter or press filter	pH and CO_4^{2-} control	Obtaining a pure solution
Solution purification	Precipitation of Fe and impurities	$CaCO_3$, lime, pH control	Gradual pH uplift	Reduction of Fe, reduction of Mn loss
Get merchandise	Deposition of $MnCO_3$ or crystallization of $MnSO_4$	NH_4HCO_3 or evaporation-crystallization	Corresponds to solution composition	Get merchandise to sell
Trash management	Neutralization, water circulation	Lime, gypsum, closed water cycle	Under EHS supervision	Environmental risk reduction

The research methodology was structured at two levels. First level - characterization: Taking a representative sample from Dautash, Kyzylbayrak, Takhtakarachin, and Alisai, crushing, classification, and then determining the chemical and phase composition using XRF, ICP-OES/AAS, XRD, and SEM-EDS. The second stage is smelting-purification-product production: reductive acid smelting for oxide

ores, step-by-step smelting for mixed ores, purification of the solution from iron and other impurities, and subsequent extraction of Mn in the form of $MnCO_3$ or $MnSO_4$. Such a sequence has been repeatedly recommended in international literature for both oxide and mixed ore systems.

Conclusion

The recommended basic laboratory regime is as follows: ore fineness for oxide ores is around 80%–74 μm, liquid-solid ratio is 6:1–10:1, H_2SO_4 concentration is in the range of 1.0–2.0 mol/L, temperature is 70–90°C, and dissolution duration is 120–180 min. Three variants were tested in parallel as reducing agents: FeO, prepared sawdust/straw, and, in a separate series of experiments, FeS_2. For the carbonate-mixed part of Alisac, dissolving H_2SO_4 without the reducing agent is recommended in the first stage, while for the MnO_2-rich fraction in the residue, dissolving with the addition of a reducing agent is recommended in the second stage. These parameters correspond to the range of similar scientific works; however, optimization based on local ore is mandatory.

The table is compiled as a recommendation, and its scientific basis is based on the aforementioned literature on reductive smelting, solution purification, and carbonate precipitation.

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Section 3. ACTUAL PROBLEMS OF HISTORY, PHILOSOPHY AND SOCIOLOGY

UDC: 141.7, 321.01(575.1)

BUILDING IDEOLOGICAL RESILIENCE IN THE AGE OF GLOBALIZATION: PHILOSOPHICAL FOUNDATIONS OF THE “UZBEKISTAN-2030” DEVELOPMENT STRATEGY

Matchanova Barno Irkinovna
Independent Researcher,
Institute for Socio-Spiritual Studies

Annotatsiya. Ushbu maqolada globallashuv jarayonlari keltirib chiqargan keng ko‘lamli o‘zgarishlar sharoitida “O‘zbekiston–2030” taraqqiyot strategiyasi doirasida g‘oyaviy bardoshlilikni shakllantirishning ijtimoiy-falsafiy jihatlari tahlil qilinadi. Zamonaviy G‘arb falsafiy nazariyalarini milliy intellektual meros — jumladan, Kul Tigin bitiktoshi hamda Xo‘ja Samandar Termiziyning mumtoz risolasi bilan uyg‘unlashtirgan holda, tadqiqot g‘oyaviy bardoshlilikning tizimli-funksional modelini ochib beradi. Muallif “O‘zbekiston–2030” strategik qarashlari, Markaziy Osiyo tafakkuri an’analari hamda ochiq jamiyat va mas’uliyat etikasi bo‘yicha zamonaviy diskurs o‘rtasidagi falsafiy mutanosiblik yigirma birinchi asr chaqiriqlariga mos keluvchi g‘oyaviy rivojlanishning o‘ziga xos milliy paradigmasini tashkil etadi, degan fikrni ilgari suradi.

Kalit so‘zlar: *“O‘zbekiston–2030” strategiyasi, g‘oyaviy bardoshlilik, mafkuraviy immunitet, ma’naviy-ma’rifiy islohotlar, milliy g‘oya, Uchinchi Renessans, erkinlik sifatida taraqqiyot, mas’uliyat tamoyili, ochiq jamiyat, strategik rejalashtirish, globallashuv.*

Аннотация. В данной статье рассматриваются социально-философские аспекты формирования идеологической устойчивости в рамках стратегии развития “Узбекистан-2030” в широком контексте трансформаций, вызванных глобализацией. Путем синтеза современных западных философских теорий с национальным интеллектуальным наследием — включая надпись Кюль-тегина и классический трактат Ходжи Самандара Термизи — в исследовании сформулирована структурно-функциональная модель идеологической устойчивости. Автор утверждает, что философская согласованность между стратегическим видением «Узбекистан-2030», традициями центральноазиатской мысли и современным дискурсом открытого общества и этики ответственности формирует самобытную национальную парадигму идеологического развития, отвечающую вызовам XXI века.

Ключевые слова: *стратегия “Узбекистан-2030”, идеологическая устойчивость, идеологический иммунитет, духовно-просветительские реформы, национальная идеология, Третий Ренессанс, развитие как свобода, принцип ответственности, открытое общество, стратегическое планирование, глобализация.*

Abstract. This article examines the socio-philosophical dimensions of building ideological resilience within the framework of the "Uzbekistan-2030" development strategy, situating the analysis in the broader context of globalization-driven transformations. By synthesizing contemporary Western philosophical theories with indigenous intellectual heritage – including the Kul Tigin inscription and the classical treatise of Khoja Samandar Termiziy – the study articulates a structural-functional model of ideological resilience. The author argues that the philosophical coherence between the strategic vision of Uzbekistan-2030, the traditions of Central Asian thought, and the modern discourse of open society and responsibility ethics constitutes a distinctive national paradigm of ideological development suited to the challenges of the twenty-first century.

Keywords: *"Uzbekistan-2030" strategy, ideological resilience, ideological immunity, spiritual-educational reforms, national ideology, Third Renaissance, development as freedom, principle of responsibility, open society, strategic planning, globalization.*

Introduction

The intensifying processes of globalization and the accelerating pace of societal transformation confront modern nations with a fundamentally new set of intellectual and practical challenges. In this global context, the Republic of Uzbekistan – advancing along its independent path of development – has entered a historically new phase of strategic renewal encompassing social, political, economic, and spiritual domains. The long-term trajectories of the country's development have found their systematic expression in the "Uzbekistan-2030" strategy adopted in 2023. The philosophical core of this document rests upon an integrative conceptual approach aimed at reinforcing the spiritual-ideological foundations of society across all areas of development. As the President of the Republic of Uzbekistan Sh.M. Mirziyoyev has emphasized, "the principal criterion of our reforms must be the improvement of the quality of life and well-being of our people" [2]. This criterion defines the overarching philosophical orientation of the strategic document.

Literature Review

The preservation and evolution of national-spiritual foundations under conditions of contemporary transformation has become a matter of strategic importance. The idea of laying the foundation of the "Third Renaissance" in independent Uzbekistan, the systemic reform of spiritual-educational activities, and the elevation of ideological resilience to the level of official strategic documents – all these together form a complex set of problems that require philosophical-conceptual analysis. The scholarly problem addressed in this article consists in disclosing the philosophical foundations of the "Uzbekistan-2030" strategy and its associated reforms, and in providing a conceptual grounding for the model of ideological resilience formation. Purpose of the study consists in analyzing the ideological-spiritual foundations of the "Uzbekistan-2030" strategy and contemporary reforms, elucidating the philosophical model and mechanisms of building ideological resilience,

and providing conceptual justification for the organic interconnection between national-historical continuity and modern development.

Research Methodology

The empirical sources of this study include the strategic documents of the President of the Republic of Uzbekistan, notably the "Uzbekistan-2030" strategy (11 September 2023), Resolution No. PP-5040 "On Measures for the Fundamental Improvement of the System of Spiritual and Educational Work" (26 March 2021), and the Presidential Addresses and speeches. The theoretical framework draws upon contemporary Western philosophical theories of development – Amartya Sen's concept of "development as freedom," Karl Popper's theory of the open society, Hans Jonas's "principle of responsibility" – as well as the socio-philosophical scholarship of domestic researchers. Classical Turkic and Central Asian heritage – the Kul Tigin inscription, Khoja Samandar Termiziy's Dastur-ul muluk, Amir Timur's Regulations, and other treasures of the intellectual tradition – provide the historical-philosophical foundation. The research employs the historical-philosophical method for identifying national-spiritual continuity; socio-philosophical analysis for illuminating the philosophical foundations of contemporary reforms; conceptual modeling for describing the structural and functional dimensions of the ideological resilience system; the comparative method for juxtaposing national and universal development models; and documentary source analysis for clarifying the ideological content of strategic policy documents.

Analysis and Results

The "Uzbekistan-2030" strategy is a fundamental document that systematically defines the long-term development trajectories of the country. The philosophical essence of the strategy lies in the recognition of the human being as both the aim and the primary agent of development. This approach converges conceptually with the philosophical outlook of the Nobel Prize laureate Amartya Sen, one of the most prominent theorists of contemporary development thought. According to the philosopher, "development can be seen as a process of expanding the real freedoms that people enjoy" [3]. Consequently, the index of development is measured not merely by the quantity of material wealth, but by the expansion of individuals' capabilities to realize their life aims. The social, economic, ecological, and spiritual directions specified in the "Uzbekistan-2030" strategy have been shaped in mutual coherence precisely on the basis of this philosophical criterion. The spiritual-ideological core of the strategy is constituted by the idea of the "Third Renaissance," which carries a distinctive historical-philosophical meaning. The First Renaissance denotes the scientific-philosophical awakening of Central Asia in the ninth to twelfth centuries; the Second Renaissance corresponds to the intellectual flourishing of the Timurid era in the fourteenth to sixteenth centuries; and the Third Renaissance refers to the socio-spiritual revival and renewal now unfolding in independent Uzbekistan. This historical-

philosophical periodization underscores that the strategy is constructed on the foundation of national-cultural continuity.

Presidential Resolution No. PP-5040 of 26 March 2021 conceptually defined the contemporary stage of reforms in the spiritual-educational domain. The philosophical-strategic significance of this document lies in the fact that it explicitly identifies the systemic problems that had persisted in previous years: the absence of an integrated system for organizing spiritual-educational activities; the insufficiency of organizational and practical measures for protecting youth from spiritual threats; and the lack of effective social partnership among state institutions, civil society organizations, mass media, and the private sector [4].

The philosophical significance of this reform is further underscored by its introduction of specialized disciplines – "Spiritual Studies" (Ma'naviyatshunoslik) and "Professional Spirituality" (Kasbiy ma'naviyat) – into the bachelor's and master's curricula of higher education institutions. This is a strategic step toward transforming spiritual-ideological education into a systematic and scientifically grounded practice. As Karl Popper argued in *The Open Society and Its Enemies*, "the open society is one whose members possess critical thinking, are capable of making personal decisions, and are prepared to assume responsibility for their own lives" [5]. This view corresponds precisely to the philosophical aim of the discipline of Spiritual Studies: to cultivate critical thinking in young people, to enable them to recognize ideological manipulation, and to help them develop an autonomous spiritual position.

The Uzbek philosopher M.Khayrullaev has aptly observed that "national development in the social sphere cannot be defined by one-sided political or economic indicators alone – it is a complex process consisting of the unity of spirituality, enlightenment, and the values that sustain the national core" [6]. From this perspective, the March 2021 Resolution can be evaluated as a logical and necessary link in the country's system of reforms: it elevates the task of strengthening society's spiritual foundation to the strategic level, in tandem with material and economic transformations. The concept of ideological resilience – or, in its earlier medical-metaphorical rendering, ideological immunity – is a synthetic notion born from the transposition of a biomedical metaphor into the social domain. Whereas in medicine immunity denotes the organism's capacity to maintain its inner identity and to defend itself against external influences, in the socio-philosophical context ideological resilience refers to the ability of individuals, nations, and societies to withstand harmful ideological influences and to preserve their spiritual core. Structural analysis of this system reveals that it comprises three fundamental elements.

The first element is the system of objective knowledge that corresponds to national and universal human interests. Knowledge within the ideological resilience system must accurately and comprehensively reflect reality, enrich human spirituality, and serve societal development. This element is formed precisely through educational and scholarly-enlightenment institutions.

The second element is the system of evaluations and values that emerges from this knowledge base. When knowledge is objective and profound, the values grounded in it likewise gain durability. These values function as a firm shield against harmful

ideas. Here the dialectical harmonization of national and universal human values emerges as the central philosophical task.

The third element is the system of aims spanning the socio-economic, political, and cultural-educational domains. In the absence of a coherent constellation of aims, an individual, nation, or society remains perpetually vulnerable to overt and covert ideological pressures. This element finds its firm conceptual foundation precisely in the "Uzbekistan-2030" strategy: the framework of one hundred aims encompasses not only material-economic but also spiritual-ideological criteria.

The idea of ideological resilience and national-spiritual defense has deep roots in the historical thought of the Uzbek people. The Kul Tigin inscription contains a striking piece of wisdom concerning the tragic consequences of ideological confusion:

"You could not tell the sincere from the insincere;
when one spoke harshly, you could not recognize even the sincere.
And for this reason, heeding not the words of the Khagan who nurtured you,
you departed leaving neither name nor trace" [7].

This ancient inscription identifies the loss of critical thinking and the weakening of the capacity to distinguish sincere from insincere speech as principal causes of national and political collapse. This insight resonates conceptually with contemporary philosophical categories such as "cognitive autonomy" and "media literacy."

The far-sighted historical grounding of ideological defense finds its most vivid expression in Khoja Samandar Termiziy's Dastur-ul muluk:

"The enemy first proceeds by trickery and deceit,
then launches an assault and leaves you overwhelmed.
If the paths of this flood are not blocked in time,
countless calamities and evils shall come upon you.
If you do not seal the way of intrigue today with firmness,
tomorrow it shall only grow stronger and more entrenched!" [8]

These lines articulate with remarkable precision the necessity of foresight and preemptive action against ideological threats. Historically, this view constitutes the very foundation of contemporary strategic security theory: the philosophical principle that a threat must be countered at its root rather than at its surface manifestation is anticipated precisely in these verses.

Contemporary Western philosophy contains views that resonate with this historical wisdom. The German-American philosopher Hans Jonas, in *The Imperative of Responsibility*, proposes the following ecological-philosophical imperative: "Act so that the effects of your action are compatible with the permanence of genuine human life on Earth" [9]. This ethical principle of Jonas and the "Uzbekistan-2030" strategy stand remarkably close to one another in conceptual orientation. Both insist that present decisions must take into account the interests of future generations and must be directed toward securing the long-term continuity of development. This parallel establishes a fruitful basis for the dialectical convergence of national intellectual tradition and contemporary philosophical standards.

Conclusion

The results of the analysis conducted here indicate that the "Uzbekistan-2030" strategy and its associated reforms rest philosophically and conceptually upon two essential foundations. The first is the foundation of national-historical continuity, expressed through the unbroken ideological-spiritual thread connecting classical inscriptions to contemporary strategic documents. The second is the universal-philosophical foundation, which ensures conceptual convergence with modern theories of development, the philosophy of the open society, and the ethics of responsibility.

The synthesis of these two foundations finds its expression in the idea of the "Third Renaissance." As President Sh.M. Mirziyoyev has emphasized, "the great and lofty goal of building the foundation of the Third Renaissance constitutes the very essence of our national idea and national development." This idea serves as a philosophical highway that conceptually unites the national historical heritage with contemporary strategic goals.

The practical implementation of the study's findings can be pursued along the following directions. First, higher education institutions must apply the principle of historical-philosophical continuity in teaching the disciplines of Spiritual Studies and Professional Spirituality – that is, they must transmit to young people the ideological-spiritual evolution running from the Kul Tigin inscription to the "Uzbekistan-2030" strategy. Second, through mass media and civil society institutions, the three elements of the ideological resilience system – knowledge, values, and aims – should be cultivated in an integrated manner. Third, a priority task in this domain is the systematic scholarly elucidation and popularization of the philosophical-conceptual foundations of strategic documents. In this regard, the researcher S. Yo'ldoshev has aptly written that "the dialectical convergence of the national idea and philosophical thought is one of the principal factors ensuring the strategic stability of society" [10]. According to this principle, the clarification of the philosophical foundation of reforms carries not only theoretical but also practical-strategic importance. The fundamental conclusions of this socio-philosophical analysis can be summarized as follows. The "Uzbekistan-2030" strategy is a conceptual document constructed on the dialectical synthesis of national-historical continuity and universal philosophical principles, its core being the recognition of the human being as both the aim and the principal instrument of development. The spiritual-ideological foundation of the strategy, expressed through the idea of the "Third Renaissance," conceptually unites the historical heritage of the nation with contemporary aims of development. In the age of globalization, this integrative model constitutes a distinctive national paradigm capable of preserving cultural identity while engaging constructively with universal philosophical discourse.

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ANALYSIS OF THE DETERMINANT APPROACH IN MATERNAL AND CHILD HEALTH PROTECTION POLICY

Kutlimuratova Nigora Masharipovna
Acting Associate Professor (PhD), Urgench State Pedagogical Institute
kutlimuratova@gmail.com

Annotatsiya. Ushbu maqolada onalik va bolalikni muhofaza qilish siyosatiga determinantli yondashuv tahlil qilinadi. Unda onalik va bolalikni muhofaza qilish siyosati jamiyat farovonligini oshirish mas’uliyatini qay darajada o‘zida aks ettirishi ko‘rib chiqiladi hamda ijtimoiy-iqtisodiy rivojlanish tendensiyalariga muvofiq determinantli yondashuvning rivojlanishi o‘rganiladi. Shuningdek, tadqiqotda onalar va bolalar salomatligi hamda ularning rivojlanishini qo‘llab-quvvatlashga qaratilgan chora-tadbirlar va tashabbuslar tahlil qilinadi.

Kalit so‘zlar: *onalik va bolalikni muhofaza qilish, perinatal yordam, xavfsiz tug‘ruq amaliyoti, emlash va erta bolalik davridagi rivojlanish, dinamik ehtiyojlar, determinantli yondashuv tahlili.*

Аннотация. В данной статье анализируется детерминантный подход к политике охраны материнства и детства. Рассматривается, как политика в области охраны здоровья матери и ребенка воплощает ответственность за повышение благосостояния общества, а также исследуется развитие детерминантного подхода в соответствии с тенденциями социально-экономического развития. Кроме того, в исследовании анализируются меры и инициативы, направленные на укрепление здоровья и развитие матерей и детей.

Ключевые слова: *охрана материнства и детства, перинатальная помощь, практика безопасных родов, иммунизация и раннее развитие детей, динамические потребности, анализ детерминантного подхода.*

Abstract. This article analyzes the determinant approach to maternal and child health protection policy. It examines how maternal and child health policy

embodies the responsibility for promoting the well-being of society and explores the development of the determinant approach in line with socio-economic development trends. The study also analyzes measures and initiatives aimed at promoting maternal and child health and development.

Keywords: *maternal and child health protection, perinatal care, safe childbirth practices, immunization and early childhood development, dynamic needs, determinant approach analysis.*

Introduction

Maternal and child health protection has evolved in response to changes in the state and society. Across different geographical regions, these policies have played an important role in improving perinatal care, promoting safe childbirth practices, expanding immunization programmes, and supporting early childhood development. However, as the global landscape continues to change and inequalities persist, there is a growing need to critically evaluate the effectiveness of existing policies and to develop more inclusive, adaptive, and future-oriented policy frameworks [1-5].

This global review examines current practices in maternal and child health policy by acknowledging both achievements and continuing challenges. From north to south and from east to west, each region faces its own healthcare context, requiring a deeper understanding of policy responses. The section on current practices explores the multidimensional approaches adopted by different countries to protect maternal and child health and provides insights into both the achievements and the shortcomings that characterize the current situation. As this analysis progresses, attention extends beyond the present to consider future perspectives. The future of maternal and child health policy is envisioned as a framework shaped by innovation, equity, and sustainability. The section on future directions outlines transformative strategies for policy development to ensure that maternal and child health policies continue to evolve in response to the changing needs of women and children in an increasingly dynamic world [6, 7]. To achieve optimal maternal and child health outcomes, this global review seeks to synthesize existing knowledge, stimulate professional dialogue, and encourage collaborative action.

Literature Review

Maternal and child health protection policies serve as fundamental pillars of the public health system, ensuring the well-being of mothers and children while contributing to the overall health and vitality of society. This study provides a comprehensive analysis of maternal and child health policies by examining their historical evolution, current global practices, and future directions aimed at achieving healthier and more equitable outcomes. The determinant approach to maternal and child health protection has evolved in line with socio-economic development trends. Initially, policy measures primarily focused on reducing maternal mortality through improvements in sanitation and basic obstetric care. As societies developed, these policies expanded to include comprehensive perinatal care, safe childbirth practices, and initiatives promoting child health and development [8]. The mid-twentieth century marked a paradigm shift in maternal and child health policy with the recognition of the life-course perspective. Policymakers began to acknowledge the interrelationship

between maternal and child health outcomes and introduced programmes extending beyond childbirth to address the health needs of mothers and children throughout the life course. Maternal and child health policies vary considerably across regions, reflecting differences in healthcare systems, cultural contexts, and available resources. In developed countries, these policies generally emphasize advanced perinatal care, well-equipped maternity services, and comprehensive child healthcare. In contrast, developing countries continue to face challenges such as limited access to essential healthcare services, high maternal mortality rates, and widespread child malnutrition [9].

