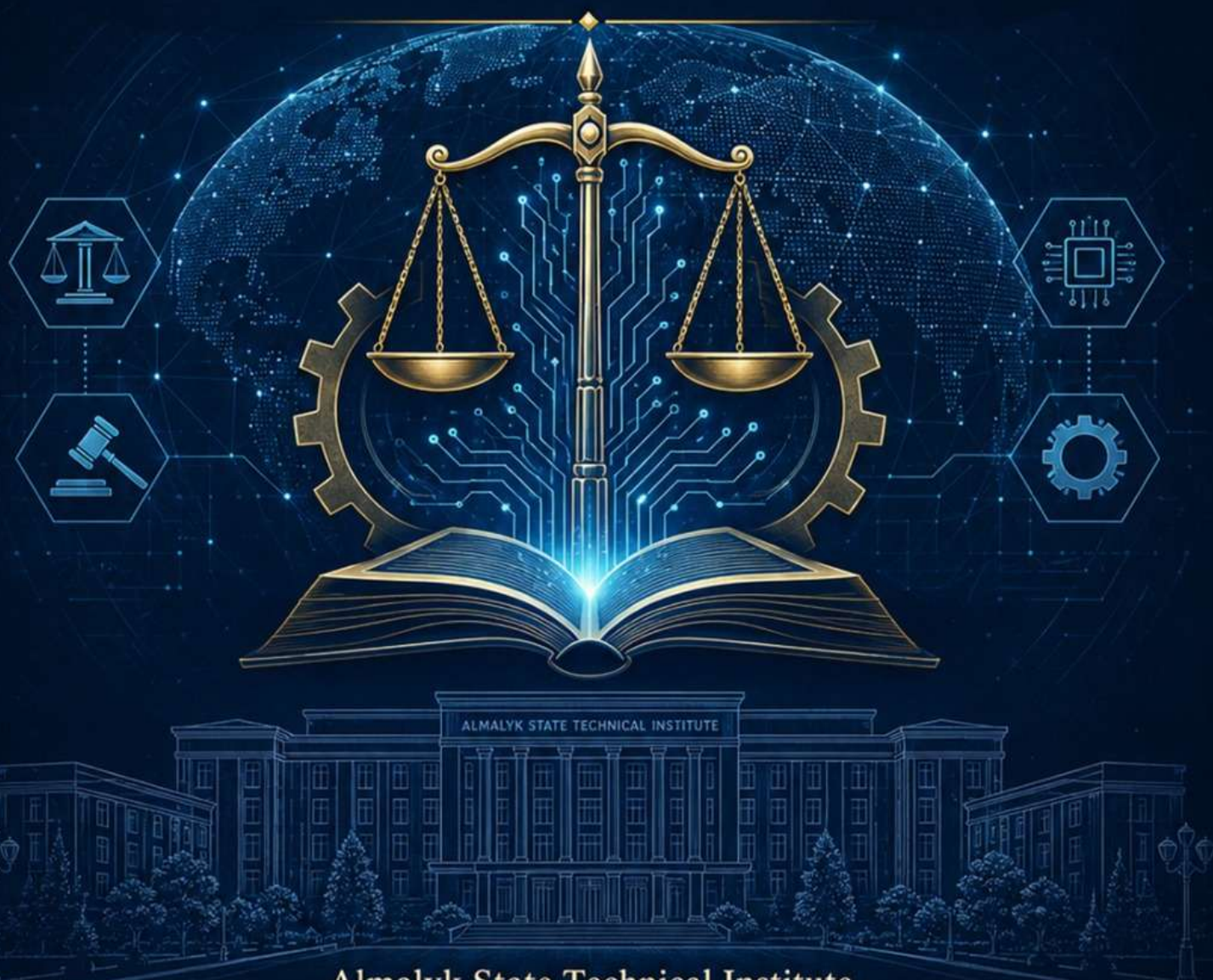


MULTIDISCIPLINARY
INTERNATIONAL SCIENTIFIC SYMPOSIUM

THE IMPACT OF TECHNOLOGICAL INNOVATIONS ON LAW IN THE DIGITAL AGE AND FUTURE PERSPECTIVES IN ENGINEERING EDUCATION



Almalik State Technical Institute
Main Building

22 July 2026
Tashkent

ISBN: 978-975-6993-46-0

2026



**OLMALIQ DAVLAT
TEXNIKA INSTITUTI**



**MULTIDISCIPLINARY INTERNATIONAL
SCIENTIFIC SYMPOSIUM on THE IMPACT OF
TECHNOLOGICAL INNOVATIONS ON LAW IN
THE DIGITAL AGE AND FUTURE PERSPECTIVES
IN ENGINEERING EDUCATION
(Proceeding Book)**

Editors:

Prof. Dr. Zokir Mamirovich Zikriyayev

Dr. Bükre Şeyma Dönder

Dr. Zeynep Çelik Gülseven

Jalolov Bakhtiyorjon Adkhamjon ugli

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

The poster is for an international scientific symposium. At the top, it features logos for ODTİ (Almalyk State Technical Institute), İZS (İstanbul Zammı Üniversitesi), and a circular emblem. The title of the symposium is prominently displayed in the center. Below the title, the venue is specified as the Almalyk State Technical Institute Main Building in Almalyk city, Uzbekistan. A section with icons provides the date (22 July 2026), starting times for Turkey (14:00) and Uzbekistan (16:00), and the format (Hybrid: Face to Face + Online). The symposium topics are listed in a row: Digital technologies and law, Artificial intelligence and legal regulation, Modern perspectives in engineering education, International scientific cooperation, and A collection of scientific papers will be published. The organizers are listed as Almalyk State Technical Institute, in partnership with Istanbul Zammı University and Balıkesir University. The participants include Professors and Lecturers, Researchers, Doctoral Students, and Independent Researchers. At the bottom, contact information for inquiries is provided via email.