Case studies demonstrate successful practices in different regions. For example, the Nordic countries have achieved exemplary maternal health outcomes through low maternal mortality rates and comprehensive antenatal and postnatal care services. At the same time, several developing countries have made significant progress in reducing child mortality through targeted immunization programmes and community-based interventions. Current maternal health policies prioritize continuity of care throughout pregnancy, childbirth, and the postpartum period. Access to quality antenatal care, skilled birth attendance, and postnatal care constitutes the foundation of these policies.

Research Methodology

Innovative approaches, including telehealth services, maternal education programmes, and mental health support, have become increasingly important in addressing the diverse needs of women. Child health policies place particular emphasis on early childhood development, immunization, and nutrition. Immunization programmes have played a crucial role in reducing the incidence of infectious diseases and lowering child mortality rates. Furthermore, initiatives promoting breastfeeding, nutritional supplementation, and early childhood education play a decisive role in improving child health outcomes [10]. Despite considerable progress, disparities persist. Access to quality healthcare services remains unequal, resulting in disparities in maternal and child health outcomes. Social determinants such as income, education, and geographical location continue to influence the effectiveness of health policies and require targeted interventions to address systemic inequalities. Future maternal and child health policies are expected to promote integrated approaches that transcend traditional sectoral boundaries. Recognizing the interdependence of maternal and child health, policymakers are increasingly adopting a life-course perspective. Comprehensive models of care are designed to address not only the perinatal period but also the evolving healthcare needs of individuals during adolescence and beyond.

Analysis and Results

The future of maternal and child health policy requires a strong commitment to addressing the social determinants that contribute to health inequalities. Gender equality occupies a central place in this process by promoting women's empowerment and eliminating barriers to access to healthcare [11]. At the same time, the values and worldview of the younger generation are increasingly influenced by factors such as artificial intelligence and virtual environments. Therefore, innovative approaches play a decisive role in fostering a healthy generation.

Digital health interventions, telemedicine, and mobile health (mHealth) platforms improve access to healthcare services and enhance service delivery. Integrating technology into perinatal monitoring, health education, and evidence-based decision-making is essential for optimizing health outcomes. Future maternal and child health policies should prioritize community participation and cross-sectoral collaboration. Empowering communities to actively participate in healthcare decision-making increases the effectiveness of public health interventions. Case studies illustrate effective maternal and child health policies in different contexts. The Nordic countries, recognized for their comprehensive maternal health policies, demonstrate how investments in education, healthcare infrastructure, and social support contribute to positive health outcomes. In contrast, community-based interventions in Sub-Saharan Africa highlight the importance of empowering local communities to address maternal and child health challenges. Despite these achievements, numerous challenges remain, ranging from economic constraints and inadequate infrastructure to cultural and social barriers. In many regions, limited resources hinder the implementation of comprehensive maternal and child health policies. Cultural norms and gender inequalities continue to influence access to healthcare services, requiring targeted strategies to overcome these deeply rooted challenges. Opportunities for improvement lie in strengthening global cooperation and promoting research- and evidence-based policymaking. International collaboration facilitates knowledge sharing, resource exchange, and the dissemination of best practices, thereby increasing the effectiveness of health interventions. Furthermore, advances in research methodologies and the use of big data provide a stronger evidence base for the development of effective health policies. As we address the complex challenges of maternal and child health, a clear call to action emerges. Every family living in New Uzbekistan looks to the future with hope. Therefore, collective efforts are essential to create a healthier and more prosperous future. Through sustained commitment, adaptive strategies, and a shared vision, the global community can ensure a sustainable future for maternal and child health. The determinant approach to maternal and child health protection requires every mother and every child to adopt a conscious attitude toward health and well-being. It plays a decisive role in promoting well-being and serves as a foundation for the broader public health system. This approach provides a comprehensive understanding of current global maternal and child health policies and offers insights into the multifaceted strategies implemented to protect maternal and child health [12]. Accordingly, the determinant approach represents a systematic framework that combines both theoretical foundations and empirical evidence by recognizing the complex set of factors influencing maternal and child health outcomes. Maternal and child health policies demonstrate considerable regional variation, reflecting differences in healthcare systems, economic development, cultural contexts, and available resources. In high-income countries, these policies generally emphasize advanced perinatal care, modern maternity services, and comprehensive child healthcare. In contrast, many developing countries continue

to face challenges such as limited access to essential healthcare services, high maternal mortality rates, and widespread child malnutrition.

Current maternal health policies prioritize the continuum of care, covering the pre-pregnancy period, pregnancy, perinatal care, safe childbirth, and postnatal care. Access to quality antenatal care remains a key priority, with particular emphasis on regular medical examinations, monitoring high-risk pregnancies, and the early detection of pregnancy-related complications [13]. Recognizing the vulnerability of both mothers and newborns during the postpartum period, contemporary health policies increasingly emphasize postnatal care. This includes breastfeeding support, mental health services, and comprehensive care designed to address the specific challenges encountered during the early postnatal period. Immunization remains one of the cornerstones of child health policy worldwide. Vaccination programmes targeting preventable diseases have made a substantial contribution to reducing child mortality. Accordingly, health policies continue to emphasize the importance of timely and comprehensive immunization schedules. Nutritional interventions also play a decisive role in child health policy. Initiatives promoting breastfeeding, nutritional supplementation, and early childhood development contribute significantly to improving children's overall health outcomes. These policies are intended to prevent malnutrition while supporting optimal physical and cognitive development. Despite these achievements, disparities in policy effectiveness persist due to factors such as economic inequality, geographical accessibility, and cultural practices. Consequently, policymakers are required to develop targeted interventions that reduce these disparities and ensure equitable access to healthcare services [14]. For this reason, the determinant approach extends beyond healthcare to include upbringing, education, and self-development. Recognizing and addressing these key determinants is essential for developing policies that respond effectively to the needs of diverse populations and produce positive health outcomes. Digital health interventions, including telehealth services, have become an important component of maternal and child health policy. Bodyhealth enables remote consultations, monitoring, and health education, thereby overcoming geographical barriers and improving access to healthcare services.

Robust health information systems support evidence-based policymaking by providing reliable data for decision-making. Data-driven approaches enable policymakers to monitor health outcomes in real time, optimize resource allocation, and identify areas requiring targeted intervention.

Advanced perinatal monitoring technologies have further improved the quality of care provided to pregnant women. Wearable devices, mobile applications, and remote monitoring systems facilitate the early detection of complications and support proactive health management throughout pregnancy.

Mobile health (mHealth) platforms deliver health information, educational resources, and support directly to mothers and their families. These platforms improve health literacy, encourage active participation in health management, and serve as effective tools for disseminating essential health information. Recognizing the importance of community participation, current maternal and child health

policies emphasize the active involvement of local communities. Trained community health workers provide basic healthcare services and health education, acting as a bridge between formal healthcare systems and local communities while improving both accessibility and cultural relevance. Intersectoral collaboration remains an integral component of successful maternal and child health policies. Cooperation among the healthcare, education, and social service sectors, together with community organizations, promotes comprehensive and integrated interventions. This collaborative approach acknowledges that the determinants of maternal and child health extend well beyond the healthcare sector alone. Limited financial resources continue to present significant challenges to the implementation of comprehensive maternal and child health policies. Adequate funding is essential to ensure access to quality healthcare services, develop healthcare infrastructure, and maintain the sustainability of health programmes. Deeply rooted cultural norms and social expectations may also hinder the effective implementation of health policies. Addressing cultural sensitivities, promoting cultural competence among healthcare professionals, and engaging local communities are important strategies for overcoming these challenges [15]. International cooperation provides valuable opportunities for knowledge exchange, resource sharing, and collaborative research. Global partnerships contribute to a broader understanding of best practices and enable countries to learn from one another's successes and challenges. Further opportunities lie in strengthening international collaboration and advancing research methodologies. Cooperation among countries promotes the exchange of knowledge and resources while supporting collaborative research aimed at improving the evidence base for effective policymaking. Advances in research methods, data analysis, and international cooperation enable policymakers to develop maternal and child health policies that are evidence-based, adaptable, and effective. One of the approaches currently implemented in practice is the Focused Antenatal Care (FANC) policy, which is designed to address the specific needs of pregnant women, particularly in resource-limited settings. This policy streamlines antenatal services to maximize their effectiveness while ensuring that expectant mothers receive essential care. It focuses on optimizing healthcare resources by reducing the number of routine antenatal visits without compromising the quality of care. The implementation of this policy has significantly improved access to antenatal services in remote and underserved areas and has reduced barriers to healthcare for pregnant women. Another effective model of child health policy integrates healthcare, education, and community participation to promote comprehensive early childhood development. This model begins during pregnancy and continues throughout early childhood, addressing both healthcare and educational needs. It ensures that mothers receive comprehensive support during pregnancy and the postpartum period, including medical examinations, nutritional counselling, and mental health services. The model also incorporates early childhood education programmes, recognizing the crucial role of early stimulation and learning in child development. Community health workers play a vital role in implementing this policy by supporting families and facilitating access to essential healthcare and educational services.

Consequently, this integrated approach has contributed to lower child mortality rates and has demonstrated the effectiveness of simultaneously addressing healthcare and educational needs.

Conclusion

In conclusion, maternal and child health policy embodies a commitment to promoting the well-being of society. From its historical evolution to current practices and future directions, maternal and child health policy reflects the dynamic interaction between healthcare, social development, and technological progress. Adopting integrated, equitable, and innovative approaches offers the prospect of raising healthier future generations. Today, the successful implementation of childhood immunization programmes demonstrates the effectiveness of targeted public health interventions. These programmes emphasize comprehensive vaccination coverage, effective public communication, and the use of innovative strategies to ensure that all children are reached. The policy implemented within this programme relies on healthcare workers to provide services in remote and underserved areas, ensuring that every child has access to essential vaccines.

It also incorporates immunization monitoring technologies through the use of electronic records to monitor vaccination coverage and identify areas requiring additional attention. The nationwide implementation of this programme has contributed significantly to the prevention of many infectious diseases. It should be emphasized that this well-planned and effectively implemented immunization policy has substantially reduced the incidence of childhood diseases.

The results achieved further highlight the important role of community participation in the successful implementation of maternal and child health policies. The active involvement of healthcare professionals and local communities ensures that health policies are culturally sensitive, reach remote populations, and are accepted by the public. Adapting interventions to the specific needs and cultural context of individual communities enhances both the effectiveness and acceptability of health policies. The success of maternal and child health protection also demonstrates the importance of adopting a holistic approach to maternal health. In addition to medical care, attention should be given to mental health, gender equality, and postpartum support, all of which contribute to improved maternal outcomes and overall well-being. Policymakers should recognize that maternal health extends beyond childbirth and adopt a comprehensive, woman-centred approach. Investment in mental health services, lactation support, and community-based programmes can make a significant contribution to maternal well-being. Maternal and child health policy operates within a dynamic environment shaped by economic, cultural, and social factors. Although significant challenges remain, considerable opportunities for improvement also exist.

By promoting collaborative approaches, strengthening international cooperation, and developing policies based on sound scientific evidence, countries can overcome existing barriers and achieve better health outcomes for mothers and children. The development of effective maternal and child health policies requires balance, adaptability, and a shared vision of the future, ensuring that every mother and every child has access to high-quality, culturally appropriate healthcare services.

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EFFECTIVE DEVELOPMENT OF THE SYSTEM FOR TRAINING PROMISING YOUNG LEADERS IN UZBEKISTAN: INSTITUTIONAL PROBLEMS AND SOCIOLOGICAL MECHANISMS

Tursunboyev Jahongir Shodiyor Ugli
PhD Candidate, Samarkand State University named after Sharof Rashidov
shodiyorovich1202@gmail.com

Annotatsiya. Ushbu maqolada sotsiologik va institutsional yondashuvlar asosida O‘zbekiston davlat xizmatida istiqbolli yosh rahbarlarni tanlash, o‘qitish, kasbiy rivojlantirish va ularning mansab pog‘onasidan ko‘tarilishini ta’minlash tizimini takomillashtirish masalalari ko‘rib chiqilgan. Tadqiqotning empirik bazasini davlat xizmati, hokimiyat tizimi, yoshlar siyosati, yetakchilikni o‘qitish dasturlari, ta’lim va ilm-fan sohalaridan jalb etilgan 50 nafar ekspert bilan o‘tkazilgan yarim tuzilmali intervyular tashkil etdi. Ma’lumotlar tematik kodlash, kontent-tahlil va qiyosiy talqin qilish usullari yordamida qayta ishlandi. Natijalar shuni ko‘rsatdiki, istiqbolli yosh rahbarlarga bo‘lgan ehtiyoj miqdoriy emas, balki birinchi navbatda sifat jihatidan muhimdir. Ekspertlar strategik va analitik tafakkur, qaror qabul qilish, jamoani boshqarish, muloqot, emotsional intellekt, raqamli savodxonlik, innovatsion yondashuv hamda etik mas’uliyatni zamonaviy rahbarning asosiy kompetensiyalari sifatida belgilaydilar. Shu bilan birga, tadqiqot yosh rahbarlarni tayyorlash tizimida nazariya va amaliyot o‘rtasidagi uzilish, amaliy rahbarlik tajribasining yetishmasligi, murabbiylik (mentoring) va kouching mexanizmlarining institutsionallashuvi yetarli emasligi, mansab pog‘onasidan ko‘tarilishda byurokratik va norasmiy to‘siqlar, meritokratiyaning amaliyotda to‘liq joriy etilmagani hamda raqamli baholash mexanizmlariga ishonch muammolarini aniqladi. Tadqiqot natijalari D. Nortning institutsional nazariyasi, G. Bekkerning inson kapitali nazariyasi, P. Burdiyening ijtimoiy kapital konsepsiyasi, P. Sorokinning ijtimoiy harakatchanlik nazariyasi, J. Dyuning tajriba orqali o‘rganish konsepsiyasi va R. Katsning rahbarlik kompetensiyalari yondashuvi orqali talqin qilindi. Olingan natijalar asosida yosh rahbarlarni rivojlantirishning institutsional mexanizmi va “Muammo → Sabab → Oqibat” tahliliy modeli taklif etildi. Maqolada meritokratik tanlov, kompetensiyalarga asoslangan baholash, uzluksiz kasbiy rivojlanish, amaliy yetakchilik, murabbiylik, raqamli monitoring hamda strategik kadrlar prognozini davlat xizmatida yosh rahbarlar korpusini shakllantirishning yagona tizimiga integratsiya qilish zarurligi asoslab berilgan.

Kalit so‘zlar: *yosh rahbarlar, davlat xizmati, meritokratiya, inson kapitali, ijtimoiy harakatchanlik, ijtimoiy kapital, yetakchilik kompetensiyalari, karyera taraqqiyoti, murabbiylik, raqamli boshqaruv, institutsional rivojlanish, davlat kadrlar siyosati.*

Аннотация. В данной статье с использованием социологического и институционального подходов рассматривается совершенствование системы отбора, подготовки, профессионального развития и обеспечения

карьерного роста перспективных молодых лидеров на государственной службе Узбекистана. Эмпирическую базу исследования составили полуструктурированные интервью, проведенные с 50 экспертами из числа государственных служащих, системы хокимиятов, сферы молодежной политики, программ подготовки лидеров, образования и науки. Обработка данных осуществлялась методами тематического кодирования, контент-анализа и сравнительной интерпретации. Результаты показывают, что потребность в перспективных молодых лидерах носит преимущественно качественный, а не количественный характер. Эксперты выделили стратегическое и аналитическое мышление, принятие решений, управление командой, коммуникацию, эмоциональный интеллект, цифровую грамотность, инновационный подход и этическую ответственность в качестве ключевых компетенций современного руководителя. В то же время исследование выявило разрыв между теорией и практикой в системе подготовки молодых лидеров, недостаток практического опыта управления, неадекватную институционализацию механизмов наставничества и коучинга, бюрократические и неформальные барьеры для карьерного роста, неполную реализацию меритократии на практике, а также проблемы доверия к цифровым механизмам оценки. Полученные результаты интерпретированы через институциональную теорию Д. Норта, теорию человеческого капитала Г. Беккера, концепцию социального капитала П. Бурдье, теорию социальной мобильности П. Сорокина, концепцию обучения через опыт Дж. Дьюи и подход к управленческим компетенциям Р. Каца. На основе полученных результатов предложены институциональный механизм развития молодых лидеров и аналитическая модель “Проблема → Причина → Последствие.” В статье обоснована необходимость интеграции меритократического отбора, оценки на основе компетенций, непрерывного профессионального развития, практического лидерства, наставничества, цифрового мониторинга и стратегического прогнозирования кадрового потенциала в единую систему формирования корпуса молодых лидеров на государственной службе.

Ключевые слова: *молодые лидеры, государственная служба, меритократия, человеческий капитал, социальная мобильность, социальный капитал, лидерские компетенции, развитие карьеры, наставничество, цифровое управление, институциональное развитие, государственная кадровая политика.*

Abstract. This article examines the improvement of the system for selecting, training, professionally developing, and ensuring the career advancement of promising young leaders in the civil service of Uzbekistan through sociological and institutional approaches. The empirical basis of the study consisted of semi-structured interviews conducted with 50 experts drawn from the civil service, the hokimiyat system, youth policy, leadership training programs, education, and research. The data were processed using thematic coding, content analysis, and comparative interpretation. The findings show that the need for promising young

leaders is primarily qualitative rather than quantitative. Experts identified strategic and analytical thinking, decision-making, team management, communication, emotional intelligence, digital literacy, an innovative approach, and ethical responsibility as the key competencies of a modern leader. At the same time, the study identified a gap between theory and practice in the training system for young leaders, insufficient practical leadership experience, inadequate institutionalization of mentoring and coaching mechanisms, bureaucratic and informal barriers to career advancement, incomplete implementation of meritocracy in practice, and problems of trust in digital assessment mechanisms. The findings were interpreted through D. North's institutional theory, G. Becker's human capital theory, P. Bourdieu's concept of social capital, P. Sorokin's theory of social mobility, J. Dewey's concept of learning through experience, and R. Katz's leadership competency approach. Based on the findings, an institutional mechanism for developing young leaders and the analytical "Problem → Cause → Consequence" model are proposed. The article substantiates the need to integrate meritocratic selection, competency-based assessment, continuous professional development, practical leadership, mentoring, digital monitoring, and strategic workforce forecasting into a unified system for forming a corps of young leaders in the civil service.

Keywords: *young leaders, civil service, meritocracy, human capital, social mobility, social capital, leadership competencies, career development, mentoring, digital governance, institutional development, public personnel policy.*

Introduction

The effectiveness of modern public administration is increasingly dependent on the quality of human capital, mechanisms for selecting and placing personnel in the civil service, opportunities for developing leadership potential, and the formation of professional career trajectories. Digital transformation, the transition of public services to electronic formats, the increasing complexity of socio-economic processes, and growing public demands toward state institutions are creating new requirements for civil servants, particularly for managerial personnel.

Under these conditions, explaining the formation of an effective leader in public administration solely through educational attainment or length of service is insufficient. Leadership potential requires a set of interrelated competencies, including strategic thinking, analytical decision-making, team management, communication, emotional resilience, the use of digital technologies, innovative thinking, and institutional responsibility. Robert Katz associated leadership effectiveness with the combination of technical, human, and conceptual skills [1].

Uzbekistan is implementing important institutional changes aimed at professionalizing the civil service and strengthening meritocratic principles. The Law of the Republic of Uzbekistan "On Civil Service," adopted on 8 August 2022 as No. ZRU–788, represented an important stage in establishing a unified legal framework in the field of civil service [2]. The law institutionally regulates relations concerning admission to the civil service, career service, development of professional

competencies, formation of a personnel reserve, and assessment of civil servants' performance.

One of the important mechanisms established in the legislation is the National Personnel Reserve. Under the current approach, the National Personnel Reserve is regarded as a system of centralized selection, training, retraining, and continuous professional development of civil servants in order to provide managerial positions with qualified personnel [2].

The "Uzbekistan – 2030" Strategy adopted in 2023 also links the professionalization of public administration, human capital, institutional effectiveness, and digital transformation with the country's strategic development priorities [3].

In addition, Presidential Decree No. PF–95 of 2025, aimed at organizing the civil service on the basis of new approaches, introduced mechanisms such as the formation of a professional and performance-oriented civil service corps, special courses for first-time entrants to the civil service, online monitoring of professional competency development, and the formation of a sustainable reserve of promising leaders.

From this perspective, the training of young leaders should be viewed as a process considerably broader than recruitment into the civil service. It constitutes a unified institutional cycle encompassing early identification of a promising candidate → selection → training → acquisition of practical experience → mentoring → performance assessment → career development → promotion to a leadership position.

Douglas North's institutional approach is particularly important for theoretically explaining this problem. North interprets institutions as systems of formal and informal constraints that regulate political, economic, and social relations among people [4]. His approach makes it possible to explain the potential difference between the existence of laws and formal regulations in the civil service and the way these rules actually function in practice. Gary Becker's human capital theory views education, professional training, and skills as investments that affect human productivity [5]. Becker's classic work connects investments in education and training with economic outcomes.