ODTİ ALMALYK STATE TECHNICAL INSTITUTE

İZS İstanbul Zammı Üniversitesi

INTERNATIONAL SCIENTIFIC SYMPOSIUM

"THE IMPACT OF TECHNOLOGICAL INNOVATIONS ON LAW IN THE DIGITAL AGE AND FUTURE PERSPECTIVES IN ENGINEERING EDUCATION"

VENUE:
ALMALYK STATE TECHNICAL INSTITUTE
MAIN BUILDING
(Almalyk city, Uzbekistan)

DATE:
22 JULY 2026

STARTING TIME:
TÜRKİYE TIME
14:00
UZBEKİSTAN TIME
16:00

FORMAT:
HYBRID
(FACE TO FACE + ONLINE)

SYMPOSIUM TOPICS

- Digital technologies and law
- Artificial intelligence and legal regulation
- Modern perspectives in engineering education
- International scientific cooperation
- A collection of scientific papers will be published

ORGANIZERS

- Almalyk State Technical Institute
- in partnership with
- İstanbul Zammı University
- Balıkesir University

PARTICIPANTS

- Professors and Lecturers
- Researchers
- Doctoral Students
- Independent Researchers

FOR INQUIRIES:
turkoglu@balikesir.edu.tr

VENUE and DATE:

Almalyk State Technical Institute Main Building, 22 July 2026

DOI: <https://doi.org/10.5281/zenodo.22106743>

ISBN: 978-975-6993-46-0

Scientific Committee

Prof. Dr. Utkir Mirzakamolovich Xalikulov, Rector, Almalyk State Technical Institute

Prof. Dr. Yücel Oğurlu, Rector, Balıkesir University

Prof. Dr. Zokir Mamirovich Zikriyayev, Vice-Rector, Almalyk State Technical Institute

Prof. Dr. Sarvar Toshpo'latovich Parmonov, Vice-Rector, Almalyk State Technical Institute

Prof. Dr. Canan Küçükali, Dean, Faculty of Law, Istanbul Sabahattin University

Prof. Dr. Mustafa Yasan, Dean, Faculty of Law, Balıkesir University

Prof. Dr. Jordan Delev, Dean, Faculty of Law, International University of Vision

Prof. Dr. Şafak Narbay, Dean, Faculty of Law, Sakarya University

Prof. Dr. Mehmet Emin Bilge, Dean, Faculty of Law, Social Sciences University of Ankara

Prof. Dr. Turan Yıldırım, Faculty of Law, Marmara University

Prof. Dr. Liudmila Bukalero, Dean, RUDN University

Prof. Dr. Abdül Halim Zaim, Dean, Istanbul Technical University

Prof. Dr. Muhammed Ali, University of Sharjah

Prof. Dr. Ömer Çınar, Constitutional High Court

Prof. Dr. Fülurya Yusufoglu Bilgin, Faculty of Law, Galatasaray University

Prof. Dr. Şahin Akıncı, Faculty of Law, Istanbul Commerce University

Prof. Dr. Ayşenur Berzek, Faculty of Law, Marmara University

Prof. Dr. Ayşe Boztosun, Faculty of Law, Akdeniz University

Prof. Dr. Murat Doğan, Faculty of Law, Erciyes University

Prof. Dr. Mustafa Fadıl Yıldırım, Faculty of Law, Ankara Hacı Bayram Veli University

Assoc. Prof. Dr. Kemale Valiyeva, Istanbul Commerce University

Assist. Prof. Dr. Yasin Poyraz, Ankara Yıldırım Beyazıt University

Contents

FIRST SESSION	3
FUTURE PERSPECTIVES in ENGINEERING EDUCATION	3
Developing Innovative Thinking in Engineering Education and Supporting the Potential of Young Researchers.....	28
Introduction	29
Innovative Thinking as a Core Competency in Engineering Education	30
Institutional Strategies for Supporting the Potential of Young Researchers	32
Building an Innovation Ecosystem in Engineering Universities.....	33
Future Perspectives for Engineering Education and Young Researchers	35
The Strategic Significance of Metallurgy and The Copper Mining Industry in The Economic and Industrial Development of Uzbekistan	40
Mechanism of H ₂ S Corrosion in Absorption and Recycling Processes	47
Development of an Eco-Friendly and Highly Efficient Process For the Selective Recovery of Valuable Metal Ions From Zinc and Cadmium Cakes Generated at the Zinc Plant of Jsc “Almalyk Mining and Metallurgical Complex” Using Immobilized Organic Reagents	52
Using Digital Technologies and Artificial Intelligence in Chemical Engineering Education: A Case Study on the Selective Recovery of Rhenium from Industrial Solutions	61
Legal-Regulatory Implications of AI and Automation in Hydrometallurgical Zinc Residue Processing: Occupational Safety and Workforce Transition.....	67
Production of Copper(I) Phosphide (Cu ₃ P) From Copper-Bearing Raw Materials Using Digitally Automated, Environmentally Safe Technologies: Research Directions and Prospects.....	72
Determination of the Toxicity of Phenyl-2-Chloropropionate and 4-Hydroxyphenyl-2-Chloropropionate	78
Optimization of Copper Smelting Processes Using Artificial Intelligence and In-Situ Alkali Modification for Recovery of Iron and Valuable Metals	84
Google Lookout as an AI-Enabled Assistive Tool for Inclusive Engineering Education: Opportunities, Ethical Risks, and an Implementation Framework.....	89
Effect of the Physicochemical Properties of Molten Gold on Its Recovery during the Pyrometallurgical Processing of Copper Oxide Mineral Raw Materials	96