This approach is also important for the civil service: expenditures on the education and training of young personnel should be measured not merely through certificates or diplomas, but through their actual managerial outcomes. If education is limited to providing theoretical knowledge, the institutional return on investment in human capital may be low. The issue of young leaders is also important from the perspective of social mobility. Pitirim Sorokin interpreted social mobility as the process through which individuals and social groups change their positions within the social structure [6]. The openness of career advancement channels in the civil service constitutes an important institutional channel through which young people can attain higher social status. If these channels are formally open but practically constrained by informal relationships, young people's institutional trust may decline.

The scientific problem of the article is manifested precisely at this point: under conditions in which formal institutional mechanisms for training young leaders in Uzbekistan are developing, what competency-based, organizational, and socio-psychological barriers affect the practical effectiveness of these mechanisms?

The aim of the study is to analyze the current state of the system for training and developing promising young leaders in Uzbekistan on the basis of expert assessments,

identify the main institutional and competency-related problems, and develop effective institutional mechanisms aimed at overcoming them.

The study sought answers to the following questions:

1. What is the nature of the demand for young leaders in the civil service?
2. Which competencies are insufficiently developed among young leaders?
3. What institutional barriers affect meritocratic selection and career advancement?
4. How do relations between young and older generations of leaders affect personnel development?
5. What role can digitalization and performance-based assessment play in developing young leaders?
6. On the basis of what integrated institutional model can the system for training promising young leaders be improved?

Research Methodology

The study was conducted using a qualitative sociological methodology. The primary empirical data were obtained through semi-structured interviews, with a total of 50 experts participating in the study. The expert sample was formed taking into account the institutional multidimensionality of the research object. Experts were recruited from the civil service, the hokimiyat system, youth policy, leadership training programs, education, and research.

Table 1. Institutional composition of experts

Expert group	Number	Share, %
Representatives of the civil service	15	30
Representatives of the hokimiyat system	10	20
Youth policy specialists	7	14
Participants and specialists of leadership training programs	7	14
Representatives of educational institutions	6	12
Research experts	5	10
Total	50	100

As the table shows, 30% of the experts were representatives of the civil service and 20% were representatives of the hokimiyat system. These two groups provided an empirical base closely connected to management practice. Representatives of youth policy, leadership programs, education, and research made it possible to assess the educational, social, and institutional dimensions of the issue. Three main methods were used to analyze the research data: content analysis, thematic coding, and comparative interpretation. First, primary codes were extracted from the interview materials according to their content. They were then combined into broader themes. As a result, the following main thematic areas were formed:

• demand for young leaders;

- leadership competencies;
- practical management experience;
- meritocracy and selection;
- career advancement;
- bureaucratic and informal barriers;
- mentoring and intergenerational relations;
- digital competencies;
- youth participation in decision-making;
- institutional trust.

Given the qualitative nature of the study, the thematic codes in the experts' responses were not mutually exclusive. For example, one expert could simultaneously comment on insufficient practical experience, weak mentoring, and institutional barriers to career advancement.

Therefore, the shares of thematic positions should not be interpreted as mutually exclusive statistical groups of respondents. To increase reliability, experts were selected from different institutional positions. Thus, leadership processes in the civil service were analyzed not from a single perspective, but from the viewpoints of government bodies, educational institutions, youth policy, and the research sector. Another methodological basis of the study was institutional analysis. The analysis focused separately on the gap between formal rules and practice, meritocratic mechanisms and informal relations, and education and practical managerial competencies. At the same time, interpretation of the findings relied on D. North's institutional theory [4], G. Becker's human capital approach [5], P. Bourdieu's concept of social capital [7], P. Sorokin's theory of social mobility [6], J. Dewey's concept of learning through experience [8], and R. Katz's model of leadership skills [1].

Analysis and Results

The findings show that the need for promising young leaders in Uzbekistan is high. However, it would not be appropriate to understand this need merely as an increase in the number of young people occupying leadership positions. From the experts' perspective, the primary need is associated with developing a new quality of leadership potential for the civil service. A modern leader is expected to demonstrate strategic thinking, analytical ability, decision-making in complex situations, teamwork, emotional intelligence, the use of digital technologies, and social responsibility. In this respect, the training of young leaders emerges not simply as a personnel policy issue in public administration, but as an issue of human capital and institutional development. According to Becker's human capital theory, education and professional training constitute investments in future productivity [5]. From this perspective, the effectiveness of educational and organizational resources allocated by the state to training young leaders should be assessed through their actual managerial outcomes.

One of the most frequently recurring problems identified in the study was the gap between theory and practice. According to the experts, young personnel often acquire the necessary theoretical knowledge through education and professional development programs, but lack practical experience in decision-making in real management situations, team management, conflict resolution, resource allocation, and

assuming responsibility. This problem can be explained through John Dewey's concept of experiential learning. Dewey connects education with real experience, action, and subsequent reflection [8]. Therefore, in training young leaders it is important to use not only lectures and theoretical courses, but also real management cases, simulations, project activities, internships, shadowing, and on-the-job learning mechanisms.

This is also consistent with R. Katz's concept of leadership skills. Katz considers the combination of technical, human, and conceptual skills important for an effective administrator [1]. In training young leaders, this triad can be expanded in line with the requirements of modern public administration: technical competence + interpersonal competence + strategic-conceptual competence + digital competence + ethical competence. The second major block identified in the findings concerns meritocracy and career advancement.

In Uzbekistan, mechanisms such as open competition, electronic platforms, competency-based assessment, and the formation of personnel reserves in the civil service are being institutionally strengthened. Presidential Decree No. PF–95 of 2025 also provides for mechanisms such as the formation of a professional and performance-oriented civil service corps, a unified portal for vacant positions, online monitoring of professional competencies, and the formation of National and Potential Personnel Reserves. However, the experts noted a certain discrepancy between formal institutions and informal practices. Perceptions of favoritism, informal connections, subjective decisions, and bureaucratic barriers were still identified as factors affecting career advancement in the civil service. This situation can be explained through Douglas North's institutional approach. North views institutions not merely as formal laws, but as a system encompassing customs, social norms, and informal constraints alongside formal rules [4]. Therefore, introducing meritocracy into the civil service is not sufficient by itself. An institutional culture of meritocracy in practice must also be formed. Pierre Bourdieu's concept of social capital is also important here. According to Bourdieu, social ties, networks, and relationships can provide individuals with particular resources and opportunities [7]. If informal social capital becomes more influential than formal professional capital, an environment of open competition may be weakened. In the civil service, this can negatively affect the institutional effectiveness of meritocratic principles. The study identified bureaucracy, an unreliable personnel policy, vertical hierarchy, and informal relations as factors hindering the career advancement of young personnel. These factors may increase institutional frustration among young people, reduce initiative, and weaken the motivation of highly capable personnel to remain in the civil service over the long term. Therefore, career development should not be organized merely as upward movement through positions, but on the basis of the chain: competence → results → professional recognition → expanded responsibility → leadership position. Another important finding concerns gaps in the practical leadership competencies of young leaders. Experts emphasized that young personnel do not yet possess sufficient practical management experience, critical thinking, negotiation skills, decision-making skills in crisis situations, and team management skills.

This situation indicates the need to shift personnel training in the civil service from the traditional "knowledge transmission" model to a "competency development" model. Accordingly, it is necessary to expand leadership schools, management laboratories, case-study centers, simulation training, and internships based on real public administration projects. For example, a promising young personnel training program could conditionally use the following distribution:

- 20% — theoretical and academic preparation;
- 30% — practical cases and simulations;
- 20%— project activities;
- 15% — mentoring and shadowing;
- 15% — individual reflection, assessment, and career planning.

This distribution is not empirical statistics, but rather a proposed training design derived from the research findings. Mentoring is also of particular importance. In the study, 23 experts noted the existence of positive cooperation, experience exchange, and mentor–mentee relationships between older and younger leaders. This indicates the availability of a positive institutional resource for institutional memory and experience transfer in public administration. However, 8 experts noted that representatives of the older generation do not always fully accept young people's initiative and innovative ideas. Conversely, 2 experts emphasized that some young leaders do not sufficiently value the experience of the older generation. Thus, the intergenerational problem is not one-sided. Two types of institutional resources interact: the older generation — experience, institutional memory, and caution; the younger generation — digital capacity, innovation, speed, and new management methods.

Therefore, generations should not be positioned against each other; rather, they should be integrated as mutually complementary resources. For this purpose, alongside traditional mentoring, reverse mentoring can be introduced, whereby young personnel participate as advisers to older-generation representatives on digital technologies, new communication tools, and innovative approaches. Another important issue identified in the study was young people's participation in decision-making. Experts noted that the views of young personnel are sometimes not taken sufficiently into account.

This situation can be interpreted through Jürgen Habermas's theory of communicative action. In the communicative approach, institutional decisions are associated with processes of dialogue, understanding, and consensus among stakeholders [9]. From this perspective, involving young people in decision-making does not mean merely formal participation; it means incorporating their institutional views and proposals into the decision-making process. For this purpose, youth advisory councils under government bodies, platforms for innovative ideas, groups of young experts, and leadership forums can be developed.

The next area of the study concerns digital governance and digital assessment. In Uzbekistan, the digitalization of public services and the integration of government information systems are accelerating. Presidential Resolution No. PQ–162 of 2023 established important tasks related to the digital transformation of public services and sectors [10]. Within the framework of Presidential Decree No. PF–95 of 2025, mechanisms have also been established for collecting and analyzing civil servants' KPI results and monitoring the development of professional competencies online.

Table 2. Institutional mechanism for developing promising young leaders

№	System-forming element	Main content	Main function
1.	Institutional and legal framework	Rules for admission, selection, assessment, and promotion in the civil service	Ensuring meritocracy, equal opportunities, and transparency
2.	Competency assessment	Assessment of strategic, analytical, communicative, digital, and leadership competencies	Determining the level of readiness for leadership
3.	Personnel reserve and career development	Early identification of promising young people and formation of a targeted training reserve	Ensuring a sustainable leadership personnel pipeline
4.	Continuous professional development	Professional development, retraining, mentoring, coaching, shadowing	Continuous development of competencies
5.	Digital monitoring	KPI, competency diagnostics, and electronic career profile	Increasing performance and transparency
6.	Strategic forecasting	Identifying future competencies and forecasting personnel needs	Ensuring the competitiveness of the civil service

However, digitalization does not automatically ensure objectivity. If KPI indicators are defined incorrectly, if only numerical indicators are measured instead of outcomes, or if the assessment algorithm is unclear, a problem of trust in the digital system may arise. Therefore, three principles are important in a digital assessment system:

1. measurability — the indicator must be clearly measurable;
2. transparency — the employee must know on what basis they are being assessed;
3. verification — there must be an opportunity to verify the assessment result.

These requirements can reduce the human factor in the civil service while also mitigating the risk of algorithmic subjectivity. Based on a synthesis of the research findings, an institutional mechanism for developing young leaders consisting of six interconnected elements is proposed. The fundamental feature of this mechanism is that its elements should function not separately, but as a unified talent management cycle. That is: identification → selection → assessment → training → practical experience → mentoring → performance assessment → career advancement → leadership → reassessment. Such a cycle enables the civil service to develop personnel throughout their entire professional lives rather than merely training them once.

“Problem → Cause → Consequence” analytical model

Based on the research findings, the “Problem → Cause → Consequence” model was developed to systematize problems in the civil service and the system for young leaders.

The scientific significance of this model lies in its ability to view a problem not only in terms of its external manifestation, but together with its internal causes and social consequences. For example, the conclusion that “young people are not advancing in their careers” describes the external manifestation of the problem.

Sociological analysis seeks its causes in factors such as bureaucracy, informal networks, limited channels of vertical mobility, and weak competency assessment. The consequences may include declining motivation, institutional distrust, and the movement of talented personnel to other sectors.

Table 3. "Problem → Cause → Consequence" model.

Problem	Main causes	Social-institutional consequence
Incomplete formation of meritocracy	Non-uniform selection criteria, subjective assessment, informal connections	Decline in institutional trust
Barriers to young people's career advancement	Bureaucracy, vertical hierarchy, informal relations	Declining motivation and personnel outflow
Insufficient practical leadership skills	Predominance of theoretical education, limited exposure to real management environments	Difficulties in decision-making
Young people's views not sufficiently taken into account	Vertical management culture, communication distance	Institutional alienation
Hesitation toward digital assessment	Uneven digital competencies, problems of trust in assessment criteria	Reduced effectiveness of digital transformation
Mentoring is not systematic	Mentor–mentee relationships have not been transformed into a formal mechanism	Weakening of institutional experience transfer

Integrated competency model for young leaders.

Based on the research findings, the following integrated competency model is proposed for a modern young state leader: Strategic thinker + analytical decision-maker + results-oriented manager + human-centered communicator + ethically responsible leader + digitally and innovatively competent specialist.

This model can be integrated into five main blocks:

1. Strategic-analytical block
• strategic thinking;
• systems analysis;
• data-driven decision-making;
• forecasting;
• risk assessment.

2. Management-organizational block
• planning;
• resource management;
• results-oriented management;
• team motivation;
• project management.

3. Social-communicative block
• communication;
• negotiation;
• conflict management;
• emotional intelligence;
• public communication.

4. Digital-innovative block
• digital technologies;
• data analysis;
• electronic public services;
• understanding the potential of artificial intelligence;
• innovation management.

5. Ethical-institutional block

- integrity;
- justice;
- responsibility;
- public interest;
- zero tolerance for corruption;
- institutional loyalty.

Such a model contributes to developing a young leader not merely as a "knowledgeable specialist," but as a leader capable of generating results, working with people, and managing institutional change.

The research findings can be explained at the intersection of several theoretical approaches. First, from the perspective of institutional theory, problems in the civil service are associated with relations between formal and informal institutions. Laws and selection mechanisms define the formal institutional environment, while favoritism, social networks, and informal trust relations may influence decision-making in practice. Therefore, the success of civil service reforms should be measured not only by the adoption of new rules, but also by the formation of a new institutional culture [4]. Second, human capital theory makes it possible to explain the effectiveness of investments in training young leaders. Expenditures on education and professional development do not automatically produce results. They become human capital only when transformed into competencies that can be applied in the workplace [5]. Third, social mobility theory makes it possible to view the civil service as a channel of upward social mobility for young people. When career advancement is open and fair, the civil service functions as an institution providing social mobility. Conversely, when informal resources dominate, channels of vertical mobility become narrower [6]. Fourth, social capital theory is important for explaining the influence of informal relationships on career opportunities. However, the existence of social capital in the civil service is not automatically negative. The problem arises when social networks are given priority over professional merit [7]. Fifth, the concept of learning through experience substantiates the importance of a practical environment in training young leaders. Dewey closely links education with individuals' real experience [8]. Therefore, leadership competencies should be developed not only in the classroom, but also through real management tasks.

Conclusion

The findings of the study demonstrate that the training of promising young leaders in Uzbekistan is extending beyond the framework of public administration personnel policy and is becoming an important factor in human capital, social mobility, and institutional development. The first major conclusion of the study is that the need for young leaders in the civil service is primarily qualitative rather than quantitative. Simply attracting more young people to the civil service is insufficient. The main task is to form a corps of leaders who think strategically, make analytical decisions, manage teams, master digital technologies, and possess a high level of ethical responsibility.

The second conclusion is that the gap between theory and practice in training young leaders is one of the most important competency-related problems. The presence

of theoretical knowledge does not automatically ensure the ability to make effective decisions in real management situations. Therefore, case studies, simulations, internships, project activities, mentoring, coaching, and shadowing mechanisms should be expanded within the personnel training system. The third conclusion is that although meritocratic institutions in the civil service are developing, the problem of divergence between formal and informal institutions remains. Laws and electronic selection mechanisms are important, but they should be strengthened by institutional culture, transparent assessment, mechanisms for verifying decisions, and measures limiting informal influence. The fourth conclusion is that young people's career development in the civil service cannot be considered separately from recruitment. Identification, selection, training, mentoring, performance assessment, and promotion of promising personnel should be organized as a unified talent management cycle.

The fifth conclusion is that mentoring and intergenerational cooperation constitute an important institutional resource for developing young leaders. To combine the institutional memory of the older generation with the digital and innovative potential of the younger generation, reverse mentoring mechanisms should be introduced alongside mentoring. The sixth conclusion is that digital assessment creates significant opportunities to strengthen transparency in the civil service. However, digital technology itself is not a guarantee of meritocracy. KPIs and other assessment mechanisms must be clear, measurable, understandable, and verifiable.

Based on the research findings, it is appropriate to develop the system for training promising young leaders in Uzbekistan according to the following institutional chain: Early identification → meritocratic selection → competency diagnostics → targeted training → practical leadership → mentoring → digital monitoring → results-based assessment → career development → leadership position. This approach makes it possible to transform the training of young leaders in the civil service from a collection of fragmented courses into a comprehensive institutional system. Furthermore, the integrated model of a young leader proposed for the civil service on the basis of the study can be expressed by the following formula: Strategic thinking + analytical decision-making + practical leadership + human-centered communication + ethical responsibility + digital competence. Thus, the next stage in the development of the system for training promising young leaders in Uzbekistan should be characterized by a transition from the "knowledge transmission" model to the "knowledge → practical experience → competence → results → leadership" model. Such institutional transformation will contribute to increasing the effectiveness of human capital utilization in the civil service, expanding young people's opportunities for social mobility, strengthening institutional trust in the civil service, and ensuring a stable generational renewal of the professional leadership corps.

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HISTORICAL PROCESSES THAT TOOK PLACE IN THE TASHKENT OASIS

Qadamboev Shahriyorbek Sharifboy Ugli
Researcher, Urgench State University named after Abu Rayhon Beruni
shahriyorbek.kadamboyev@mail.ru

Annotatsiya. Maqolada Toshkent vohasi davri xo‘jalik-madaniy hududlarda iqtisodiy omillar ta’sirida etnik jarayonlar taxlil qilingan.

Kalit so‘zlar*: Qasimov M.R, Mamedov E.D, Juraqulov M.J, Sobirov Q, Kabirov J, Sagdullaev A, Abdullaev O‘.I, Duke X, Normurodov D, O‘zbekiston, Xorazm, Zarafshon, Farg‘ona, Toshkent, Chotqol, Kulbuloq, Qo‘shilish, Bo‘zsuv, Burganlik.*

Аннотация. В статье анализирован этнические процессы в связи влияние экономические факторы культурно-хозяйственных территории периода Ташкентским оазисе.

Ключевые слова: *Касымов М.Р, Мамедов Э.Д, Журакулов М.Ж, Сабиров К, Кабиров Ж, Сагдуллаев А, Абдуллаев У.И, Дуке Х, Нормуродов Д, Узбекистан, Хорезм, Зарафшан, Фергана, Ташкент, Чаткал, Кульбулок, Кушилиш, Бузсув, Бурганлик.*

Abstract. This article analyzes the ethnic processes that occurred in the Tashkent Oasis, with particular emphasis on the influence of economic factors and the cultural and economic characteristics of the region.

Keywords: *M.R. Kasymov, E.D. Mamedov, M.Zh. Jurakulov, K. Sabirov, Zh. Kabirov, A. Sagdullaev, U.I. Abdullaev, H. Duke, D. Normurodov, Uzbekistan, Khorezm, Zarafshan, Fergana, Tashkent, Chatkal, Kulbulak, Kushilish, Bozsuv, Burganlik.*

Introduction

The geographical location of Uzbekistan is highly favorable. Under the influence of paleotectonic and paleogeographic processes, the country has developed geo-economic, historical, and cultural regions with distinct geomorphological characteristics. These features have determined the strategic significance of these regions in the socio-economic development of Uzbekistan throughout different historical periods and stages of its development.

In particular, the agricultural oases of Khorezm, Zarafshan, Surkhandarya, Fergana, and Tashkent, characterized by both mountainous and lowland landscapes, have played an important role in the historical development of human settlements from the early Stone Age to the Iron Age. During the 3rd –2nd millennia BCE, the inhabitants of these regions utilized natural resources to meet their economic needs.

At the same time, under the influence of the geographical environment, climatic conditions, anthropogenic landscapes, and ecological factors, they developed various branches of the economy. This article aims to examine the historical development of these processes and the evolution of economic activities in these agricultural oases.

Literature Review

The historical data recorded in scholarly works published from the twentieth century to the mid-2020s provide an opportunity to analyze the socio-economic, ethnic, and cultural relations that characterized the Tashkent Oasis during the Iron Age within a historical and chronological framework. The Ahangaran Valley, frequently referred to in the literature as the Ahangaran River Basin, extends to the spring-fed areas located within the Chatkal Mountain Range.