Automation and AI-Based Control in Metal Recovery from Metallurgical Waste Solutions: Regulatory Implications for Occupational Safety and Labor Displacement	101
Investigation of Mineralogical Composition and Complex Processing Methods for Out-of-Balance Ores of the Kalmakyr Deposit	107
Mineralogical Assessment of Gold Department in the Yoshlik I Deposit	111
SECOND SESSION	116
THE IMPACT OF TECHNOLOGICAL INNOVATIONS ON LAW IN THE DIGITAL AGE	116
Lawmaking Engineering in the Digital Age: The Integrated Lawmaking Optimization Model	117
Bridging Explainable AI and Legal Accountability in Financial Fraud Detection through Neural-Symbolic Compliance.....	128
Protection of Children’s Privacy and Personality Rights in Digital Environments	136
Criminal Liability of Artificial Intelligence: Fundamental Principles of Criminal Law and New Approaches.....	142
AI-Assisted Inventions and The Problem of Inventorship: From The Dabus Cases To Human-AI Collaboration	148
Withdrawal, Restitution, and Human Intervention in the Face of Smart Contract Immutability	154
Online Dispute Resolution and the Right to a Fair Trial: Balancing Efficiency and Procedural Guarantees in Digital Justice.....	164
Occupational Accidents and the Transformation of Social Security Law in the Digital Workplace: The Case of Kazakhstan.....	168
Digitalisation of Civil Justice In EU	175
Artificial Intelligence and the Displacement of Procedural Justice in Criminal Proceedings.....	181
Current Trends in the Internationalization of Engineering Education and International Scientific Cooperation	191
Priority Areas for the Integration of Higher Education and Industry in the Innovative Development of Engineering and Technical Fields	203
Technology Transfer, Legal Regulation and Future Perspectives of Engineering Education in the Digital Era	214
Modern Approaches to Infrastructure Development and Efficient Resource Utilization in Technical Higher Education Institutions	227

Electronic Monitoring In Penal Enforcement Law: Between Technological Surveillance and Fundamental Rights	235
Transparency, Accountability, and Administrative Liability in Algorithmic Administrative Decisions	242
The Legal Nature of Crypto-Assets and Investor Protection in Digital Financial Markets	249
The Legal Nature of Standard Computer Program Transfer Agreements Enabling Permanent Use: An Assessment under Turkish Contract and Copyright Law.....	257
The Legal Nature of Crypto Assets under Digital Transformation: A Comparative Analysis and Regulatory Framework	264
The Legal Taxonomy of R&D Contracts within the Framework of Sui Generis Obligations	270
Data Protection and Digital Evidence: An Assessment of the Turkish Constitutional Court's Ruling on the Annulment of Article 134 of the Code of Criminal Procedure (Case No. 2023/128 E. and Decision No. 2026/36 K.) in the Light of German Criminal Procedure Law.....	277
The Impact of Artificial Intelligence on Turkish Joint Stock Companies Law.....	285
The Issue of the Legal Nature of Digital Services Taxes: an Assessment from the Perspectives of Double Taxation and Fiscal Sovereignty	292

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

FIRST SESSION

FUTURE PERSPECTIVES in ENGINEERING EDUCATION

Foreword

Technological innovation is reshaping not only engineering practice but also the legal, ethical, educational, and institutional frameworks within which modern societies operate. Developments in artificial intelligence, automation, digital platforms, data-driven systems, and emerging technologies are creating new opportunities while also raising complex questions that cannot be addressed adequately within the boundaries of a single discipline.

The International Symposium entitled *The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education* was held on 22 July 2026 under the hosting of Almalyk State Technical Institute, in partnership with Istanbul Sabahattin Zaim University and Balıkesir University. Organised in a hybrid and workshop-based format, the symposium brought together a selected group of invited scholars, researchers, legal experts, and engineering academics.

The principal aim of the symposium was to examine the legal issues arising from technological development and emerging digital applications through the perspectives of different branches of law. At the same time, the event sought to evaluate the effects of technological transformation on engineering education, professional practice, and the future direction of engineering disciplines.

Particular attention was devoted to the growing relationship between law and technology. Artificial intelligence, automated decision-making systems, digitalisation, and new forms of technological infrastructure increasingly influence contractual relations, criminal responsibility, administrative decision-making, intellectual property rights, financial systems, data governance, and access to justice. These developments require legal systems to reconsider established concepts and regulatory approaches while preserving fundamental rights, legal certainty, accountability, and fairness.

The symposium also addressed the consequences of technological transformation for engineering education. The rapid pace of innovation requires educational institutions to reconsider curricula, teaching methods, research priorities, and the skills expected of future engineers. Technical knowledge alone is no longer sufficient. Engineers must increasingly understand the legal, ethical, social, and regulatory implications of the systems they design and implement.

The workshop format of the symposium enabled participants to discuss these matters in a focused and interdisciplinary environment. Rather than approaching law, technology, and engineering as separate fields, the presentations demonstrated that many

contemporary problems emerge precisely at the points where these disciplines intersect. The exchange of different academic perspectives therefore formed one of the most valuable aspects of the event.

The papers included in this proceedings book reflect the diversity of the subjects discussed during the symposium. They address current and future challenges created by technological innovation and offer legal, technical, regulatory, and educational perspectives on these challenges. Although the contributions differ in subject matter and methodology, they share a common concern with understanding how law and education can respond effectively to rapid technological change.

We would like to express our sincere gratitude to Almalyk State Technical Institute for hosting the symposium and for its valuable institutional support. We also extend our appreciation to Istanbul Sabahattin Zaim University and Balıkesir University for their contributions to the organisation of the event and for their commitment to international academic cooperation.

Our special thanks are due to all invited speakers and participants whose research, presentations, and discussions enriched the scholarly content of the symposium. We are equally grateful to the members of the Organising Committee and to all those who contributed to the preparation of the programme and the publication of this proceedings book.

We hope that this volume will contribute to further academic discussion on the relationship between technological innovation, law, and engineering education. We also hope that the symposium will encourage new interdisciplinary studies, institutional partnerships, and international research collaborations in these rapidly developing fields.