The Kulbulak archaeological site, situated on the adjacent plains, was inhabited by prehistoric communities. The abundance of springs, rich flora and fauna, and the natural resources of the Chatkal Mountains created favorable environmental and economic conditions that enabled continuous human occupation from the Late Stone Age through the Neolithic period, making the region an important center of prehistoric settlement [1-4]. According to historical evidence presented by researchers, archaeological studies indicate that beginning in the Middle Stone Age, prehistoric populations inhabited the Tashkent Oasis, particularly the Chirchiq Valley. The cave sites of Obi-Rakhmat and Khujand, together with the Kulbulak site, were occupied by

hunter-gatherer communities who preserved and continued the economic traditions established by their ancestors throughout the Mesolithic and Bronze Ages [5]. Historical and archaeological evidence further suggests that by the end of the Middle Stone Age, a group of hunter-gatherers from Obi-Rakhmat expanded their settlement area during the Mesolithic period (12^{th}–7^{th} millennia BCE), moving into the surroundings of present-day Tashkent. This migration contributed to the expansion of the geographical distribution of ethnic communities and intensified cultural interactions within the region. According to historical sources, archaeological monuments such as Qo‘shilish and Bo‘zsuv, located within the territory of the Tashkent Oasis, represent important evidence of the earliest stages of human settlement and socio-economic development in present-day Uzbekistan. The Obishir site in Central Fergana, Machay in Surkhandarya, Aydabol on the Ustyurt Plateau, and Sazagan-1 in the Middle Zarafshan region are among the Mesolithic archaeological sites identified in Uzbekistan [6]. Historical and archaeological literature provides only limited information regarding the ethnogeographic and ethnodemographic characteristics of the hunter-gatherer communities that inhabited Uzbekistan during the Stone and Mesolithic Ages. It remains difficult to determine the extent to which these populations abandoned permanent cave settlements and practiced seasonal hunting and gathering in mountainous areas. Similar conditions have also been observed in other parts of Central Asia. Furthermore, the economic traditions of the Neolithic rural communities that inhabited the archaeological sites of **Qo‘shilish** and **Bo‘zsuv** in the vicinity of present-day Tashkent have received little attention in historical scholarship. According to historical studies, during the Mesolithic period the hunter-gatherer communities of Central Asia, including present-day Uzbekistan, developed two principal forms of subsistence in response to the natural and geo-economic environment. River channels and floodplains created numerous depressions that gradually became lakes and wetlands rich in flora and fauna. These ecosystems supported abundant populations of birds, wild animals, and fish, providing favorable conditions for hunting, gathering, and fishing. In contrast, communities inhabiting mountainous areas relied primarily on hunting and gathering. These economic activities collectively reflect the socio-economic landscape of Mesolithic society [7]. Archaeological investigations conducted in the Tashkent Oasis, particularly in the Ahangaran Valley near the village of Burgulyuk, have revealed settlements dating to the Iron Age. These discoveries are commonly referred to in the archaeological literature as the “Burganlik Culture” [8]. According to H. Duke, the economic traditions of the Burganlik population originated from tribes associated with the Andronovo–Tozabagyab cultural tradition of the Late Bronze Age. However, this interpretation remains open to debate. In our opinion, the creators of the Burganlik Culture may instead have been descendants of the indigenous populations represented by the Kulbulak archaeological complex. It is therefore reasonable to conclude that many of the economic practices established during the Bronze Age continued into the Iron Age.

H. Duke further argues that the economic traditions established by the creators of the Burganlik Culture persisted throughout the Iron Age. Their principal occupation

was household-based livestock breeding, while “qayr” agriculture (floodplain or moisture-dependent farming) served as a supplementary economic activity [9, 10].

Research Methodology

The research is based on the principles of objectivity, historical and chronological consistency, theoretical and comparative analysis, critical discussion, generalization of research findings, and the formulation of final conclusions.

Analysis and Results

Based on the synthesis of historical data published during the twentieth century and the first half of the twenty-first century, and drawing upon new ideas and scholarly approaches, this study examines the development of socio-economic and ethno-cultural relations in the Tashkent Oasis during the period preceding the Iron Age.

It also explores the historical transformations and ethnic processes that took place up to the Classical (Antique) period. Furthermore, the study analyzes patterns of population settlement and the evolution of ethnic processes in the Tashkent Oasis during the Bronze and Iron Ages. On the basis of this analysis, the following findings were obtained: Repeated paleotectonic movements brought about significant geophysical changes in the Tashkent Oasis. These geological transformations played a decisive role in shaping the region's natural environment, landscape, and the subsequent development of human settlement and socio-economic activities. The following findings were obtained: First, the study found that the Ahangaran and Chirchiq geo-economic regions of the Tashkent Oasis differ significantly in terms of their geographical landscapes, which influenced the patterns of human settlement in each area. Furthermore, from the Paleolithic period to the end of the Iron Age, prehistoric communities effectively utilized the region's natural resources, creating favorable conditions for the development of various branches of the economy.

Conclusion

Based on the historical evidence, analysis, and findings presented in this study, it can be concluded that the socio-economic development of the Tashkent Oasis during the Iron Age was largely determined by its geographical and environmental conditions. The Ahangaran River and other open river systems, fed by snowmelt and rainfall from the surrounding high mountains, played a crucial role in the development of the region. These water resources provided favorable conditions for the local population to engage in household livestock breeding as their primary economic activity, while cultivation on fertile liman (floodplain) lands served as an important complementary branch of agriculture. The study also concludes that, unlike the Fergana Valley, the Tashkent Oasis did not experience comparable processes of urbanization during the Iron Age.

Accordingly, the following recommendations are proposed:

1. To clarify the historical geography of the Tashkent Oasis and the Fergana Valley through a historical and chronological analysis of the evidence presented in geographical and archaeological literature.
2. To explain the strategic significance of the Ahangaran River Basin in relation to the geographical characteristics and historical development of the Tashkent Oasis.

3. To further analyze the influence of the oasis's geographical characteristics on patterns of human settlement, ethnogeographical distribution, and ethnodemographic changes throughout its historical development.

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Section 4. ACTUAL PROBLEMS OF NATURAL SCIENCES

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METHODS FOR PROTEIN EXTRACTION FROM ARTEMIA BIOMASS AND THEIR PRACTICAL SIGNIFICANCE: A LITERATURE-BASED REVIEW

Hajibayev Quvvat Ganievich
Senior Researcher, Laboratory of Bioorganic chemistry, Karakalpak Scientific Research Institute of Natural Sciences
xajibayevquvvat@gamil.com

Asemenova Nurjamol Yakupbaevna
Doctorate Student, Laboratory of Bioorganic chemistry, Karakalpak Scientific Research Institute of Natural Sciences
nurjamalasemenova@gmail.com

Satimova Mohira Rashidovna
Independent Researcher, Karakalpak Scientific Research Institute of Natural Sciences
Mohirasatimova620@gmail.com

Annotatsiya. Sho‘r suv qisqichbaqasi Artemia (Anostraca, Branchiopoda) dunyo akvakulturasining 85% dan ortig‘ida qo‘llaniladigan asosiy jonli va quruq ozuqa manbai bo‘lib, uning oziqaviy qiymati birinchi navbatda tarkibidagi yuqori oqsil miqdori (quruq moddaga nisbatan 30–80%) va muvozanatli aminokislotalar profili bilan belgilanadi. Ushbu maqolada 1969-2023 yillar oralig'ida chop etilgan o‘ttizdan ortiq ilmiy manba asosida Artemia sistalari, dekapsulyatsiyalangan sistalari, naupliuslari va katta yoshdagi individlaridan oqsilni ajratib olish, miqdorini aniqlash va sifatini baholashning klassik (Kjeldahl, Biuret) hamda zamonaviy (Lowry, BCA, HPLC-aminokislota tahlili, elektroforez, CsCl izodensita sentrifugalash) usullari tizimlashtirilgan. Shuningdek, oqsil miqdori va sifatiga ta’sir etuvchi asosiy omillar - ozuqa tarkibi, boyitish (enrichment), sho‘rlanish va harorat stressi, jins hamda rivojlanish bosqichi, geografik shtamm - tahlil qilingan. Olingan oqsil mahsulotining amaliy qo‘llanilish yo‘nalishlari (akvakultura va dekorativ baliqchilik lichinkalarini boqish, parranda ozuqasi, funksional bio-ozuqa va bioenkapsulyatsiya, biomeditsina hamda molekulyar-biologik tadqiqotlar) ko‘rib chiqilgan. Natijalar shuni ko‘rsatadiki, Artemia’dan oqsil olish samaradorligi yetishtirish sharoiti, tayyorlash texnologiyasi va tanlangan analitik usulga bog'liq holda sezilarli darajada o‘zgaradi, bu esa maqsadli qo‘llash uchun integratsiyalashgan yondashuv zarurligini ko‘rsatadi.

Kalit so‘zlar: *Artemia, oqsil ekstraksiyasi, dekapsulyatsiya, Kjeldahl usuli, Lowry usuli, boyitish (enrichment), akvakultura, aminokislota profili.*

Аннотация. Артемия (Anostraca, Branchiopoda) - солоноватоводный рачок, являющийся основным источником живого и сухого корма, используемым более чем в 85% мировой аквакультуры; его пищевая ценность определяется прежде всего высоким содержанием белка (30-80% от сухой массы) и сбалансированным профилем аминокислот. В данной статье на основе более тридцати научных источников, опубликованных в 1969-2023 годах, систематизированы классические (метод Кьельдаля, биуретовый метод) и современные (метод Лоури, BCA, аминокислотный анализ методом ВЭЖХ, электрофорез, изопикническое центрифугирование в CsCl) методы извлечения, количественного определения и оценки качества белка из цист, декапсулированных цист, науплиусов и взрослых особей артемии. Также проанализированы основные факторы, влияющие на содержание и качество белка, - состав корма, обогащение

(enrichment), стресс солёности и температуры, пол и стадия развития, географический штамм. Рассмотрены направления практического применения полученного белкового продукта (кормление личинок аквакультурных и декоративных рыб, кормление птицы, функциональные биокорма и биоинкапсуляция, биомедицинские и молекулярно-биологические исследования). Результаты показывают, что эффективность получения белка из артемии существенно варьируется в зависимости от условий выращивания, технологии подготовки и выбранного аналитического метода, что указывает на необходимость комплексного подхода при целевом использовании.

Ключевые слова: *артемия, экстракция белка, декапсуляция, метод Кьельдаля, метод Лоури, обогащение (enrichment), аквакультура, аминокислотный профиль.*

Abstract. The brine shrimp Artemia (Anostraca, Branchiopoda) is the primary live and dry feed source used in more than 85% of world aquaculture, and its nutritional value is determined chiefly by its high protein content (30-80% of dry matter) and balanced amino acid profile. Based on more than thirty scientific sources published between 1969 and 2023, this article systematizes the classical (Kjeldahl, Biuret) and modern (Lowry, BCA, HPLC amino acid analysis, electrophoresis, CsCl isopycnic centrifugation) methods used for extracting, quantifying, and evaluating the quality of protein from Artemia cysts, decapsulated cysts, nauplii, and adult individuals. It also analyzes the key factors affecting protein content and quality - diet composition, enrichment, salinity and temperature stress, sex and developmental stage, and geographic strain. The practical applications of the resulting protein product - feeding aquaculture and ornamental fish larvae, poultry feed, functional bio-feed and bioencapsulation, and biomedical and molecular-biology research - are reviewed. The findings show that the efficiency of protein recovery from Artemia varies considerably depending on culture conditions, processing technology, and the analytical method chosen, indicating the need for an integrated approach for targeted application.

Keywords: *Artemia, protein extraction, decapsulation, Kjeldahl method, Lowry method, enrichment, aquaculture, amino acid profile.*

Introduction

Artemia (Artemia salina, Artemia franciscana, Artemia urmiana, Artemia tunisiana, and other species), a small crustacean living naturally in salt lakes, is the most widely used live and dry feed source in aquaculture owing to its high protein content, rapid reproduction, and ease of enrichment [1, 2]. The protein content of Artemia biomass can range from 30 to 80% of dry mass, a level that makes its nutritional value higher than that of many other natural feed sources [1, 2]. Traditional protein sources for monogastric animals (poultry, fish larvae) - fish meal and meat-and-bone meal - have a number of drawbacks: high-temperature processing reduces amino acid bioavailability, there is a risk of Salmonella contamination, and the enzyme thiaminase may persist [12, 13]. For this reason, Artemia biomass, which contains no bone, feather, or gastrointestinal residues and offers high protein digestibility (>90%), is being studied as an alternative source [12, 13].

Special proteins in Artemia haemolymph - haemoglobins - serve as an important model for studying its physiological adaptation mechanisms, extending its significance beyond food applications into fundamental biochemistry and molecular biology [4]. At the same time, the rising price and limited supply of high-quality Artemia cysts on the world market make the efficient extraction of protein from the available biomass, the assessment of its quality, and its targeted use increasingly relevant issues [5].

The purpose of this review is to synthesize, on the basis of existing scientific literature, the laboratory methodology for extracting and detecting protein from Artemia, to systematize the factors affecting protein content and quality, and to outline the directions in which the resulting protein can be applied in various fields (aquaculture, poultry farming, functional feed, biomedicine).

Literature Review

More than thirty scientific sources (journal articles, conference proceedings, and technical manuals) published between 1969 and 2023, concerning Artemia salina, Artemia franciscana, Artemia urmiana, and Artemia tunisiana from various geographic regions (Tunisia, Egypt, Iran, Turkey, Mexico, the USA, Bangladesh, Russia, and others), were reviewed. The sources were analyzed by grouping them into the following thematic categories: (a) studies characterizing the biochemical composition of natural populations [6, 11, 19, 23, 26, 30, 31]; (b) studies examining the effect of developmental stage, sex, and diet on protein composition [4, 22, 28]; (c) studies examining artificial enrichment technologies [3, 14, 15, 21, 25, 29]; (d) studies examining methods for improving cyst hatching quality [20, 24]; (e) fundamental studies examining the protein-to-RNA ratio at the molecular level [27]; (f) studies evaluating the practical application of the resulting protein product in poultry farming and aquaculture [7, 9, 12, 13, 18].

Research Methodology

This article is structured as a narrative literature review: sources were grouped and qualitatively compared according to the protein extraction/detection method, the influencing factor, and the field of practical application. Owing to the methodological differences among studies (species, developmental stages, analytical methods used), a quantitative meta-analysis was not performed; instead, findings were systematically compared and analyzed.

Analysis and Results

Sample preparation and protein extraction procedures. Artemia biomass is collected from natural salt lakes (Urmia, Maharlu, Meyghan, Sfax, Wadi El Natrun, and others) using a fine net (~100 microns), after which it is cleaned of mud and other debris [6, 19, 23]. The biomass is dried in sunlight or at 45-60 degrees C and then ground into meal [12, 13]. Because the chitin-lipoprotein shell (chorion) of the cysts is indigestible, it is removed by decapsulation before use as feed or for analysis [20, 26, 30]. Two main methods are used: the hypochlorite method (NaOCl or $Ca(OCl)_2$ solution, 3-15 minutes, pH>10, temperature not exceeding 40 degrees C) provides a yield of approximately 97%, but carries a risk of residual chlorine [5, 9]; the acid method (1-5% sulfuric acid, 10-50 minutes) is a safer alternative - treatment with 1% acid for 50 minutes gives a 92.4% yield, a result close to that of the hypochlorite method [20].

After decapsulation, the sample is homogenized (using a Potter homogenizer or mortar) and usually dissolved in an alkaline solution (1N NaOH, 60-100 degrees C) or distilled water [22]. To separate total protein from other components (lipid, carbohydrate), sequential extraction is applied: the sample is first delipidated with a chloroform-methanol (2:1) mixture, then treated with 15% and 5% trichloroacetic acid (TCA), yielding a precipitated protein fraction [28]. To isolate ribosomal proteins, extraction with LiCl/urea or dialysis against acetic acid has been used, with acetic acid extraction giving a cleaner protein fraction free of RNA [27]. Decapsulated or non-decapsulated cysts are subsequently incubated in salt water (28-35 g/l) at around 28 degrees C, under approximately 2000 lux illumination and aeration for 24 hours, converting them to the Instar I nauplius stage; at this stage the proximate composition (protein, lipid, carbohydrate) differs from that of the cyst [14, 20].

Methods for quantitative determination of total protein. The reviewed literature applies several complementary methods for determining protein content. The macro-Kjeldahl method - the most widely used classical method - determines total nitrogen through mineralization and titration, then converts it to crude protein using the N*6.25 coefficient [1, 7, 22, 29]; its drawback is that it accounts for non-protein nitrogenous compounds as well, which can result in an overestimation of true protein content [7]. The Lowry method (Folin-Ciocalteu reagent) is a spectrophotometric method (550 nm) based on the reaction of copper ions with protein in an alkaline medium, and is the most frequently used method among the reviewed sources [9, 10, 14, 23, 25-28, 31]. The Biuret method is based on the reaction of copper sulfate with peptide bonds in an alkaline medium, with results calibrated against a BSA standard curve [30]. The BCA (bicinchoninic acid) method, a modification of the Lowry method, offers higher sensitivity for small-volume samples and is less susceptible to interference from ammonium ions [7].

To assess the qualitative indicator of protein, the amino acid profile is determined using HPLC (high-performance liquid chromatography, e.g., the Pico-Tag method) or ion-exchange chromatography/automated amino acid analyzers; for this, the sample is typically hydrolyzed in 6N HCl at 105-110 degrees C for 12-16 hours [1, 2, 16, 17, 22, 28]. To isolate and classify individual proteins (e.g., haemoglobins), cellulose-polyacetate or agar electrophoresis, as well as ion-exchange chromatography (DEAE-Sephadex), are used [4]. As a physicochemical control method, CsCl isopycnic centrifugation relates the buoyant density of particles to their chemical composition (protein fraction), providing an independent confirmation of colorimetric results [27]. In poultry-feed studies, the Sibbald bioassay is used to determine metabolizable energy values (AME, AMEn, TME, TMEn) [12, 13, 18], while in vitro/in vivo digestibility tests use chromic oxide (Cr_2O_3) as a marker to assess ileal amino acid digestibility [7, 22].The methods applied and the protein-content values reported across the various sources are summarized in Table 1.

Factors affecting protein content and quality. The reviewed studies show that protein content and quality in Artemia depend on a number of factors. Regarding diet type and composition, feeding on mixtures of various microalgae (Tetraselmis, Dunaliella, Nannochloris, Chlorella, Spirulina, Nannochloropsis) and diatoms (Chaetoceros calcitrans, Skeletonema costatum) significantly increases protein content [1, 2]. Regarding the enrichment process, short-term (4-24 hour) enrichment with additives such as Spirulina, canthaxanthin, fish liver oil, microalgal emulsions, and vitamin C increases not only protein but also carotenoid and polyunsaturated fatty acid (PUFA, DHA/EPA) content [3, 14, 15, 25, 29]; enrichment with probiotics (Pseudoalteromonas piscicida) and prebiotics (mannan-oligosaccharide) significantly improves protein content and the composition of essential amino acids (leucine, arginine, lysine) [21].

Table 1. Protein detection methods and results reported in the reviewed sources.

Author(s), year	Protein detection/extraction method	Protein content (% dry weight)	Main application
Garcia-Ortega et al., 1998	Kjeldahl (N x 6.25), in vitro digestibility, protease activity	50.6-56.3%	Evaluating feed quality for fish larvae
Guermazi et al., 2008	Lowry method	9.9 +/- 8.9 ug/ind	Assessing DHA/EPA and protein ratio
Ben Naceur et al., 2012	Lowry method	42.1-57.1%	Selecting geographic strains
Ben Naceur et al., 2010	Lowry method	30.3-51.2%	Assessing annual/population variability
Landau & Riehm, 1985	Biuret method	38.5-56.5%	Explaining differences among strains
Claus et al., 1979	Modified Lowry (TCA precipitation)	47.2-65.0%	Effect of diet type and starvation
Nieuwenhuysen et al., 1978	Lowry/Hartree, CsCl centrifugation	1 A260 = 42.4 ug protein	Ribosomal protein-RNA ratio
Sveshnikova et al., 2023	Kjeldahl (titrimetric)	47.9-57.8%	Probiotic/vitamin-enriched bio-feed
Rizk et al., 2018	Proximate analysis	53.5-57.8%	Improving local strain quality
Raj Kumar & Babu, 2015	Lowry method	43.8-44.4%	Determining optimal abiotic parameters
Zarei, 2010, 2013	Proximate analysis, Sibbald bioassay	40-60%	Poultry (broiler) feed
Corazza & Saylor, 1983	Kjeldahl, Sibbald (TME)	~45-55%	Fish meal substitute in broiler diets
Castro et al., 2009	Macro-Kjeldahl, HPLC (amino acids)	40-80%	Monitoring aquaculture feed quality
Herawati et al., 2014	Proximate analysis	60-80%	Enrichment with diatom feed

Environmental conditions also play an important role: oxygen deficiency, elevated CO_2 concentration, iron-EDTA, and the addition of certain amino acids/vitamins (tryptophan, cysteine, glutamate) enhance haemoglobin synthesis several-fold [4]. Under salinity stress (150-200 ppt), a

dynamic change in protein content has been observed: short-term stress (1-6 hours) reduces protein content owing to increased protease activity, whereas prolonged exposure (24 hours) enhances protein biosynthesis through small heat-shock proteins [10]; in addition, at a moderate salinity level (around 110 g/l) the amino acid ratio is most balanced [16]. Under optimal temperature (~29 degrees C), light (~2000 lux), and salinity (~29 ppt), protein content reaches its maximum, demonstrating that abiotic factors directly affect protein synthesis and metabolism [9].

Sex and developmental stage are also significant: total protein (haemoglobin) content is higher in female Artemia than in males, and the expression of certain protein types decreases with age [4]; the proximate composition also differs between decapsulated cysts and nauplii [22]. Finally, regarding geographic strain, Artemia populations from different countries and lakes show considerable variation in protein content, ranging from 30 to 65%, indicating the need to select strains suited to each climate and purpose [6, 19, 23, 26, 30, 31]; comprehensive studies on temperature-salinity tolerance allow practitioners to select strains scientifically suited to particular conditions [11].

Practical application results of the resulting protein product. The principal and most widespread application is feeding the larvae of marine and freshwater organisms (fish, Penaeus vannamei, Macrobrachium rosenbergii) [1, 2]. In Atlantic cod larvae, the apparent digestibility coefficient (ADC) of live Artemia nauplius protein is 47-58% - lower than that of microparticulate (artificial) diets (76-86%), although live-feed consumption is higher [7]; therefore, the effectiveness of Artemia as a protein source depends not only on its protein content but also on its digestibility and palatability [7]. Decapsulated cysts are used directly as a protein-rich dry feed and have 30-55% higher individual energy and weight than newly hatched nauplii, since the embryo does not expend energy breaking through the shell [5, 9, 22]; such a product is also distinguished by its small particle size, resistance to leaching in water, and long storage life [5].

In poultry farming, Artemia meal is used as a substitute for fish meal: it provides 40-60% crude protein and >90% protein digestibility [12, 13], and replacing 5% of fish meal with Artemia in broiler diets has not significantly affected growth rate or feed conversion, although differences in metabolizable energy (TME) and sodium/chlorine content should be taken into account [18]. Enriched Artemia is used as a functional (biofortified) product in ornamental fish farming to improve pigmentation, immune system function, and growth hormone expression [3, 14], and also serves as a carrier vehicle (bioencapsulation matrix) for DHA/EPA and probiotics/prebiotics [8, 15, 21]. In addition, electrophoretic separation of Artemia haemoglobins is used as a model for studying organisms' adaptation mechanisms to hypoxic conditions [4], while determination of the ribosomal protein-to-RNA ratio serves molecular biology and diapause physiology research [27]. In the future, the high protein content (in some cases 60-80%) also makes Artemia biomass a promising functional food additive for human consumption, although this direction remains insufficiently studied [2, 18].

Analysis and Results

The reviewed literature shows that several complementary approaches exist for extracting and determining protein from Artemia. The Kjeldahl method predominates for industrial and regulatory purposes owing to its speed and standardization, but because it accounts for non-protein nitrogen it may overestimate true protein content. Colorimetric methods such as Lowry and Biuret give more accurate results, though they require more time and reagents, and more sensitive modifications such as BCA are preferred for small-volume biological samples (e.g., individual haemolymph). HPLC-based amino acid analysis and electrophoresis allow evaluation not only of protein quantity but also of qualitative indicators (essential amino acid composition, individual protein types), although these methods require expensive equipment and complex sample preparation. Therefore, in practice, method selection should be guided by the research objective - quantitative control, quality assessment, or fundamental research.

The choice between the hypochlorite and acid methods at the decapsulation stage is also practically significant: the hypochlorite method achieves a higher yield but residual chlorine may pose a risk to product safety [5], whereas the acid method, though slightly less efficient, offers similar effectiveness with a safer alternative [20] - a consideration of particular importance when the protein product is intended for direct use in human or animal feed. A comparative analysis of enrichment

technologies (microalgae, oil emulsions, salinity stress, probiotics/prebiotics) shows that natural enrichment (e.g., via salinity) can provide a balanced amino acid profile without additional chemical substances [16], although the effectiveness of this method varies by strain and developmental stage [3, 14, 15, 21, 25, 29], making it difficult to propose a universal protocol.

From a practical standpoint, Artemia protein is used most extensively in feeding aquaculture larvae, secondarily in poultry farming and in the production of functional bio-feed enriched with bioactive substances, and to a limited extent in fundamental biochemical and molecular-biology research. At the same time, the substantial variability across geographic regions and species (protein content ranging from 30 to 80%) complicates direct comparison of results and highlights the need for standardized protocols. A limitation of this review is its narrative character; owing to methodological differences among studies, a quantitative meta-analysis was not conducted, and a systematic review and meta-analysis based on standardized methodology would be worthwhile in future work.

Conclusion

The literature analysis conducted shows that extracting protein from Artemia biomass generally requires an integrated four-stage approach: (1) at the culture stage, maximizing protein synthesis by maintaining optimal abiotic parameters (temperature ~25-29 degrees C, salinity 25-35 ppt, illumination ~2000 lux); (2) at the extraction/preparation stage, using live nauplii, decapsulated cysts, or lyophilized biomass depending on the purpose, and monitoring protein content using the Kjeldahl, Lowry, Biuret, or BCA methods; (3) at the quality-enhancement stage, increasing the biological value of the protein-lipid complex through enrichment with microalgae, oil emulsions, salinity stress, or probiotics/prebiotics; (4) at the application stage, selecting the most effective feed form (live, decapsulated, or enriched) taking into account the digestive characteristics of the target organism.

Future research should focus on developing inexpensive, safe, and environmentally friendly technologies for industrial-scale extraction of Artemia protein (e.g., optimizing acid decapsulation), standardizing differences across geographic regions and species, and further exploring its application potential beyond aquaculture - in poultry farming, pharmaceuticals, and the food industry (including for human consumption).

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SYNTHESIS AND STRUCTURE OF MIXED LIGAND COMPLEXES BASED ON AMIDE DERIVATIVES AND METAHYDROXOBENZOATE

Kurbanova Rakhila Saliyevna
Doctorate Student, Khorezm Mamun Academy
raxila.qurbonova.94@gmail.com

Khasanov Shodlik Bekpo'latovich
Senior researcher, Khorezm Mamun Academy, Khiva
shadlik@mail.ru

Abdullayeva Zubayda Shavkatovna
Associate Professor (PhD), Urgench RANCH University
zubayda.abdullayeva.91@mail.ru

Annotatsiya. Mazkur ishda amid hosilalari bilan ikki valentli kobalt (Co(II)) ioni asosida olingan $[Co(C_7H_5O_3)_2(L_{1,2,3})_2]$ (bu yerda L_1-nikotinamid, L_2-tiokarbamid, L_3-atsetamid) kompleks birikmalarning sintezi, ularning tuzilishi, kvant kimyoviy tahlillari va spektroskopik xossalari o'rganildi. Dastlabki ligand sifatida m-gidroksobenzoy kislota (mgb) ishlatilingan. Kompleks birikmalarning kvant-kimyoviy hisob-kitoblari tahlili qilindi, IQ spektrlari taqqoslanib ligandlarning funksional guruhlaridagi tebranish chastotalarida o'zgarishlar qayd etildi.

Kalit so'zlar: *amid hosilalari, Co(II) sulfat, m-gidroksobenzoy kislota, kompleks birikma, kvant kimyoviy hisoblar, IQ spektroskopik tavsif.*

Аннотация. В данной работе изучены синтез комплексных соединений $[Co(C_7H_5O_3)_2(L_{1,2,3})_2]$ (где L_1-никотинамид, L_2-тиокарбамид, L_3-ацетамид), полученных на основе двухвалентного иона кобальта (Co(II)) с амидными производными, их структура, квантово-химический анализ и спектроскопические свойства. В качестве исходного лиганда использована м-гидроксобензойная кислота (мгб). Проанализированы квантово-химические расчеты комплексных соединений, сопоставлены ИК-спектры и зафиксированы изменения частот колебаний функциональных групп лигандов.

Ключевые слова: *производные амида, сульфат Co(II), м-гидроксобензойная кислота, комплексное соединение, квантово-химические расчеты, ИК-спектроскопическая характеристика.*

Abstract. In this work, the synthesis, structure, quantum chemical analysis, and spectroscopic properties of complex compounds $[Co(C_7H_5O_3)_2(L_{1,2,3})_2]$ (where L_1-nicotinamide, L_2-thiocarbamide, L_3-acetamide) obtained on the basis of the divalent cobalt (Co(II)) ion with amide derivatives were studied. M-hydroxobenzoic acid (mgb) was used as the initial ligand. Quantum-chemical calculations of the complex compounds were analyzed, IR spectra were

compared, and changes in the vibration frequencies of the ligands' functional groups were recorded.

Keywords: *amide derivatives, Co(II) sulfate, m-hydroxobenzoic acid, complex compound, quantum chemical calculations, IR spectroscopic.*

Introduction

Today, cobalt (II) complexes are widely used as biologically active compounds, including in the modeling of active enzyme centers, in antibacterial drugs, and as chemical catalysts. These possibilities are directly related to their structural composition and the nature of the coordination bonds between the central ion and the ligand. Therefore, the synthesis of complex compounds of cobalt ions based on new ligands and their in-depth analysis is one of the important scientific tasks. Amides are ligands coordinated with oxygen and nitrogen atoms, capable of forming stable complexes with various metal ions due to their molecular structure, functional groups, and electron distribution. Amide derivatives such as nicotinamide, thiocarbamide, and acetamide are structurally distinct but widely used compounds as potential ligands. Each of them can form a different type of coordination medium with cobalt ions. In this study, the synthesis of complex compounds formed on the basis of nicotinamide, thiocarbamide, and acetamide with Co(II) ions, their spectroscopic characteristics, quantum chemical calculations, coordination properties, and comparison with ligands were studied. The complexes were synthesized in an aqueous medium, and changes in their structure were analyzed using IR (infrared) spectroscopy.

Literature Review

Cobalt (II) ions are one of the most widely studied metal ions in coordination chemistry due to their unique biological activity, participation in catalytic processes, and important physicochemical properties. In addition to participating in certain biological processes in living organisms, cobalt ions also act as effective catalysts in various chemical reactions [1]. It has been established that new complex compounds of Co(II), Ni(II), Cu(II), and Zn with 5-(3-hydroxyphenyl)-1,3,4-oxadiazolin-2-thione have been synthesized, and their structure has been studied using modern physicochemical research methods. IR and PMR spectroscopic analysis methods were used to determine the structure of the obtained complexes. The research results showed that this ligand exhibits polydentate properties with metal ions, forming a coordination bond through nitrogen and sulfur donor atoms within its composition. The spatial structure of the complexes is characterized by a tetrahedral configuration, and mixed-ligand molecular-ionic complex compounds are formed [2]. Amide derivatives are functional ligands that contain an amide group (-CONH2) and can bind to the metal center via carbonyl oxygen or amine nitrogen [3]. In the next study, mixed-ligand complexes with Cr(III), Co(II), Ni(II), and Cu(II) ions were synthesized in the presence of a Schiff base and 2-nitroaniline obtained by the condensation of 4-dimethylaminobenzaldehyde and 2-aminophenol, and the electronic spectral properties of mixed-ligand chelate complexes were studied in DMF solution. Spectral analyses have identified the molecular ionic peaks of the complexes and the characteristic fragment ions formed during their decomposition. These results confirm the composition and structure of the synthesized complex compounds, demonstrating

the ability of Schiff bases and nitrogen-containing organic ligands to form stable coordination compounds with transition metals [4]. In many studies, complexes of simple ligands such as nicotinamide (pyridine-ring amide), thiocarbamide (S-acetyl amide), and acetamide with various metals, including Co(II), have been analyzed. The nicotinamide molecule is a bifunctional ligand capable of coordination via pyridine nitrogen and amide oxygen. This significantly affects the structure of the resulting complexes [5]. Thiocarbamide, on the other hand, is considered a soft ligand as a ligand, meaning it is usually strongly bonded to soft metals (e.g., Co(II), Cu(I)) via a sulfur (S) atom. Its complexation with Co(II) depends on various conditions, causing significant changes in the coordination number, geometry, and spectroscopic properties [6]. Although acetamide has a simple structure, it is recognized as an interesting ligand in coordination chemistry. It is weakly bonded to Co(II) only by a carbonyl group. Nevertheless, clear shifts in the physicochemical properties of the obtained Co(II) complexes in the presence of acetamide are also observed [7]. In spectroscopic analysis methods-especially infrared (IR), ultraviolet-visible (UV-Vis), and magnetic sensitivity methods-are widely used to study the structure of Co(II) complexes. In the IR spectrum, the coordination state of the ligand is determined by the shift of ν (C=O) and ν (N–H) oscillations characteristic of the amide group. In the UV–Vis spectra, d–d transitions characteristic of Co(II) ions are observed, based on which the geometric structure of the complex (e.g., octahedral or tetrahedral) is determined [8]. The biological activity of Co(II) complexes has also been studied in the literature. It has been shown that complexes based on nicotinamide and thiocarbamide possess antibacterial [9], antifungal, and cytotoxic activity [10], which provides grounds for their application in the pharmaceutical industry.

Research Methodology

In this study, m-hydroxobenzoic acid was additionally synthesized with Co(II) and L_1, L_2, and L_3 ligands. Initially, 0.1 g of m-hydroxobenzoic acid was mixed in 50 ml of distilled water and gradually heated. After the acid was completely dissolved, 5 ml of 0.1 n KOH solution was added to the solution to create an alkaline medium. Then 0.8 g of $CoSO_4 \cdot 7H_2O$ was dissolved in 10 ml of distilled water and added to the solution. 20 ml of the prepared solution was poured into 3 equal glasses.

$$2C_7H_6O_3 + 2KOH + CoSO_4 \cdot 7H_2O \rightarrow [Co(C_7H_5O_3)_2] + K_2SO_4 + 8H_2O$$

Nicotinamide (L_1) and Co(mgb) complex: 0.24 g of nicotinamide was slowly added to 1 cup of Co(mgb) solution after complete dissolution in 5 ml of distilled water. During the experiment, it was observed that the solution turned dark pink, indicating that Co(II) ions had formed a complex.

Thiocarbamide (L_2) and Co(mgb) complex: 0.15 g of thiocarbamide was completely dissolved in 5 ml of distilled water and slowly added to 2 cups of Co(mgb) solution. During the experiment, it was observed that with the addition of thiocarbamide, the solution turned purple, meaning it participated in the formation of the complex structure as a secondary ligand.

Acetamide (L_3) and Co(mgb) complex: 0.22 g of acetamide was completely dissolved in 5 ml of distilled water and slowly added to 3 cups of Co(mgb) solution. During the experiment, it was observed that the solution had taken on a light pink color.

The resulting complexes were left at room temperature for 10 days, and crystal growth was observed.

Analysis and Results

Quantum-chemical calculation methods allow for the prediction of competitive donor centers for multifunctional ligands undergoing coordination. Here, the reactivity of molecules in the synthesized $[Co(C_7H_5O_3)_2(L_{1,2,3})_2]$ complexes was quantum-chemically analyzed using the semi-empirical method of the HyperChem 8.07 program, and the energy, geometric, and electronic properties of the molecules were calculated. The values of bond angles and bond lengths in the ligands were also determined. These calculations were performed using the semi-empirical/AM1/UHF method (Figure 1).

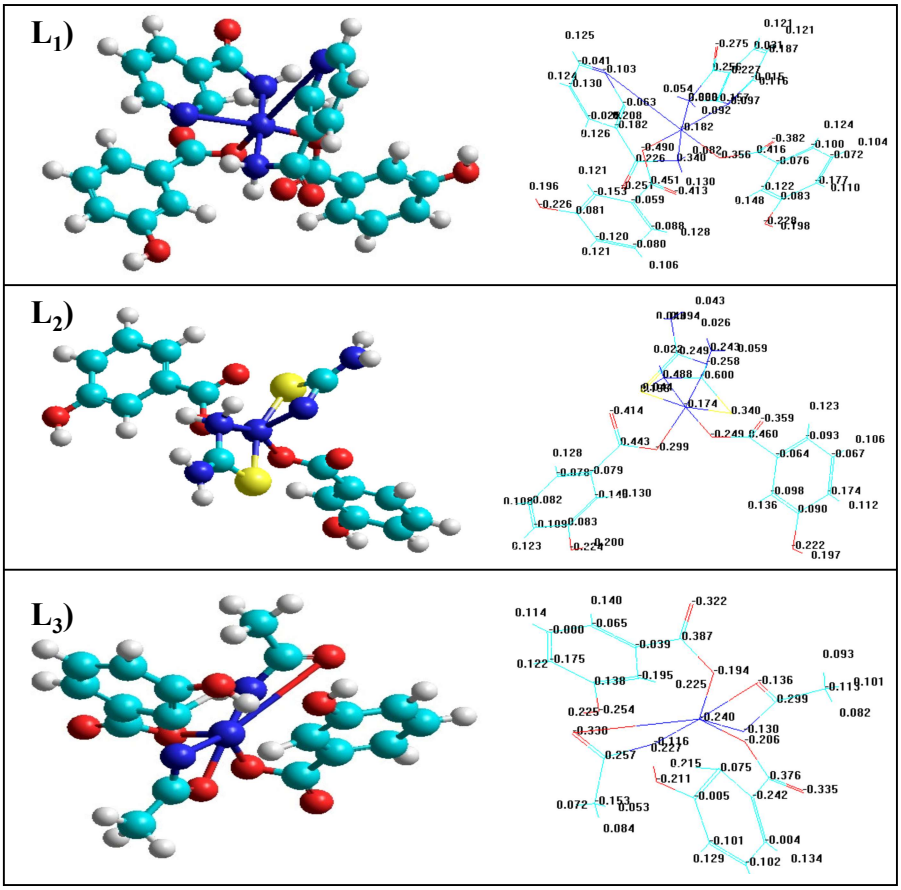

Figure 1. Distribution of effective charges in complex molecules using the Semiempirical/AM1/UHF method.

As a result of the calculations, the minimum energy of ligand formation in the complexes was determined. The low formation energy of ligand molecules indicates their high stability (Table 1).

Table 1. Energy of ligand molecules indicates their high stability

Complex name	Semi-empirical/AM1/UHF			
	E (Hartree)	Co	N	O
$[Co(C_7H_5O_3)_2(L_1)_2]$	-7174,4	-0,182	-0.103	-0,382
$[Co(C_7H_5O_3)_2(L_2)_2]$	-5096,9	-0,174	-0,258	-0.359
$[Co(C_7H_5O_3)_2(L_3)_2]$	-5232,2	-0.240	-0,130	-0,338

To determine changes in functional groups, coordination types, and the formation of new bonds in ligands, a comparative analysis of the IR spectra of the starting materials and the resulting complex compound was conducted.

The IR spectra of the samples were recorded in the IRTracer-100 (SHIMADZU CORP., Japan, 2017) spectrum using the MIRacle-10 diamond/ZnSe prism in the 400-4000 cm^{-1} region.

The theoretically calculated spectrum of the synthesized complex compound (Fig. 2) was compared with the experimentally obtained IR spectrum (Fig. 3). During the comparison process, the absorption frequencies of the main functional groups, their shift, and their intensity were analyzed. In the practical IR spectrum, the strong absorption peaks observed in the range of 1620–1645 cm^{-1} and 1350–1450 cm^{-1} belong to asymmetric (νas) and symmetric (νs) oscillations of the –COO- group, respectively. These peaks are also observed in almost the same regions of the theoretical spectrum, confirming the presence of oxalate and acetate ligands in the complex. The average intensity absorption observed in the range of 1000–1300 cm^{-1} corresponds to the vibrations of C–O and C–C bonds. These signals in the practical spectrum have good compatibility with the theoretical spectrum, indicating the preservation of the ligand skeleton. The absorption peaks appearing in the low-frequency region of the practical IR spectrum at 400–600 cm^{-1} belong to the vibrations of Co–O bonds, and corresponding signals are also observed in this region in the theoretical spectrum. This clearly confirms that the Co(II) ion is bonded to ligands through oxygen atoms. The observation of wide absorption in the range of 3200–3500 cm^{-1} in the practical spectrum indicates the presence of hydrogen bonds.