Prof. Dr. Utkir Mirzakamolovich Xalikulov, Rector, Almalyk State Technical Institute

Prof. Dr. Yücel Oğurlu, Rector, Balıkesir University

For behalf of Symposium Organising Committee of *“The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education”*

22 July 2026

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

FIRST SESSION

THE FUTURE PERSPECTIVES IN ENGINEERING EDUCATION

Morphological and Magnetotransport Properties of Mn-Substituted ZnO Thin Films Prepared by Ultrasonic Spray Pyrolysis

Sh. Yuldashev¹, A. Arslanov², A. Nebesniy³, A. Odilov⁴

Abstract

Diluted magnetic semiconductors (DMSs) offer unique combinations of semiconducting and magnetic properties, making them attractive for spintronic applications. Among oxide semiconductors, Mn-substituted ZnO stands out due to its wide band gap, chemical stability, and potential for room-temperature magnetism. This study compares pure ZnO and $\text{Zn}_{0.95}\text{Mn}_{0.05}\text{O}$ thin films deposited on Si(100) substrates by ultrasonic spray pyrolysis. Zinc acetate and manganese acetate served as precursors, with thiourea added to aid film formation. Structural morphology was analyzed via scanning electron microscopy (SEM); magnetotransport properties were assessed by room-temperature magnetoresistance measurements. SEM revealed compact, polycrystalline films composed of uniformly distributed nanograins, with average thickness around 200 nm. Magnetoresistance measurements showed negligible response in pure ZnO, while Mn substitution led to significant positive magnetoresistance, attributed to spin-dependent carrier scattering by magnetic ions. These findings confirm that Mn incorporation effectively enhances the magnetotransport properties of ZnO thin films without degrading their morphology, highlighting their promise for future spintronic and magnetoelectronic devices.

¹, Center for Nanotechnology Development, National University of Uzbekistan; shavkaty@yahoo.com; ORCID: 0000-0002-2187-5960

² Department of Physics, National University of Uzbekistan, Tashkent, Uzbekistan; Azamat20296@gmail.com; ORCID: 0009-0000-4817-8770

³ Center for Nanotechnology Development, National University of Uzbekistan; nebesny-andrey@yandex.ru; ORCID: 0009-0000-3029-2284

⁴ Department of Mathematics and Natural Sciences, Almalyk State Technical Institute, Almalyk, Uzbekistan; akromoligarx@gmail.com; ORCID: 0009-0002-4449-413X

Keywords: ZnO thin films; Mn doping; ultrasonic spray pyrolysis; diluted magnetic semiconductors; magnetoresistance; spintronics.

1. Introduction

Diluted magnetic semiconductors (DMSs) have emerged as one of the most promising classes of multifunctional materials because they combine semiconducting behavior with magnetic properties. Unlike conventional semiconductor materials, DMSs provide the possibility of utilizing both the charge and spin of electrons, thereby opening new opportunities for the development of spin-based electronic devices. Such materials have attracted significant attention for applications in spin field-effect transistors, magnetic random-access memory (MRAM), magnetic sensors, and quantum information technologies (Wolf et al., 2001).

Among various oxide semiconductors, zinc oxide (ZnO) is considered one of the most attractive host materials for DMS applications because of its wide direct band gap (3.37 eV), high exciton binding energy (60 meV), excellent optical transparency, chemical stability, and environmental compatibility. In addition, ZnO can be synthesized using various deposition techniques while maintaining good crystalline quality and relatively low production cost. These characteristics make ZnO a promising candidate for optoelectronic, transparent electronic, and spintronic devices (Pearson et al., 2003).

One of the most effective approaches to modify the magnetic and electrical properties of ZnO is the incorporation of transition-metal ions into its crystal lattice. Among different magnetic dopants, manganese (Mn) has received particular attention because its ionic radius is close to that of Zn^{2+} , allowing substitution with minimal lattice distortion. Theoretical investigations performed by Dietl et al. (2000) predicted that Mn-doped ZnO could exhibit ferromagnetism above room temperature under suitable carrier concentrations, which stimulated extensive experimental studies on this material system.

Although numerous investigations have been reported during the last two decades, the magnetic origin of Mn-doped ZnO remains a subject of debate. The observed magnetic and electrical properties strongly depend on the preparation technique, Mn concentration, crystalline defects, oxygen vacancies, and the possible formation of secondary phases. Consequently, careful structural characterization together with magnetotransport analysis is essential for understanding the interaction between localized magnetic moments and charge carriers in Mn-substituted ZnO thin films (Chen et al., 2011).

Among the available thin-film fabrication techniques, ultrasonic spray pyrolysis (USP) has attracted increasing interest because of its simplicity, low equipment cost, high deposition efficiency, and suitability for large-area coating. Furthermore, USP enables

precise control of the chemical composition of thin films while maintaining good structural uniformity. Recent studies have shown that optimization of deposition parameters significantly influences the microstructure and electrical transport characteristics of ZnO-based thin films, highlighting the importance of detailed structural and magnetotransport investigations (Khan et al., 2022; Kumar et al., 2024).

Despite considerable progress in the development of Mn-doped ZnO thin films, comprehensive studies correlating structural morphology with room-temperature magnetotransport properties for films prepared by ultrasonic spray pyrolysis are still relatively limited. Therefore, further investigation is required to better understand the influence of Mn incorporation on carrier transport mechanisms and the potential applicability of these materials in spintronic devices.

The objective of the present study is to investigate the structural and magnetotransport properties of pure ZnO and $\text{Zn}_{0.95}\text{Mn}_{0.05}\text{O}$ thin films deposited on Si(100) substrates by ultrasonic spray pyrolysis. Particular attention is devoted to evaluating the influence of Mn substitution on the structural morphology and magnetoresistance behavior of ZnO thin films in order to assess their potential for future spintronic and magnetoelectronic applications.

2. Materials and Methods

2.1. Thin Film Preparation

Pure ZnO and Mn-substituted ZnO ($\text{Zn}_{0.95}\text{Mn}_{0.05}\text{O}$) thin films were deposited on Si(100) substrates using the ultrasonic spray pyrolysis (USP) technique. Zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$) and manganese acetate tetrahydrate ($\text{Mn}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$) were used as precursor materials for Zn and Mn ions, respectively. Thiourea ($\text{CH}_4\text{N}_2\text{S}$) was added to the precursor solution to improve the film formation process and enhance the uniformity of the deposited layers.

The precursor solutions were prepared by dissolving the required amounts of the starting materials in distilled water under continuous magnetic stirring until a clear and homogeneous solution was obtained. The Mn concentration was adjusted to 5 at.% by partially substituting Zn with Mn in the precursor solution. The prepared solution was sprayed onto cleaned Si(100) substrates using an ultrasonic atomizer under controlled deposition conditions. During deposition, the substrate temperature was maintained at an appropriate level to ensure complete thermal decomposition of the precursor droplets and the formation of crystalline oxide thin films.

2.2. Structural Characterization

The surface morphology and microstructural characteristics of the deposited thin films were examined using scanning electron microscopy (SEM). SEM analysis was employed to investigate the grain morphology, grain size distribution, surface homogeneity, and film continuity. The average thickness of the deposited films was determined from cross-sectional SEM images and compared for both undoped and Mn-substituted ZnO samples.

3. Results

3.1. Structural Morphology

Figure 1 presents the SEM image of the undoped ZnO thin film and the room-temperature magnetoresistance curves of pure ZnO and Zn_{0.95}Mn_{0.05}O thin films.

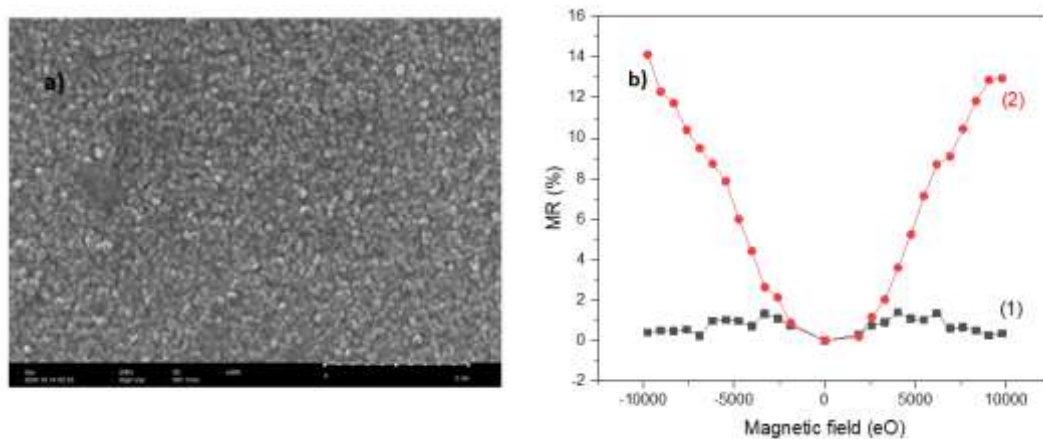


Figure 1. (a) SEM micrograph of the undoped ZnO thin film; (b) Room-temperature magnetoresistance curves of undoped ZnO (1) and Zn_{0.95}Mn_{0.05}O (2).

The surface morphology of the undoped ZnO thin film deposited by ultrasonic spray pyrolysis was examined using scanning electron microscopy (SEM). As shown in Figure 1(a), the deposited film exhibits a dense and continuous polycrystalline structure composed of uniformly distributed nanocrystalline grains. No noticeable cracks, pinholes, or large agglomerates are observed, indicating good surface homogeneity and successful film formation.

The average grain size is approximately **100 nm**, while the average thickness of both the undoped ZnO and Zn_{0.95}Mn_{0.05}O thin films is about **200 nm**. These observations indicate that the incorporation of 5 at.% Mn does not significantly influence the film growth process or the overall morphology under the selected deposition conditions.

3.2. Magnetotransport Properties

The room-temperature magnetoresistance (MR) curves of pure ZnO and Zn_{0.95}Mn_{0.05}O thin films are presented in Figure 1(b). The magnetoresistance was calculated using

$$MR = \frac{R(H) - R(0)}{R(0)} \times 100\%$$

where $R(H)$ and $R(0)$ denote the electrical resistance measured in the presence and absence of an external magnetic field, respectively. All measurements were performed using a constant current of **40 μ A**.

As shown in Figure 1(b), the undoped ZnO thin film exhibits only a weak variation in electrical resistance over the investigated magnetic-field range, with MR values remaining close to zero. In contrast, the Zn_{0.95}Mn_{0.05}O thin film demonstrates a pronounced positive magnetoresistance that increases with increasing magnetic field strength. The maximum MR reaches approximately **13–14 %** at magnetic fields close to **± 10 kOe**. Furthermore, the MR curves are nearly symmetric with respect to the positive and negative magnetic-field directions, indicating reproducible magnetotransport behavior.

The experimental results clearly demonstrate that Mn substitution considerably enhances the magnetic-field response of ZnO thin films while preserving their structural integrity.

4. Discussion

The structural and magnetotransport results demonstrate that Mn incorporation significantly influences the electrical transport properties of ZnO thin films without causing noticeable deterioration of the film morphology. The SEM observations reveal a dense and homogeneous nanocrystalline microstructure, indicating that ultrasonic spray pyrolysis provides favorable conditions for the growth of high-quality ZnO-based thin films. The absence of visible cracks or large agglomerates suggests that the selected deposition parameters are suitable for obtaining continuous thin films.

The most remarkable result of this study is the significant enhancement of positive magnetoresistance after Mn incorporation. While the undoped ZnO thin film exhibits negligible magnetoresistance over the investigated magnetic-field range, the Zn_{0.95}Mn_{0.05}O sample reaches a maximum MR of approximately **13–14 %** at magnetic fields close to **± 10 kOe**. This substantial increase confirms that Mn ions effectively modify the carrier transport mechanism in the ZnO lattice.