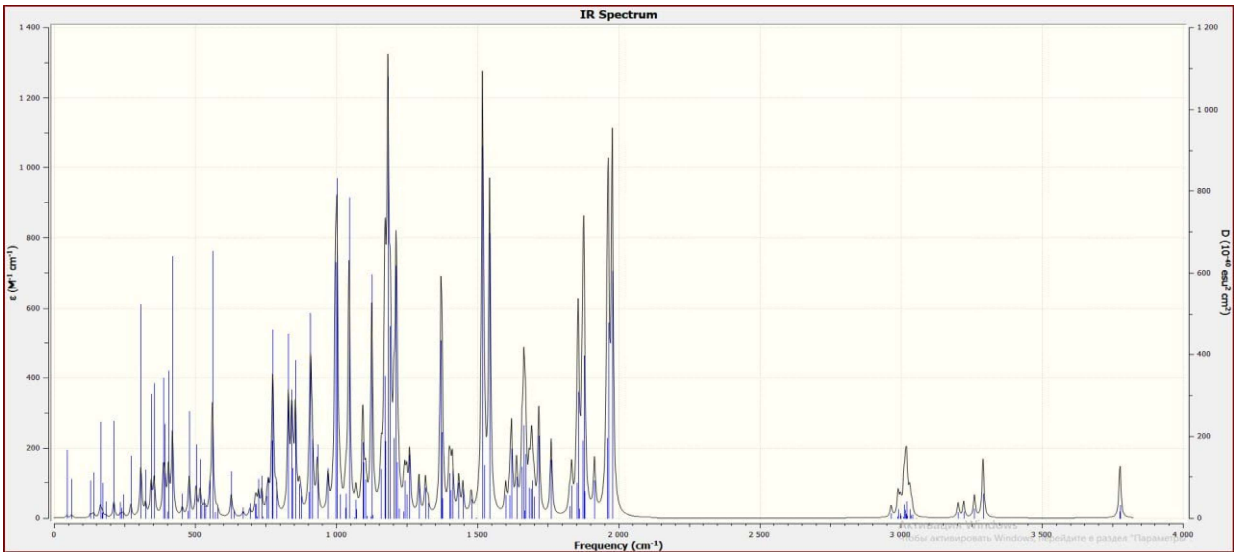

Figure 2. Quantum-chemically theoretically calculated IR spectrum of the complex compound $[Co(C_7H_5O_3)_2(C_6H_6N_2O)_2]$

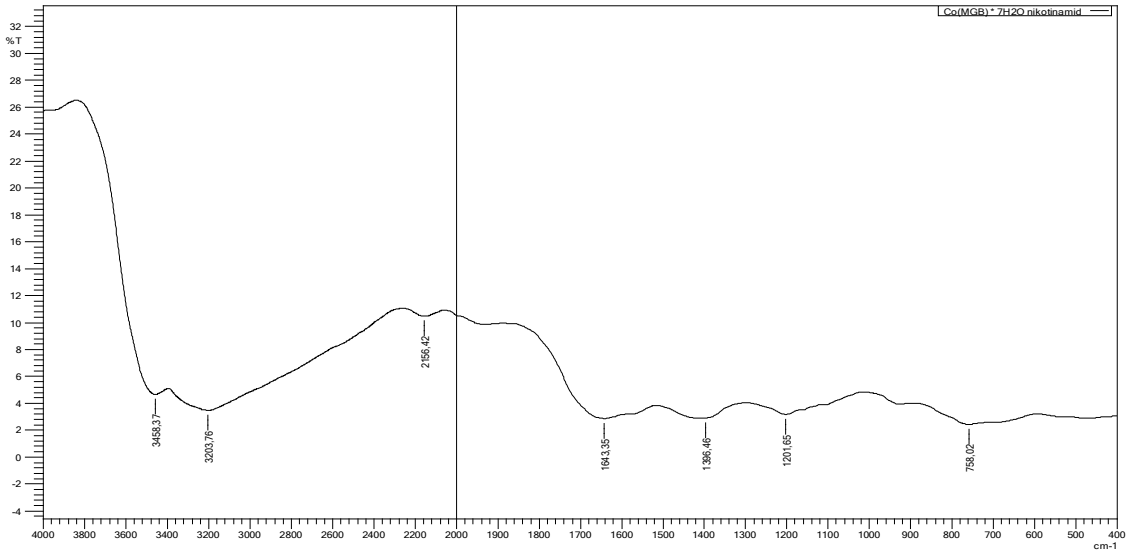

Figure 3. IR spectrum of the complex compound $[Co(C_7H_5O_3)_2(C_6H_6N_2O)_2]$.

In the theoretical spectrum, this peak is observed with relatively low intensity or not at all, which is explained by the fact that environmental factors and hydrogen bonds were not fully taken into account in the calculations. The small shifts (10–40 cm^{-1}) between theoretical and practical IR spectra are explained by the following factors: experimental conditions (solid phase, crystal lattice effect), hydrogen bonds, the actual coordination environment of the ligands, and the adoption of ideal conditions in the calculation method. In the IR spectra of the synthesized complexes, significant shifts in the vibration frequencies of the functional groups and ph values were detected (Table 2).

Table 2. IR spectra of the synthesized complexes, significant shifts in the vibration frequencies of the functional groups and ph values.

Complex name	Principal vibrations (ligand) complex displacements		Control of the complex (stability pH = 6–7)	Complex color	Productivity
$[Co(C_7H_5O_3)_2(L_1)_2]$	ν(C=O) ≈ 1620-1645 sm^{-1}, ν(N–H)	ν(O–H), ≈ 3200-3500 sm^{-1}	Upper	Dark Pink	85–90%
$[Co(C_7H_5O_3)_2(L_2)_2]$	ν(C=S) ≈ 1590-1610 sm^{-1}, ν(N–H)	ν(O–H), ≈ 3200 sm^{-1}	Medium	Purple-soft	80–85%
$[Co(C_7H_5O_3)_2(L_3)_2]$	ν(C=O) ≈ 1615-1635 sm^{-1} ν(N–H)	ν(O–H), ≈ 3180-3220 sm^{-1}	Low	Light Pink	75–80%

Conclusion

According to the research results, it was established that amide derivatives successfully form complexes with Co(II) ions, and these complexes have an octahedral structure. According to the results of the analysis, nicotinamide is the strongest ligand, and the stability of the cobalt (II) complexes formed by it is high, the coordination field is strong, and spectroscopic changes are revealed. Thiocarbamide is a soft ligand that

forms good complexes with cobalt (II), but its stability is lower than that of nicotinamide. Acetamide is a simple ligand the complexes formed with it are weakly stable, and coordination occurs only through the carbonyl group. The results of the minimum energies in the molecules of the complexes were compared using the Semiempirical/AM1/UHF method. Such complexes can be used in the future as catalysts, biologically active substances, or in materials science.

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Section 5. ACTUAL PROBLEMS OF MATHEMATICS, PHYSICS AND MECHANICS

UDC: 621.383

OPTICAL AND ELECTRICAL ANALYSIS OF CIGS SOLAR CELLS ENHANCED WITH METALLIC NANORODS

Khaitbaev Eldorbek Shakir Ugli
Doctorate Student, Urgench State University named after Abu Rayhan Biruni
eldorkhaitbaev@urdu.uz

Qodirberganova Oltinoy Arislonbek Kizi
Student, Urgench State Pedagogical Institute
oltinoyqodirberganova04@gmail.com

Annotatsiya. Ushbu tadqiqot ishida biz quyosh elementi sirtida integratsiyalashgan metall nanosterjenlar (nanozarrachalar) bilan boyitilgan yupqa plyonkali CIGS quyosh elementlarining ikki o‘lchovli raqamli tahlilini taqdim etamiz. ANSYS Lumerical’ning FDTD va CHARGE hisoblash dasturlaridan foydalanib, biz mis (Cu), oltin (Au) va kumush (Ag) nanosterjenlari bo‘lgan quyosh elementlarining optik va elektr xususiyatlarini nasterjen kiritilmagan oddiy quyosh elementiga nisbatan taqqosladik. Qurilma tuzilishi Al kontaktlaridan (katod), ZnO shaffof o‘tkazuvchan oksid qatlamidan, CdS bufer qatlamidan, CIGS asosiy yutuvchi qatlamidan va Al orqa kontaktidan (anoddan) iborat. Simulyatsiyalar nanosterjenlardan plazmonik yorug‘likning tarqalishi optik yutilish va zaryad yig‘ilishini sezilarli darajada oshirishini ko‘rsatadi. Xususan, Cu ya’ni, mis nanosterjenlari boshqa barcha dizaynlardan ustun bo‘lib, 7,2 mA/sm² va 7,4% bazaviy qiymatlarga nisbatan 17,4 mA/sm² qisqa tutashuv tok zichligi va 17,8% quvvatni konvertatsiya qilish samaradorligini berdi. Natijada, sirtga integratsiyalashgan plazmonik nanostrukturalar yupqa plyonkali quyosh energiyasini konvertatsiya qilishni rivojlantirish uchun kuchli salohiyatga egaligini ko‘rsatdi.

Kalit so‘zlar: *CIGS quyosh elementlari, metall nanosterjenlar, plazmonik effekt, quvvatni konvertatsiya qilish samaradorligi, volt-amper xususiyatlari (VAX), PV xususiyatlari (quvvat-kuchlanish), simulyatsiya, mis (Cu), oltin (Au), alyuminiy (Al).*

Аннотация. В данном исследовании представлен двумерный численный анализ тонкопленочных солнечных элементов CIGS, улучшенных за счет интеграции металлических наностержней в поверхность. Используя решатели FDTD и CHARGE из ANSYS Lumerical, мы оценили оптические и электрические характеристики элементов с наностержнями из меди (Cu), золота (Au) и серебра (Ag) относительно неструктурированного базового образца. Структура устройства включает в себя эмиттер из алюминия (катод), прозрачный проводящий оксидный слой ZnO, буферный слой CdS, поглощающий слой CIGS и задний контакт из алюминия (анод). Моделирование показывает, что плазмонное рассеяние света от

наностержней значительно усиливает оптическое поглощение и сбор заряда. В частности, наностержни из меди превзошли все остальные конструкции, обеспечив плотность тока короткого замыкания 17,4 мА/см² и эффективность преобразования энергии 17,8% по сравнению с базовыми значениями 7,2 мА/см² и 7,4%. Следовательно, интегрированные в поверхность плазмонные наноструктуры демонстрируют большой потенциал для развития тонкопленочного преобразования солнечной энергии.

Ключевые слова: *Солнечные элементы CIGS, металлические наностержни, плазмонный эффект, эффективность преобразования энергии, вольт-амперные характеристики (VAX), фотоэлектрические характеристики (мощность-напряжение), моделирование, медь (Cu), золото (Au), алюминий (Al).*

Abstract. In this study, we present a two-dimensional numerical analysis of thin-film CIGS solar cells enhanced with surface-integrated metallic nanorods. Employing ANSYS Lumerical's FDTD and CHARGE solvers, we evaluated the optical and electrical characteristics of cells with copper (Cu), gold (Au), and silver (Ag) nanorods relative to an un-patterned baseline. The device structure comprises an Al emitter (cathode), a ZnO transparent conducting oxide layer, a CdS buffer layer, a CIGS absorber layer, and an Al back contact (anode). The simulations demonstrate that plasmonic light scattering from the nanorods significantly enhances optical absorption and charge collection. Specifically, Cu nanorods outperformed all other designs, yielding a short-circuit current density of 17.4 mA/cm² and a power conversion efficiency of 17.8%, compared to baseline values of 7.2 mA/cm² and 7.4%. Consequently, surface-integrated plasmonic nanostructures demonstrate strong potential for advancing thin-film solar energy conversion.

Keywords: *CIGS solar cells, metallic nanorods, plasmonic effect, power conversion efficiency, IV characteristics, PV characteristics, simulation, copper (Cu), gold (Au), aluminum (Al).*

Introduction

This study investigates the use of surface modification to enhance the current-voltage (I-V) characteristics and overall efficiency of CIGS solar cells. Specifically, we evaluate the comparative effectiveness of silver (Ag), gold (Au), and copper (Cu) nanorods for performance optimization.

Copper indium gallium selenide (CIGS) is a highly promising thin-film solar cell material characterized by superior physical and electronic properties [1]. Its direct bandgap and high absorption coefficient allow a 1 μm-thick absorber layer—nearly 100 times thinner than traditional crystalline silicon (c-Si)—to capture ~99% of incident solar radiation, significantly reducing material consumption [1,2]. Adjusting the gallium-to-indium ratio tunes the bandgap from 1.0 eV to 1.7 eV [3,4], providing tailored illumination response and tandem architecture integration that rigid c-Si or fixed-bandgap CdS cannot match [4].

Beyond baseline efficiency, CIGS excels in real-world operating conditions. It maintains strong low-irradiance performance, high thermal stability (temperature coefficient of -0.36%/°C vs. -0.3 to -0.5%/°C for c-Si) [5], and exceptional radiation tolerance for space applications [6]. Deposition on flexible plastic or metal substrates enables lightweight, curved, and portable photovoltaics—such as building-integrated photovoltaics (BIPV), solar vehicles, and smart textiles—with bifacial designs further boosting energy yield [7]. Environmentally, CIGS features a low carbon footprint (12–20 g CO_2/kWh, matching wind energy and well below c-Si's ~40 g CO_2/kWh), low material waste, and cost-competitive production relative to CdS [7].

In this work, we investigate the effect of plasmonic metallic nanorods on the performance of CIGS thin-film solar cells through a comparative numerical study. Using two-dimensional simulations, we evaluate the influence of nanorods composed of silver (Ag), gold (Au), and copper (Cu) on light absorption, photocurrent generation, and overall device efficiency. A baseline CIGS structure without nanorods is simulated and compared with three enhanced configurations incorporating nanorods made of different materials [8]. The optical and electrical analyses are performed using the FDTD and CHARGE solvers in ANSYS Lumerical [9, 10]. The primary objective is to identify the most effective nanorod material for enhancing photovoltaic performance and to provide insights into the design of high-efficiency CIGS solar cells integrated with plasmonic nanostructures.

Research Methodology

The optical and electrical behavior of the CIGS solar cells was simulated using two-dimensional models developed in ANSYS Lumerical with the FDTD and CHARGE solvers. The device consists of a vertically stacked thin-film structure with a total surface area of 1 μm × 1 μm, comprising the following layers, arranged from bottom to top [8]:

1. Aluminum (Al) back contact – 500 nm
2. CIGS absorber layer – 1000 nm, p-type doping concentration of 1×10^{16} cm^{-3}, with a bandgap of 1.351 eV
3. CdS buffer layer – 100 nm, n-type doping concentration of 1×10^{18} cm^{-3}
4. ZnO transparent conductive oxide (TCO) – 100 nm, n-type doping concentration of 1×10^{20} cm^{-3}.

An Al emitter contact with dimensions of 100 nm × 100 nm × 1000 nm was placed along one edge of the ZnO layer, leaving most of the surface exposed to illumination. The incident light was modeled as a broadband plane wave directed onto the exposed ZnO surface while avoiding the shadowed region beneath the Al emitter.

To investigate the effects of plasmonic nanostructures, nine metallic nanorods, each measuring 50 nm × 50 nm × 1000 nm, were periodically arranged on the ZnO surface with a center-to-center spacing of 50 nm. Simulations were performed for four configurations:

1. Bare reference cell: without nanorods;
2. Ag-nanorod cell: incorporating Ag nanorods;
3. Au-nanorod cell: incorporating Au nanorods; and
4. Cu-nanorod cell: incorporating Cu nanorods.

Optical simulations were carried out using the FDTD solver, where field distributions and wavelength-dependent absorption were calculated. The vertical (Z) axis used perfectly matched layer (PML) boundaries, and the lateral (X) axis used periodic boundary conditions (PBC) [11]. The results were transferred to the CHARGE solver for electrical simulation.

In the CHARGE solver:

- The DC permittivity for the CIGS layer was set to 11.5.
- The work function was specified as 4.7 eV.
- The effective mass for electrons and holes in CIGS was set to $0.09m_e$ and $0.72m_e$ respectively.
- Recombination processes were modeled using a combination of trap-assisted (Shockley-Read-Hall), Auger, and radiative mechanisms [11].

Electrical boundary conditions were defined by biasing the Al back contact at +2 V, while the Al emitter (front contact) was maintained at ground potential (0 V). This configuration enabled the extraction of current–voltage (I–V) characteristics under simulated standard AM1.5 illumination.

The simulations were performed under standard one-sun illumination using the AM1.5 solar spectrum over a wavelength range of 0.28 μm to 0.83 μm. This spectral range was selected to correspond to the absorption characteristics of the CIGS absorber and to ensure appropriate excitation of plasmonic effects across the visible to near-infrared region [12].

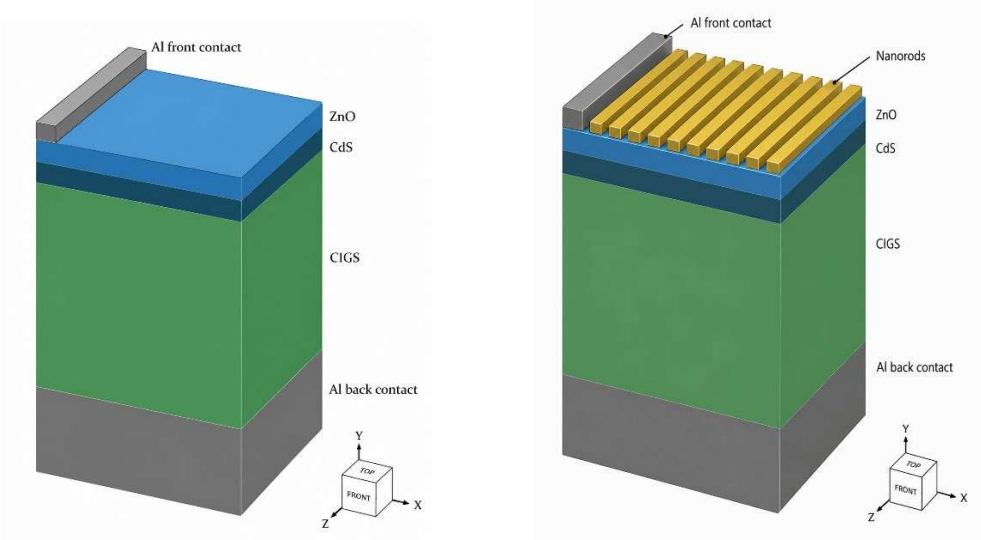

Figure 1. Schematic of the simulated CIGS solar cell: the structure without nanorods is shown on the left, while the enhanced design with surface-integrated metallic nanorods is shown on the right.

Analysis and Results

Spectral Absorption Analysis. Figure 2 presents the wavelength-dependent absorption spectra of the four simulated CIGS solar cell structures under AM1.5 illumination over the 0.28–0.83 μm wavelength range. The incorporation of metallic nanorods resulted in noticeable changes in the absorption behavior compared with that of the bare device.

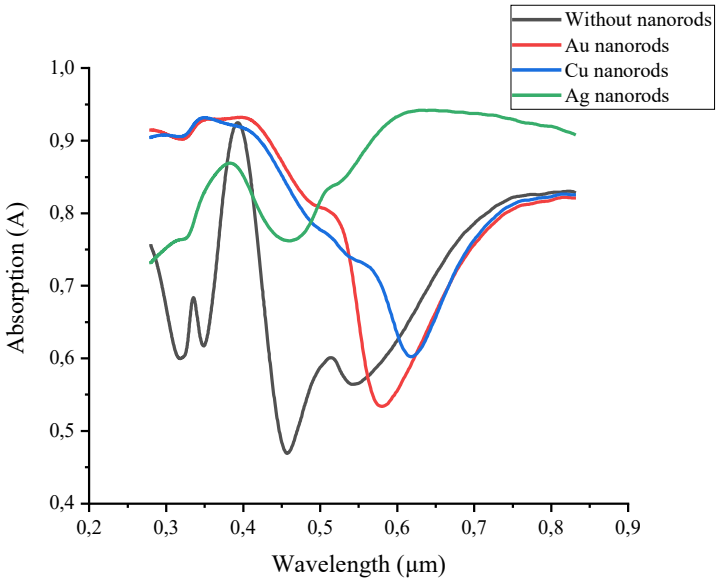

Figure 2. Wavelength-dependent absorption spectra of CIGS solar cells with and without metallic nanorods. The incorporation of metallic nanorods modifies the absorption profile across the investigated wavelength range, with Cu nanorods providing enhanced and relatively balanced absorption over a broad spectral region.

The reference cell exhibited relatively stable absorption across a broad portion of the investigated spectrum, particularly in the near-infrared region above 0.65 μm. However, its absorption in the shorter-wavelength range of 0.3–0.55 μm showed noticeable variations and dips. Cells with metallic nanorods showed enhanced and more structured absorption profiles due to plasmonic scattering and near-field localization effects: The Cu nanorods provided a relatively balanced absorption response across the investigated spectrum, with enhanced absorption particularly evident in the 0.45–0.75 μm range.

- Ag nanorods exhibited pronounced spectral features in the visible range, including distinct absorption peaks and variations between approximately 0.4 and 0.6 μm.
- Au nanorods exhibited relatively high absorption in the 0.35–0.5 μm range, followed by a noticeable decrease near 0.6 μm and reduced absorption at longer wavelengths compared with Cu.

Overall, the absorption spectra indicate that the incorporation of metallic nanorods modifies and enhances light absorption over different spectral regions, with Cu nanorods providing a relatively balanced response across a broad wavelength range. This behavior is consistent with the enhanced photocurrent generation observed in the electrical characteristics.

Current–Voltage Characteristics. Figure 3 (a) displays the current–voltage (IV) characteristics of the CIGS solar cells with and without metallic nanorods. The reference device (green curve) shows a short-circuit current density (J_{SC}) of 7.2 mA/cm². Introducing nanorods significantly boosts current density: Cu nanorods (blue) achieve the highest J_{SC}, reaching approximately 17.4 mA/cm², demonstrating over a 2x improvement.

- Au nanorods (red) follow with ~16.5 mA/cm²,

- Ag nanorods (black) reach ~12.1 mA/cm².