The enhancement of magnetoresistance can be explained by **spin-dependent carrier scattering**. When Mn^{2+} ions substitute Zn^{2+} sites, localized magnetic moments are introduced into the ZnO crystal lattice. Under an applied magnetic field, interactions between conduction electrons and these localized magnetic moments increase the scattering probability of charge carriers, resulting in an increase in electrical resistance. Similar positive magnetoresistance behavior has been reported for Mn-doped ZnO thin films by Chen et al. (2011), while the theoretical possibility of magnetic ordering in Mn-substituted ZnO was first predicted by Dietl et al. (2000).

The obtained results are also consistent with the general concept of diluted magnetic semiconductors proposed by Wolf et al. (2001), who emphasized that incorporating magnetic ions into semiconductor materials enables simultaneous manipulation of electron charge and spin. Furthermore, Pearson et al. (2003) reported that transition-metal-doped ZnO is one of the most promising oxide semiconductors for spintronic applications because of its wide band gap, structural stability, and compatibility with magnetic dopants.

Overall, the present results demonstrate that Mn substitution effectively enhances the magnetotransport response of ZnO thin films while preserving their structural quality. Therefore, Mn-substituted ZnO thin films prepared by ultrasonic spray pyrolysis represent promising candidates for future spintronic and magnetoelectronic devices.

5. Conclusion

Pure ZnO and Mn-substituted ZnO ($\text{Zn}_{0.95}\text{Mn}_{0.05}\text{O}$) thin films were successfully deposited on Si(100) substrates using the ultrasonic spray pyrolysis technique. SEM analysis confirmed the formation of dense and homogeneous polycrystalline films with uniformly distributed nanocrystalline grains, indicating that the incorporation of 5 at.% Mn does not significantly affect the growth morphology or structural quality of the deposited films.

Room-temperature magnetotransport measurements revealed a significant difference between the undoped and Mn-substituted samples. While the pure ZnO thin film exhibited negligible magnetoresistance, the $\text{Zn}_{0.95}\text{Mn}_{0.05}\text{O}$ thin film showed a pronounced positive magnetoresistance, reaching approximately 13–14 % under an external magnetic field of ± 10 kOe. The enhanced magnetoresistance is attributed to the influence of Mn ions on the carrier transport mechanism within the ZnO lattice.

The obtained results demonstrate that Mn substitution effectively improves the magnetotransport properties of ZnO thin films without degrading their structural characteristics. These findings indicate that Mn-doped ZnO thin films prepared by

ultrasonic spray pyrolysis are promising materials for future spintronic and magnetoelectronic applications. Further investigations involving different Mn concentrations and complementary structural and magnetic characterization techniques are expected to provide a more comprehensive understanding of the relationship between microstructure and spin-dependent transport properties.

References

- Dietl, T., Ohno, H., Matsukura, F., Cibert, J., & Ferrand, D. (2000). *Zener model description of ferromagnetism in zinc-blende magnetic semiconductors*. Science, 287(5455), 1019–1022. <https://doi.org/10.1126/science.287.5455.1019>
- Chen, L., Yang, S., Ramachandran, V., Zhong, J., Dai, Y., Zhang, Y., & Coey, J. M. D. (2011). *Magnetoresistance in Mn-doped ZnO thin films*. Nano Letters, 11(6), 2584–2589.
- Khan, M. A., Ahmad, R., Ali, A., & Hussain, S. (2022). *Structural, optical and magnetic properties of Mn-doped ZnO thin films prepared by spray pyrolysis*. Ceramics International, 48(18), 27143–27152.
- Kumar, R., Sharma, P., & Singh, A. (2024). *Recent advances in Mn-doped ZnO thin films for spintronic applications: A review*. Journal of Alloys and Compounds, 986, 174123.
- Pearson, S. J., Norton, D. P., Ivill, M. P., Hebard, A. F., Zavada, J. M., Chen, W. M., & Buyanova, I. A. (2003). *Advances in wide bandgap materials for semiconductor spintronics*. Journal of Applied Physics, 93, 1–13.
- Wolf, S. A., Awschalom, D. D., Buhrman, R. A., Daughton, J. M., von Molnár, S., Roukes, M. L., Chtchelkanova, A. Y., & Treger, D. M. (2001). *Spintronics: A spin-based electronics vision for the future*. Science, 294(5546), 1488–1495. <https://doi.org/10.1126/science.1065389>

Improving Molybdenum Recovery in Copper–Molybdenum Ore Beneficiation Through Process Mineralogy

Abdirashid Xasanov¹, Adxam Xasanov², Xilola Xojimuratova³

Abstract

The recovery of molybdenum from copper–molybdenum ores is one of the key challenges in mineral processing because it is strongly influenced by the ore's mineralogical characteristics, textural features, and the liberation degree of molybdenite. Process mineralogy has become an essential approach for understanding the relationship between ore properties and beneficiation performance, enabling the optimization of flotation technology and improving resource utilization. This study investigates the process mineralogical characteristics of copper–molybdenum ores from the Kalmakir deposit and evaluates their influence on molybdenum recovery during flotation.

Mineralogical observations were conducted using an ADF U300P polarizing microscope to determine mineral associations, grain size distribution, and the liberation degree of molybdenite. The chemical composition of ore samples and flotation products was determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The results demonstrate that the association of molybdenite with chalcopyrite and other sulfide minerals significantly affects flotation efficiency and contributes to molybdenum losses in tailings. It was found that an increase in the liberation degree of molybdenite under appropriate grinding conditions enhances molybdenum recovery and improves concentrate quality. The findings confirm that integrating process mineralogy with flotation studies provides valuable information for optimizing

¹ Doctor of Technical Sciences (D.Sc.), Professor, Deputy Director for Technology, Center for the Development and Implementation of Innovative Technologies, Joint Stock Company "Almalyk Mining and Metallurgical Complex" (AMMC), Almalyk, Uzbekistan; abdurashidsoli@mail.ru; ORCID: 0009-0000-8056-5930

² Doctor of Philosophy (PhD) in Technical Sciences, Associate Professor, Dean of the Faculty of Mining, Almalyk State Technical Institute, Almalyk, Uzbekistan adhamhasanov122@gmail.com; ORCID: 0009-0001-9946-7123

³ Basic Doctoral Student, Department of Mining Engineering, Faculty of Mining, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: xilolaxojimurotova@gmail.com (corresponding author); ORCID: 0009-0005-6907-7297

beneficiation parameters, reducing valuable mineral losses, and increasing the overall efficiency of copper–molybdenum ore processing. The proposed approach can serve as a scientific basis for improving mineral processing technologies in industrial applications.

Keywords: copper–molybdenum ore, process mineralogy, molybdenite, flotation, liberation degree, beneficiation, ICP-MS, ADF U300P, Kalmakir deposit.

1. Introduction

Copper and molybdenum are considered strategic metals in modern metallurgical industries due to their extensive industrial applications. In particular, the demand for molybdenum has increased significantly because of its widespread use in heat-resistant steels, high-performance alloys, and the chemical industry. Therefore, achieving high molybdenum recovery from copper–molybdenum ores has become one of the primary objectives of mineral processing technologies (Wills et al., 2023).

In copper–molybdenum ores, molybdenum mainly occurs as molybdenite (MoS_2). Such mineral associations limit the complete liberation of valuable minerals and may result in significant molybdenum losses during the flotation process (Bulatovic, 2018; Yi et al., 2021).

In recent years, process mineralogy has become an important scientific approach for optimizing mineral processing technologies through the evaluation of mineral composition, grain size distribution, liberation characteristics, and mineral associations. This approach provides a scientific basis for selecting appropriate grinding conditions, optimizing flotation reagent consumption, and improving the recovery of valuable minerals (Abdollahi et al., 2020; Tanaka et al., 2021).

The copper–molybdenum ores of the Kalmakir deposit, operated by the Almalyk Mining and Metallurgical Complex, are characterized by a complex mineralogical composition. Therefore, a comprehensive investigation of their process mineralogical characteristics is essential for improving beneficiation efficiency. The application of modern mineralogical and analytical techniques plays a significant role in optimizing flotation performance and enhancing metal recovery (Gupta & Yan, 2016; Wills et al., 2023).

2. Materials and Methods

Copper–molybdenum ore samples from the Kalmakir deposit and beneficiation products obtained from the No. 1 Copper Concentrator of the Almalyk Mining and Metallurgical Complex were investigated. The feed ore, bulk Cu–Mo concentrate, copper

concentrate, molybdenum concentrate, and flotation tailings were analyzed to evaluate the distribution and liberation of molybdenite. Mineralogical investigations were carried out using an ADF U300P polarizing microscope to determine mineral composition, grain size, and mineral associations. The chemical composition of the samples was determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The obtained mineralogical and chemical data were compared to assess the relationship between molybdenite liberation and flotation performance.

3. Results

3.1. Mineralogical Characteristics of the Kalmakir Copper–Molybdenum Ore

Microscopic investigation of the Kalmakir copper–molybdenum ore revealed a complex mineralogical composition. The principal ore minerals were chalcopyrite (CuFeS_2) and molybdenite (MoS_2), accompanied by pyrite (FeS_2), magnetite, and other gangue minerals. Photomicrographs showed that a considerable proportion of molybdenite grains remained closely associated with chalcopyrite and pyrite, while only a limited number of grains occurred in a completely liberated state (Figures 1 and 2).

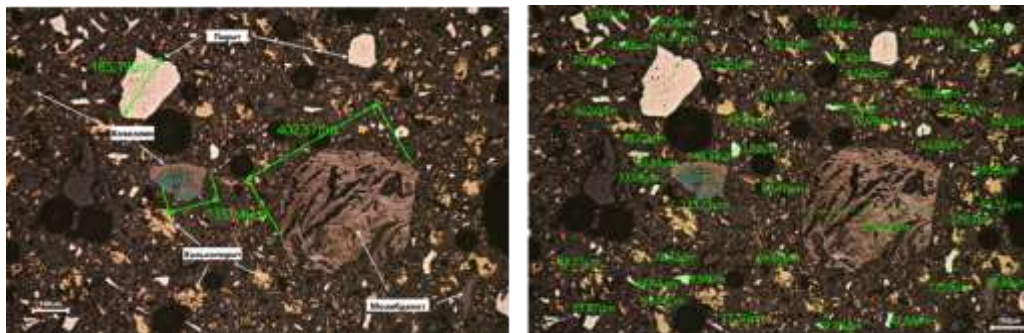


Figure 1. Photomicrograph of minerals in the Cu–Mo concentrate showing mineral phases (left) and grain size measurements (right). Magnification $\times 100$.

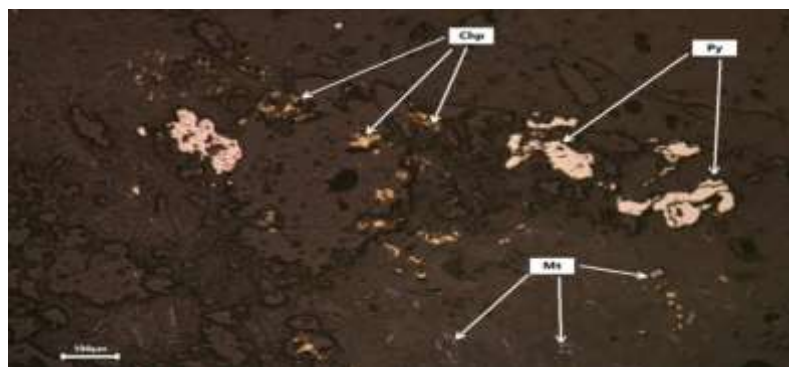


Figure 2. Disseminated pyrite (Py), chalcopyrite (Chp), and magnetite (Mt) observed in a polished briquette section. Magnification: $\times 100$.

3.2. Liberation Characteristics of Molybdenite

The mineralogical observations demonstrated that the liberation degree of molybdenite strongly depended on the grinding conditions. Insufficient grinding resulted in a high proportion of locked molybdenite grains, whereas optimal grinding increased the amount of liberated molybdenite and improved the exposure of mineral surfaces. These observations indicate that mineral liberation is one of the controlling factors affecting flotation efficiency.