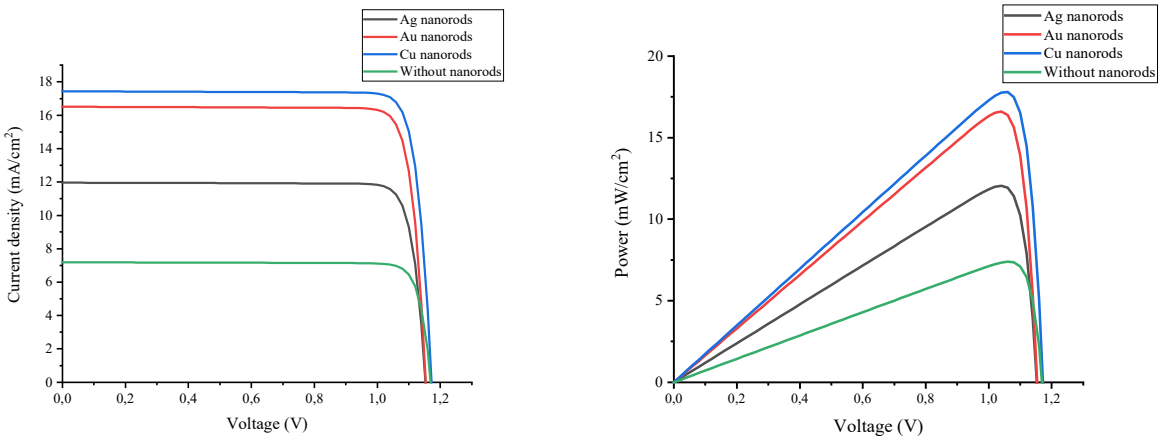

Figure 3. *Simulated electrical performance of CIGS solar cells under AM1.5 illumination: (a) Current–voltage (IV) characteristics and (b) Power–voltage (PV) curves.*

All nanorod-enhanced configurations exhibit similar open-circuit voltage (VOC) values of approximately 1.18 V. The Cu-nanorod configuration exhibits the highest current density and a pronounced improvement in the I–V characteristics, indicating enhanced electrical performance compared with the reference device.

Power–Voltage Performance. Figure 3(b) illustrates the power–voltage (P–V) characteristics of the simulated CIGS solar cells. The incorporation of metallic nanorods substantially increases the maximum output power compared with the bare device. The Cu-nanorod configuration exhibits the highest peak power density of approximately 17.8 mW/cm², followed by the Au- and Ag-nanorod configurations with approximately 16.6 mW/cm² and 12.1 mW/cm², respectively. The bare cell exhibits a maximum power density of approximately 7.4 mW/cm². These results demonstrate that the Cu-nanorod configuration provides the highest power output among the investigated structures.

The Cu-enhanced device exhibits the highest power output and a pronounced improvement in the P–V characteristics, further supporting its superior overall photovoltaic performance.

Power Conversion Efficiency. In addition to the current and power characteristics, the simulated power conversion efficiency (PCE) values further confirm the performance enhancement achieved through the incorporation of metallic nanorods:

Table 1. *Summary of simulated photovoltaic performance parameters for CIGS solar cells with and without metallic nanorods. Cu nanorods yield the highest short-circuit current density and power conversion efficiency.*

Cu	17.8%
Au	16.6%
Ag	12.1%
Bare	7.4%

These results indicate that Cu is the most effective plasmonic material among the three investigated materials, providing both broad-spectrum light absorption and

efficient charge transport. The observed improvement in PCE is consistent with the absorption spectra and current-generation trends presented in Figure 2 and Figure 3.

Conclusion

This study demonstrated the effectiveness of metallic nanorods in enhancing the optical and electrical performance of CIGS solar cells through two-dimensional numerical simulations. Among the investigated materials, copper (Cu) nanorods exhibited the highest performance, increasing the power conversion efficiency from 7.4% for the bare cell to 17.8%. This improvement is attributed to enhanced light absorption and plasmonic scattering effects. These findings highlight the potential of Cu nanostructures for the development of high-efficiency thin-film photovoltaic devices.

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UDC: 621, 382.3

DEPENDENCE OF SELF-HEATING AND SHORT-CHANNEL EFFECTS ON OXIDE MATERIALS IN A 2D MoS_2 CHANNEL-BASED MOSFET

Saparov Khushnudbek Sharipbayevich
Associate Professor (PhD), Department of Physics, Urgench State University named after Abu Rayhan Biruni
xushnudbeksaparov@gmail.com

Allaberganova Barnoxon Ulugbekovna
Physics Teacher, Academic Lyceum of Urgench State Medical Institute

Annotatsiya. Ushbu ishda sonli modellashtirish usuli yordamida ikki o‘lchamli MoS_2 yarimo‘tkazgichi asosidagi metall–oksid–yarimo‘tkazgich (MOYa) tranzistorlarning issiqlik va elektr xarakteristikalariga zatvor osti hamda kanal osti oksidi materiallarining ta’siri kompleks ravishda o‘rganildi. Tadqiqotda asosiy e’tibor o‘z-o‘zidan qizish effekti (Self-Heating Effect, SHE), bo‘sag‘adan past sohadagi qiyalik (Subthreshold Slope, SS) hamda stok tomonidan induksiyalangan potensial to‘siqning pasayishi (Drain-Induced Barrier Lowering, DIBL) tahliliga qaratildi. Zatvor osti dielektrigi sifatida Al_2O_3 va HfO_2, kanal osti oksidi (Buried Oxide, BOX) sifatida esa SiO_2 va HfO_2 materiallari ko‘rib chiqildi. Turli zatvor osti va kanal osti oksidi materiallari hamda ularning kombinatsiyalari uchun bo‘sag‘adan past sohadagi qiyalik va kanal markazidagi kristall panjara haroratining zatvor uzunligiga bog‘liqligi tadqiq etildi. Tahlilda kanal qismi to‘liq zatvor osti dielektrigi bilan qoplangan tranzistor strukturasi qaraldi. Modellashtirish natijalari Al_2O_3 zatvor osti dielektrigi va SiO_2 kanal osti oksidi kombinatsiyasi bo‘sag‘adan past sohadagi qiyalikning eng kichik qiymatini ta’minlashini, bu esa kanalning elektrostatik boshqaruvi samaradorligi yuqori ekanligini ko‘rsatishini aniqladi. Shu bilan birga, HfO_2 materialidan ham zatvor osti dielektrigi, ham kanal osti oksidi sifatida foydalanish issiqlikni samaraliroq tarqatish hisobiga o‘z-o‘zidan qizish effektini sezilarli darajada kamaytirib, tranzistorning issiqlik barqarorligi va ishonchliligini oshirishi ko‘rsatildi. Olingan natijalar ikki o‘lchamli materiallar asosidagi yangi avlod yuqori unumdor, kam quvvat sarflovchi va yuqori issiqlik barqarorligiga ega MOYa tranzistorlarini loyihalash hamda optimallashtirishda amaliy ahamiyat kasb etadi.

Kalit so‘zlar: *2D MoS_2, o‘z-o‘zidan qizish effekti, bo‘sag‘adan past sohadagi qiyaligi, MOYa tranzistor, panjara harorati.*

Аннотация. В данной работе методом численного моделирования выполнено комплексное исследование влияния материалов подзатворного и подканального оксидов на тепловые и электрические характеристики металл–оксид–полупроводниковых (МОП) транзисторов на основе двумерного полупроводника MoS_2. Особое внимание уделено анализу эффекта самонагрева (Self-Heating Effect, SHE), подпороговой крутизны (Subthreshold Slope, SS) и снижения потенциального барьера,

индуцированного стоком (Drain-Induced Barrier Lowering, DIBL). В качестве материалов подзатворного диэлектрика рассмотрены Al_2O_3 и HfO_2, тогда как в качестве подканального оксида (Buried Oxide, BOX) использованы SiO_2 и HfO_2. Исследованы зависимости подпороговой крутизны и температуры кристаллической решётки в центральной области канала от длины затвора для различных комбинаций материалов подзатворного и подканального оксидов. Рассматривалась структура транзистора с каналом, полностью перекрытым подзатворным диэлектриком. Результаты моделирования показывают, что использование Al_2O_3 в качестве подзатворного диэлектрика в сочетании с SiO_2 в качестве BOX обеспечивает минимальные значения подпороговой крутизны, что свидетельствует об эффективном управлении каналом. В то же время применение HfO_2 одновременно в качестве подзатворного и подканального диэлектриков существенно снижает влияние эффекта самонагрева за счёт улучшенного теплоотвода, обеспечивая более высокую тепловую стабильность транзистора. Полученные результаты могут быть использованы при проектировании высокопроизводительных и энергоэффективных МОП-транзисторов нового поколения на основе двумерных материалов.

Ключевые слова: *Двумерный дисульфид молибдена (2D MoS_2), эффект саморазогрева, подпороговая крутизна, МОП-транзистор, Температура кристаллической решётки.*

Abstract. This study presents a comprehensive numerical investigation of the influence of gate oxide and buried oxide (BOX) materials on the electrothermal performance of two-dimensional MoS_2-based metal–oxide–semiconductor (MOS) transistors. Particular attention is devoted to the analysis of the self-heating effect (SHE), subthreshold slope (SS), and drain-induced barrier lowering (DIBL), which are among the key performance-limiting factors in nanoscale devices. Al_2O_3 and HfO_2 are considered as gate dielectric materials, while SiO_2 and HfO_2 are employed as buried oxide (BOX) materials. The dependences of the subthreshold slope and the lattice temperature at the channel center on the gate length are systematically evaluated for different combinations of gate oxide and BOX materials. A device structure with the channel fully covered by the gate dielectric is considered throughout the study. The simulation results demonstrate that the combination of an Al_2O_3 gate dielectric and a SiO_2 BOX provides the lowest subthreshold slope, indicating superior electrostatic gate control. In contrast, employing HfO_2 as both the gate dielectric and the BOX significantly mitigates the self-heating effect by improving thermal dissipation, thereby enhancing the thermal stability and reliability of the device. These findings provide valuable insights into dielectric engineering for the optimization of high-performance, low-power, and thermally reliable MoS_2-based MOS transistors intended for future nanoelectronic applications.

Keywords: *2D MoS_2, Self-heating effect, Subthreshold swing, MOSFET, Lattice temperature.*

Introduction

A distinctive feature of two-dimensional MoS_2 MOSFETs is that the atomically thin channel is sandwiched between the gate dielectric and the buried oxide (BOX). Since oxide materials generally possess relatively low thermal conductivity, heat generated in the channel cannot be efficiently dissipated, giving rise to the self-heating effect (SHE). As device dimensions continue to shrink and power density increases, SHE becomes one of the major factors limiting device performance, reliability, and lifetime [7]. Moreover, the electrostatic performance of nanoscale MOSFETs is commonly evaluated using the subthreshold slope (SS) and drain-induced barrier lowering (DIBL), both of which are critical indicators of short-channel effects. Previous studies have reported the influence of temperature on the drain current characteristics of MoS_2-based MOSFETs [8, 9] and demonstrated their excellent resistance to short-channel effects, including relatively small degradation of SS and DIBL under aggressive channel-length scaling [3].

It is well established that the magnitude of the self-heating effect is primarily determined by the thermal conductivity of the dielectric materials surrounding the channel, whereas SS and DIBL are strongly influenced by the dielectric permittivity of the gate dielectric and buried oxide layers, which governs the electrostatic control of the channel [10]. Since these degradation mechanisms originate from different physical properties, improving thermal performance does not necessarily enhance electrostatic integrity, and vice versa. Therefore, identifying an optimal combination of gate dielectric and buried oxide materials that simultaneously minimizes SHE, SS, and DIBL is of considerable importance for the design of high-performance nanoscale MOSFETs. Motivated by these considerations, this work presents a comprehensive numerical investigation of the influence of gate dielectric and buried oxide materials on the electrothermal characteristics of two-dimensional MoS_2 MOSFETs. Al_2O_3 and HfO_2 are considered as gate dielectric materials, whereas SiO_2 and HfO_2 are employed as buried oxide (BOX) materials. The dependences of the self-heating effect, subthreshold slope (SS), drain-induced barrier lowering (DIBL), and lattice temperature at the channel center on the gate length are systematically analyzed for different dielectric combinations. Owing to its relatively low dielectric constant, SiO_2 is not considered as a gate dielectric material. The obtained results provide useful guidelines for dielectric engineering and material optimization toward the development of high-performance, low-power, and thermally reliable MoS_2-based MOSFETs for future nanoelectronic applications.

Research Methodology

Simulation conditions and transistor parameters. The electrical and electrothermal characteristics of the proposed monolayer MoS_2 MOSFET were investigated using the Synopsys TCAD Sentaurus device simulation platform. Since the material database of the standard TCAD Sentaurus package does not include the physical parameters of two-dimensional (2D) MoS_2, the material properties, physical models, and simulation methodology were implemented according to the validated approaches reported in [5, 11]. These parameters include the electronic band structure, carrier effective mass, dielectric properties, electron affinity, intrinsic carrier

concentration, and transport characteristics required for accurate numerical simulation of atomically thin semiconductor devices.

To accurately capture both carrier transport and self-heating phenomena, the thermodynamic transport model was employed in combination with the conventional drift–diffusion (DD) transport model. The drift–diffusion model describes carrier transport under the influence of electric fields and concentration gradients, whereas the thermodynamic model accounts for lattice heat generation and heat diffusion arising from Joule heating. The coupled electrothermal simulation enables a more realistic prediction of device behavior, particularly for aggressively scaled devices where power density and localized temperature rise significantly influence the electrical performance and reliability. The simulation framework was calibrated by comparing the calculated transfer characteristics $I_D - V_G$ with the reference results reported in [5]. The comparison was carried out for devices with different gate lengths under identical bias conditions. The excellent agreement between the simulated and published characteristics demonstrates that the adopted material parameters, transport models, and numerical settings accurately reproduce the electrical behavior of monolayer MoS_2 MOSFETs. This calibration validates the reliability of the developed simulation framework and provides confidence in the subsequent analysis of short-channel and electrothermal effects (Figure 1).

The simulated transistor consists of a 0.65 nm-thick monolayer MoS_2 channel**,** corresponding to a single atomic layer. Depending on the investigated gate length, the total device length varies from 60 nm to 300 nm**.** For all simulated structures, the channel length was maintained at three times the gate length to ensure sufficient separation between the source/drain contacts and the channel region, thereby minimizing parasitic boundary effects and preserving electrostatic integrity during numerical simulation. The gate electrode is formed from aluminum (Al) with a fixed thickness of 2 nm, while four different gate lengths (20 nm, 30 nm, 50 nm, and 100 nm) were considered to systematically investigate device scaling and the evolution of short-channel effects.

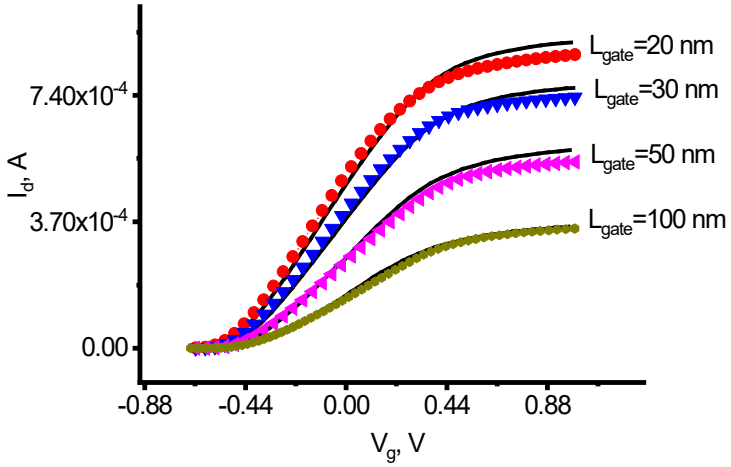

Figure 1. Simulated transfer characteristics of the proposed two-dimensional (2D) MoS_2 MOSFET for different gate lengths.

The solid lines represent the reference results reported in [5], while the symbols denote the simulation results obtained in this work. The excellent agreement between

the two sets of results confirms the accuracy and validity of the adopted simulation methodology.

The source and drain contacts were assumed to be ideal ohmic contacts in order to isolate the intrinsic transport properties of the channel. Since carrier transport in two-dimensional semiconductors is strongly influenced by dielectric screening and remote phonon scattering, the channel mobility was selected according to the gate dielectric material. When Al_2O_3 was used as the gate oxide, the electron mobility was assumed to be 125 $cm^2/V \cdot s$, consistent with the experimental and simulation results reported in [5]. In contrast, replacing the gate dielectric with HfO_2 increases dielectric screening and suppresses Coulomb scattering, resulting in an enhanced mobility of 320 $cm^2/V \cdot s$, as reported in [12]. These mobility values were directly incorporated into the simulations to evaluate the influence of different high-*k* dielectrics on the electrical and electrothermal performance of the device.

The schematic cross-sectional structure of the simulated monolayer MoS_2 MOSFET, including the gate, source, drain, dielectric layer, and channel regions, is illustrated in Figure 2. The adopted device geometry and simulation conditions provide a reliable platform for investigating scaling behavior, short-channel effects, self-heating, and the influence of high-*k* gate dielectrics on the performance of nanoscale two-dimensional MOSFETs.

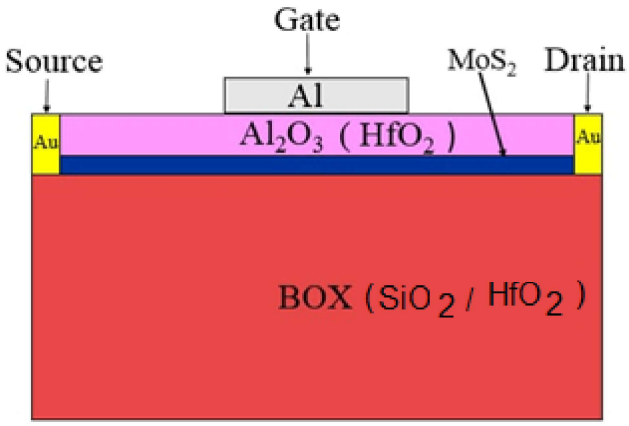

Figure 2. Schematic cross-sectional structure of the simulated monolayer MoS_2 MOSFET used in this study.

The numerical simulations were performed for the four combinations of gate dielectric and buried oxide (BOX) materials listed in Table 1. To ensure a fair comparison, the equivalent oxide thickness (EOT) of the gate dielectric was fixed at 1 nm for all device configurations. Silicon dioxide (SiO_2) was not considered as a gate dielectric because an EOT of 1 nm would result in significant direct gate leakage currents due to quantum mechanical tunneling, thereby degrading device performance. Consequently, only high-*k* dielectric materials, namely Al_2O_3 and HfO_2, were employed as gate dielectrics in this study. Furthermore, a comprehensive review of the existing literature indicates that Al_2O_3 has rarely been utilized as a buried oxide (BOX) material in either experimental demonstrations or numerical simulations of MoS_2-based MOSFETs. Therefore, Al_2O_3 was excluded from the BOX material combinations considered in this work. The thickness of the buried oxide has a significant influence on the thermal behavior of the device, particularly on the channel temperature, because

the BOX acts as the primary thermal resistance between the channel and the silicon substrate [13]. An increase in the BOX thickness reduces heat dissipation and consequently increases the channel temperature. To isolate the effect of the dielectric material itself from the influence of geometric parameters, the BOX thickness was fixed at 80 nm, following the device structure reported in [14].

Table 1. Combinations of gate dielectric and buried oxide (BOX) materials considered in this study.

Combination nomber	Gate dielectric material	Buried Oxide (BOX) Material
1	Al_2O_3	SiO_2
2	HfO_2	SiO_2
3	Al_2O_3	HfO_2
4	HfO_2	HfO_2

Analysis and Results

A. Effect of gate dielectric and buried oxide material combinations on the self-heating effect.

One of the most important parameters characterizing the self-heating effect (SHE) in MOSFETs is the lattice temperature at the center of the channel, where the maximum temperature is typically observed.

The channel temperature is determined by the balance between the heat generation rate associated with carrier transport and the heat dissipation through the surrounding dielectric layers. To ensure a fair comparison among different dielectric configurations, all simulations were performed using identical device geometries and the same bias conditions.

Consequently, the heat generation rate remained nearly identical in all cases, and the variations in channel temperature can therefore be attributed primarily to differences in the thermal properties of the gate dielectric and buried oxide (BOX) materials. The four combinations of gate dielectric and BOX materials considered in this study are listed in Table 1.

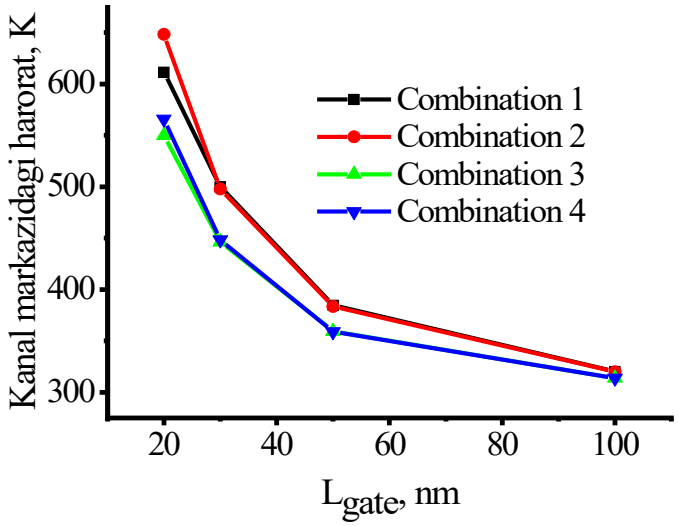

Figure 3. Dependence of the lattice temperature at the channel center (self-heating effect, SHE) on the gate length for different combinations of gate dielectric and buried oxide (BOX) materials.

Figure 3 illustrates the dependence of the lattice temperature at the center of the MoS_2 channel on the gate length for each dielectric combination. The temperature distributions were obtained under the bias conditions of $V_{GS} = 0.1\ V$ and $V_{DS} = 0.4\ V$ for all simulated structures. As shown in Figure 3, the channel-center temperature increases as the gate length decreases. This behavior can be explained by the lower channel resistance of short-channel devices, which results in a higher drain current under the same drain bias. The increased current density leads to greater Joule heat generation and, consequently, a higher channel temperature. In contrast, long-channel devices exhibit a higher channel resistance and a lower drain current, resulting in reduced heat generation and a lower lattice temperature. The thermal conductivities of the dielectric materials used in the simulations are summarized in Table 2. Since the thermal conductivity of the surrounding dielectric layers directly determines the efficiency of heat extraction from the channel, it has a pronounced influence on the magnitude of the self-heating effect. Therefore, the differences observed among the four dielectric configurations can be directly correlated with the thermal conductivities of the gate dielectric and BOX materials.

Table 2. Dielectric constants and thermal conductivities of the materials used in the simulations.

Material	**Thickness (nm)**	**Relative dielectric constant**	**Thermal conductivity $\frac{W}{K \cdot m}$**
SiO_2	80	3.9	1.4
Al_2O_3	2.385	9.3	12
HfO_2 (gate oxide)	5.641	25	2.3
HfO_2 (Box)	80	25	2.3

The simulation results indicate that the influence of the dielectric materials on the self-heating effect becomes increasingly pronounced as the gate length decreases. This behavior is attributed to the higher power density and reduced heat dissipation capability in short-channel devices. Furthermore, the lattice temperature at the channel center is strongly dependent on the combination of gate dielectric and buried oxide (BOX) materials. As shown in Figure 3, for a gate length of 20 nm, the channel-center temperature obtained for dielectric combinations 1 and 2 is noticeably higher than that for combinations 3 and 4. This difference is primarily attributed to the choice of the BOX material. In combinations 1 and 2, SiO_2 is employed as the BOX material, whereas HfO_2 is used in combinations 3 and 4. Since the thermal conductivity of HfO_2 is more than 1.5 times higher than that of SiO_2 (see Table 2), heat generated in the channel is dissipated more efficiently through the HfO_2 BOX, resulting in a lower channel temperature. These results demonstrate that the BOX material has a more significant influence on the self-heating effect than the gate dielectric because it provides the dominant thermal conduction path from the channel to the substrate. A comparison within each BOX group further reveals the influence of the gate dielectric material. For both the SiO_2-BOX group (combinations 1 and 2) and the HfO_2-BOX group (combinations 3 and 4), the channel-center temperature is higher for combinations 2 and 4, where HfO_2 is used as the gate dielectric, than for combinations 1 and 3, where Al_2O_3 serves as the gate dielectric. This behavior is explained by the

substantially lower thermal conductivity of HfO_2 compared with Al_2O_3. Depending on the film thickness and operating temperature, the thermal conductivity of Al_2O_3 ranges from approximately 6 - 30 $W \cdot m^{-1} \cdot K^{-1}$ [15]–[18], whereas that of HfO_2 varies from 0.27 - 4.3 $W \cdot m^{-1} \cdot K^{-1}$ [19], [20]. Consequently, replacing Al_2O_3 with HfO_2 as the gate dielectric increases the thermal resistance above the channel, thereby reducing heat extraction through the gate stack and leading to a higher lattice temperature. Overall, the results demonstrate that the thermal conductivity of the surrounding dielectric layers plays a decisive role in determining the magnitude of the self-heating effect in MoS_2 MOSFETs. Among the investigated dielectric layers, the BOX material exerts the strongest influence on channel temperature, while the gate dielectric provides a secondary, yet still significant, contribution to the overall thermal behavior of the device. The effect of thermal expansion of the MoS_2 channel was neglected in the present simulations because of its negligible magnitude. The thermal expansion coefficient of a monolayer MoS_2 at 550 K is approximately 6.5×10^{-5} K^{-1} [21]. Consequently, increasing the temperature from 300 K to 550 K results in only about 1.95% linear expansion of the channel. Such a small dimensional change has an insignificant influence on the electrical and electrothermal characteristics of the device and, therefore, was not considered in the numerical model.

B. Effect of gate dielectric and buried oxide material combinations on the subthreshold swing

The subthreshold slope (SS) of the investigated two-dimensional MoS_2 MOSFETs was calculated using:

$$SS = \frac{dV_g}{d(log_{10} I_d)} \quad (1)$$

where V_g is the gate voltage and I_d is the corresponding drain current.

To compare the electrostatic characteristics with the self-heating behavior, the dependence of SS on the gate length was simulated for the four combinations of gate dielectric and buried oxide (BOX) materials described in Table 1. The simulated results are presented in Figure 4. As shown in Figure 4, the dependence of SS on the gate length is more pronounced for combinations 3 and 4 than for combinations 1 and 2. Moreover, over the entire investigated gate-length range, the SS values of the devices employing HfO_2 as the BOX material (combinations 3 and 4) are consistently higher than those of the devices with SiO_2 as the BOX material (combinations 1 and 2). These results indicate that the subthreshold characteristics are more strongly influenced by the dielectric permittivity of the buried oxide than by that of the gate dielectric. An increase in the dielectric constant of the BOX leads to a systematic increase in SS, indicating a degradation of the electrostatic gate control. In contrast, the influence of the gate dielectric exhibits the opposite trend. For devices employing the same BOX material, replacing Al_2O_3 with the higher-k dielectric HfO_2 as the gate dielectric reduces the SS value owing to the enhanced gate-to-channel capacitive coupling. This behavior is clearly observed for combinations 3 and 4 throughout the investigated gate-length range. A similar trend is also found for combinations 1 and 2 when the gate length exceeds approximately 30 nm.

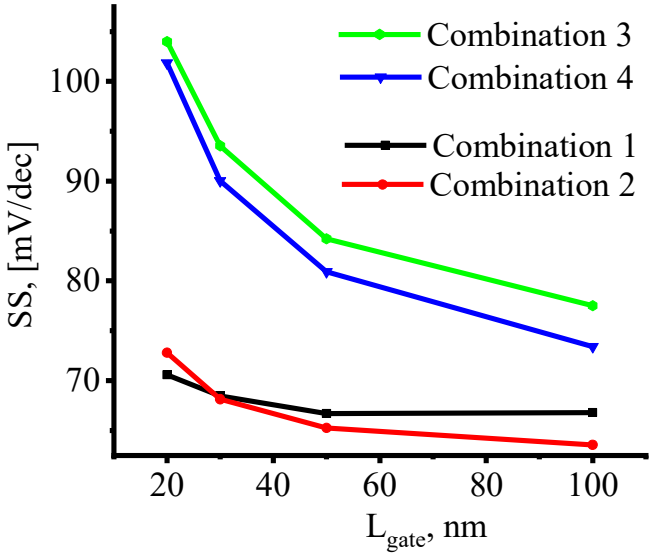

Figure 4. Dependence of the subthreshold slope (SS) on the gate length for different combinations of gate dielectric and buried oxide (BOX) materials in two-dimensional MoS_2 MOSFETs.

These results demonstrate that the gate dielectric and the buried oxide influence the subthreshold slope in opposite ways. While a high-*k* gate dielectric improves electrostatic control and suppresses SS, a high-*k* buried oxide tends to increase SS by modifying the electric-field distribution between the channel and the substrate. Therefore, simultaneous optimization of the gate dielectric and BOX materials is essential for achieving an appropriate trade-off between electrostatic performance and thermal reliability in two-dimensional MoS_2 MOSFETs. Among the four dielectric configurations considered in this study, combinations 3 and 4 exhibit the highest values of the buried oxide (BOX) dielectric permittivity, since HfO_2 is employed as the BOX material with a relative permittivity of approximately $\varepsilon_{HfO_2} = 25$. In contrast, combinations 1 and 2 utilize SiO_2 as the BOX material, whose relative permittivity is considerably lower ($\varepsilon_{Si_2} = 3.9$). Consequently, the devices with SiO_2 BOX exhibit smaller subthreshold slope (SS) values over the investigated gate-length range. The dependence of SS on the gate dielectric and BOX materials can be explained by the influence of their dielectric permittivities on the electrostatic potential and carrier distribution within the channel. Variations in the dielectric properties modify the electric-field distribution and the gate-to-channel electrostatic coupling, thereby changing the drain current characteristics and, consequently, the subthreshold slope. These results indicate that the dielectric permittivity of the BOX has a dominant influence on the subthreshold characteristics, whereas the gate dielectric primarily determines the strength of electrostatic gate control through its capacitive coupling with the channel.

C. DIBL effect for different combinations of gate oxide and back oxide materials

The simulation results indicate that, over the entire investigated gate-length range, the drain-induced barrier lowering (DIBL) is consistently higher for combinations 3 and 4 than for combinations 1 and 2, as shown in Figure 5. This observation suggests that the dielectric properties of the gate dielectric and, particularly, the buried oxide (BOX) significantly influence the electrostatic integrity

of the device. The obtained results can be interpreted using the capacitive coupling model proposed in [3], which describes the electrostatic interaction between the channel and the device terminals. According to this model, DIBL can be expressed as

$$DIBL = k\frac{C_D}{C_G} \quad (2)$$

where k is a proportionality constant, C_D is the effective drain-to-channel capacitance, and C_G is the gate-to-channel capacitance (Figure 6). The effective drain-to-channel capacitance consists of three contributions: the capacitive coupling through the channel C_{Dchan}, through the buried oxide C_{Dbox}, and through the gate dielectric $C_{D.ox}$.
Therefore,

$$C_D = C_{D.ch} + C_{Dbox} + C_{D.ox} \quad (3)$$

As indicated by (3), DIBL is proportional to the ratio of the drain-to-channel capacitance to the gate-to-channel capacitance.

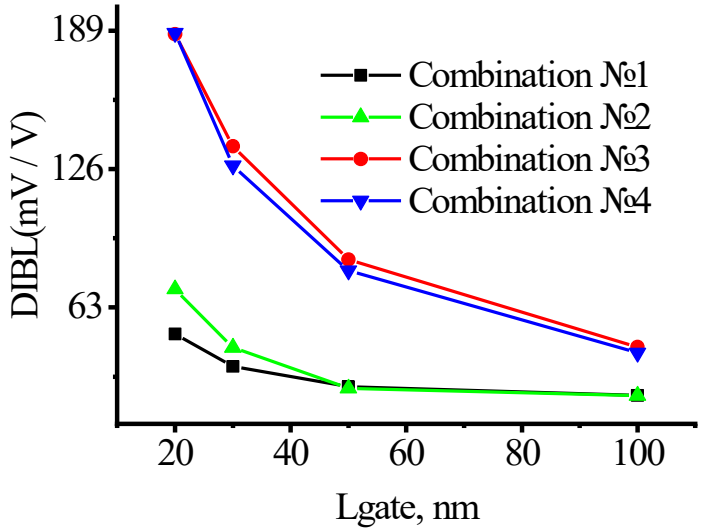

Figure 5. DIBL effect dependence on the gate length for different combinations of gate oxide and back oxide materials.

Consequently, any increase in the parasitic capacitive coupling between the drain and the channel, or any reduction in the gate electrostatic coupling, leads to an increase in DIBL. Since the dielectric permittivities of both the gate dielectric and the BOX directly affect these capacitances, the choice of dielectric materials plays a crucial role in determining the short-channel behavior of MoS_2 MOSFETs.

The capacitance components C_G, and $C_{D.ch}$ are primarily determined by the dielectric permittivity of the channel material ε_{MoS2}, whereas $C_{D.ox}$ is governed by the dielectric permittivity of the buried oxide (BOX). In the present study, the relative permittivities are $\varepsilon_{Al_2O_3} = 9.3$, $\varepsilon_{SiO_2} = 3.9$, $\varepsilon_{Al_2O_3} = 9.3$, $\varepsilon_{SiO_2} = 3.9$, $\varepsilon_{HfO_2} = 22$ and $\varepsilon_{MoS_2} = 3$. Since the dielectric permittivity of the MoS_2 channel is relatively low, the gate-to-channel capacitance C_G as well as the capacitance components $C_{D.ch}$ and $C_{D.ox}$ remain comparatively small. Consequently, the contribution of the buried oxide capacitance $C_{D.box}$ becomes dominant in determining the effective drain-to-channel capacitance C_D and, therefore, the DIBL behavior. Accordingly, the DIBL characteristics of the investigated devices are mainly controlled by the dielectric

permittivity of the BOX material. For combinations 3 and 4, HfO_2 is employed as the BOX material, providing a high relative permittivity of $\varepsilon_{Hf\ _2} = 22$. This increases the drain-to-channel capacitive coupling, resulting in larger DIBL values. In contrast, combinations 1 and 2 use SiO_2 as the BOX material, whose considerably lower relative permittivity ($\varepsilon_{SiO_2} = 3.9$) weakens the drain-to-channel coupling and consequently suppresses DIBL.

The simulation results presented in fig. 5 are in excellent agreement with this theoretical interpretation.

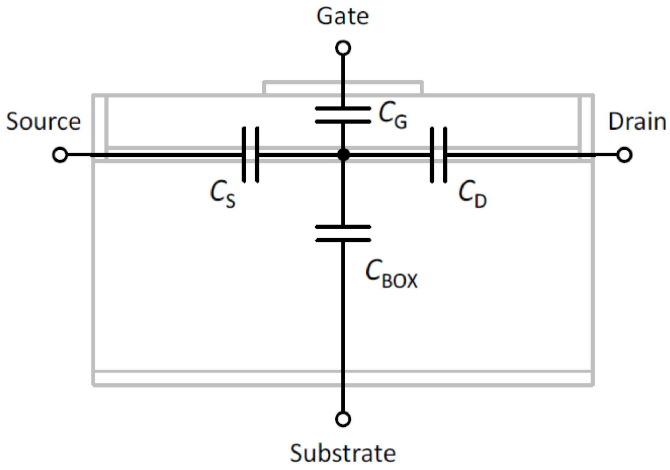

Figure 6. Equivalent circuit describing the capacitive coupling between the channel and the device electrodes in MOSFET.

Throughout the investigated gate-length range, the devices employing an HfO_2 BOX consistently exhibit higher DIBL values than those with a SiO_2 BOX, confirming that the dielectric permittivity of the buried oxide is the dominant factor governing drain-induced barrier lowering in the investigated two-dimensional MoS_2 MOSFETs.

D. Optimization of gate dielectric and buried oxide material combinations for Minimizing SHE, SS, and DIBL

Since both the self-heating effect (SHE) and the subthreshold slope (SS) become more pronounced in short-channel devices, a comparative analysis was performed for the transistor with a gate length of 20 nm. The dependences of the channel-center lattice temperature and SS on the dielectric-material combinations are summarized in Figure 7, which was constructed from the results presented in Figure 3 and Figure 4. As shown in Figure 7, the dielectric combinations affect SHE and SS in opposite ways. Devices employing SiO_2 as the buried oxide (combinations 1 and 2) exhibit lower SS values owing to the relatively low dielectric permittivity of SiO_2, but suffer from a stronger self-heating effect because of its limited thermal conductivity. In contrast, devices employing HfO_2 as the buried oxide (combinations 3 and 4) exhibit significantly lower channel temperatures due to more efficient heat dissipation, while their SS values increase because of the higher dielectric permittivity of HfO_2.

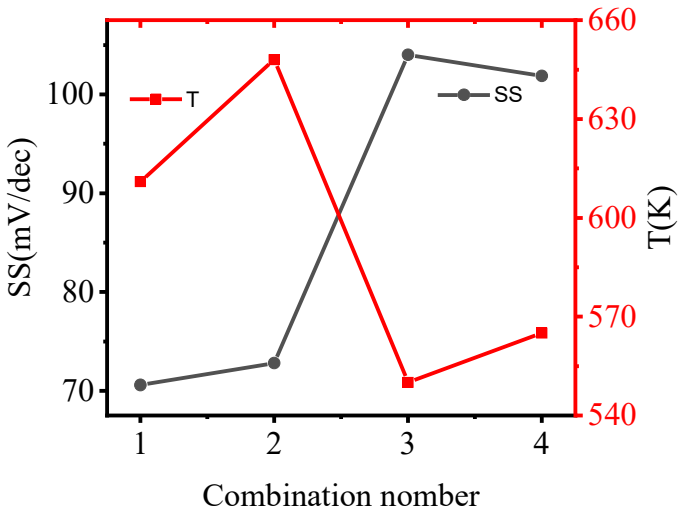

Figure 7. Dependence of SS and SHE degradation effects on the number of gate-oxide and back oxide material combinations in MOSFET.

These results clearly demonstrate the trade-off between thermal performance and electrostatic control. A similar trade-off is observed between the self-heating effect and drain-induced barrier lowering (DIBL). The dependence of the channel-center lattice temperature and DIBL on the dielectric combinations for the 20-nm gate-length device is presented in Fig. 8**.** According to the capacitive coupling model discussed in the previous section, DIBL is predominantly determined by the dielectric permittivity of the buried oxide, whereas SHE is mainly governed by its thermal conductivity. Consequently, reducing DIBL requires a BOX material with a low dielectric permittivity, while suppressing SHE requires a material with high thermal conductivity. The comparison of the investigated dielectric combinations reveals that SiO_2 effectively suppresses SS and DIBL because of its low relative permittivity, but it's poor thermal conductivity leads to a considerable increase in the channel temperature. Conversely, HfO_2 significantly reduces the self-heating effect owing to its superior thermal conductivity, although its high dielectric permittivity results in larger SS and DIBL values. Therefore, the optimization of MoS_2 MOSFETs requires a careful compromise between the electrostatic and thermal properties of the buried oxide material.

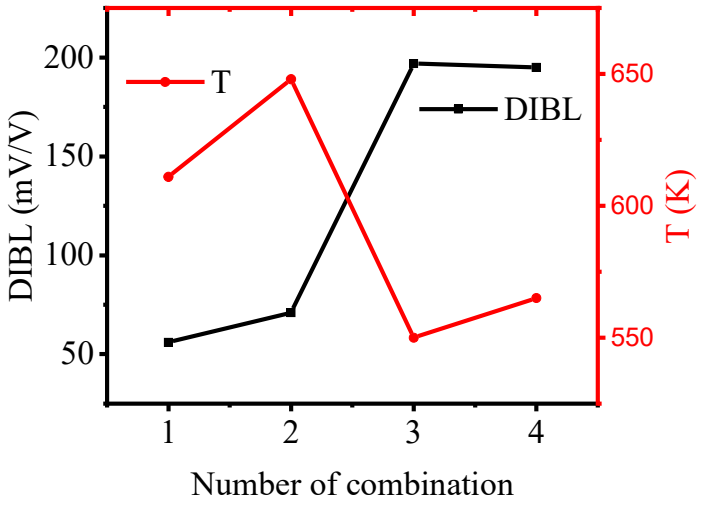

Figure 7. DIBL effect and SHE dependence of combinations of gate oxide and back oxide materials in MOSFET.

Based on the obtained results, an ideal buried oxide material for simultaneously improving the immunity against SHE, SS, and DIBL should possess a moderate dielectric permittivity together with a relatively high thermal conductivity. Such a material would provide efficient heat extraction without significantly strengthening the drain-to-channel capacitive coupling, thereby enabling improved electrothermal performance of two-dimensional MoS_2 MOSFETs.

Conclusion

A comprehensive electrothermal numerical study of two-dimensional MoS_2-based MOSFETs has been carried out to investigate the influence of gate dielectric and buried oxide (BOX) materials on the self-heating effect (SHE), subthreshold slope (SS), and drain-induced barrier lowering (DIBL). The simulation results demonstrate that the electrothermal performance of the device is strongly dependent on the dielectric properties of the surrounding oxide layers.

Among the investigated parameters, the BOX material has the dominant influence on all three degradation mechanisms. Increasing the thermal conductivity of the BOX effectively suppresses the self-heating effect by reducing the channel temperature, whereas increasing its dielectric permittivity results in larger SS and DIBL values because of stronger drain-to-channel capacitive coupling. In contrast, the gate dielectric mainly affects the electrostatic gate control and has a comparatively smaller influence on the thermal behavior.

The results indicate that simultaneous suppression of SHE, SS, and DIBL cannot be achieved by simply selecting a dielectric material with either the highest thermal conductivity or the lowest dielectric permittivity.

Instead, the optimal BOX material should combine moderate dielectric permittivity with high thermal conductivity, thereby providing an appropriate balance between thermal management and electrostatic integrity.

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