3.3. ICP-MS Analysis of Beneficiation Products

ICP-MS analysis was performed to determine the distribution of copper and molybdenum in the feed ore and beneficiation products (Table 1).

Table-1 Summary of the Main Findings of the Study

Analysis	Main Findings	Effect on Molybdenum Recovery
Microscopic analysis (ADF U300P)	Most molybdenite grains are associated with chalcopyrite and pyrite.	Reduces flotation efficiency and increases molybdenum losses.
Liberation degree	Insufficient grinding leaves molybdenite locked within sulfide minerals.	Decreases molybdenum recovery into the concentrate.
ICP-MS analysis	Most molybdenum is concentrated in the molybdenum concentrate, while a small amount remains in the tailings.	Indicates incomplete liberation of molybdenite.
Overall assessment	Optimized grinding improves mineral liberation and flotation performance.	Increases molybdenum recovery and concentrate quality.

The analytical results showed that the highest concentration of molybdenum was obtained in the molybdenum concentrate, whereas measurable amounts of molybdenum remained in the flotation tailings. This distribution indicates that a portion of molybdenite was not completely recovered during flotation because of incomplete liberation and mineral intergrowth.

3.4. Relationship Between Process Mineralogy and Flotation Performance

The combined mineralogical observations and chemical analyses confirmed a direct relationship between the liberation degree of molybdenite and molybdenum recovery. Samples containing a higher proportion of liberated molybdenite exhibited better flotation performance and produced concentrates of higher quality.

1. Discussion

The results obtained in this study demonstrate that the mineralogical characteristics of the Kalmakir copper–molybdenum ore have a decisive influence on flotation performance. The close association of molybdenite with chalcopyrite and pyrite limits the complete liberation of valuable minerals, resulting in reduced molybdenum recovery and increased metal losses in flotation tailings. These findings are consistent with previous studies, which have shown that mineral associations are among the most important factors controlling the efficiency of copper–molybdenum flotation (Abdollahi et al., 2020; Yi et al., 2021).

The mineralogical observations and ICP-MS analyses confirmed that increasing the liberation degree of molybdenite improves flotation selectivity and concentrate quality. However, excessive grinding may generate fine slimes that reduce collector adsorption and increase reagent consumption. Therefore, an optimum grinding size should be selected based on the mineralogical characteristics of the ore rather than applying a fixed grinding regime. Similar conclusions have been reported by Bulatovic (2018) and Wills et al. (2023), who emphasized that appropriate particle liberation is essential for efficient flotation.

The integration of process mineralogy with flotation studies provides a reliable basis for optimizing beneficiation parameters and improving metal recovery. The application of modern analytical techniques, including ADF U300P microscopy and ICP-MS, enables a more accurate evaluation of ore characteristics and supports scientifically based process optimization. Consequently, this approach can contribute to higher molybdenum recovery, lower metal losses, and improved economic efficiency in the processing of copper–molybdenum ores from the Kalmakir deposit.

2. Conclusion

The results of this study demonstrate that the process mineralogical characteristics of the Kalmakir copper–molybdenum ores have a significant influence on flotation performance. The close association of molybdenite grains with chalcopyrite and other sulfide minerals restricts the complete liberation of valuable minerals and contributes to molybdenum losses in flotation tailings.

Mineralogical observations conducted using an ADF U300P polarizing microscope, together with ICP-MS analyses, confirmed a direct relationship between the liberation degree of molybdenite and beneficiation performance. Optimal grinding conditions increase the proportion of liberated molybdenite grains, promote the effective

adsorption of flotation collectors onto mineral surfaces, and consequently improve molybdenum recovery into the concentrate.

The findings indicate that integrating process mineralogy into mineral processing technology provides a scientific basis for a comprehensive evaluation of ore characteristics, optimization of grinding parameters, and improvement of the technical and economic efficiency of the flotation process. The obtained results can contribute to the further development of beneficiation technologies for copper–molybdenum ores from the Kalmakir deposit and provide a practical and scientific foundation for enhancing molybdenum recovery in future research and industrial applications.

References

- Abdollahi, H., Noaparast, M., Shafaei, S. Z., & Abdollahi, M. (2020). *A process mineralogy approach to optimize molybdenite flotation in copper–molybdenum processing plants. Minerals Engineering, 157*, 106557. <https://doi.org/10.1016/j.mineng.2020.106557>
- Bulatovic, S. M. (2018). *Handbook of flotation reagents: Chemistry, theory and practice* (Vol. 1, 2nd ed.). Elsevier.
- Gupta, A., & Yan, D. S. (2016). *Mineral processing design and operation: An introduction* (2nd ed.). Elsevier.
- Kelly, E. G., & Spottiswood, D. J. (1982). *Introduction to mineral processing*. John Wiley & Sons.
- Lotter, N. O., & Kormos, L. J. (2010). Process mineralogy as a tool for improving flotation performance. *Minerals Engineering, 23*(6), 451–458.
- Tanaka, M., Ito, M., & Tsunekawa, M. (2021). Application of process mineralogy in optimization of copper–molybdenum flotation circuits. *Minerals, 11*(8), 812.

International Experience and Contemporary Technological Approaches to Manganese Recovery from Manganese-Containing Raw Materials

Sarvar Parmonov¹, Dostonbek Mirzavaliyev², Nafisa Muzafarova³

Abstract

This paper reviews global practices for extracting manganese from manganese-bearing ores, ferroalloy dusts, electrolytic manganese residues, and battery raw materials. Pyrometallurgy, reductive sulfate hydrometallurgy, reductive roasting followed by leaching, bioleaching, and combined pyro-hydrometallurgical schemes are compared, together with deep solution refining based on solvent extraction, ion exchange, electrodialysis, crystallization, and electrolysis. The analysis shows that, alongside the traditional steel market, the production of battery-grade high-purity manganese sulfate has become the key driver of the ongoing technological shift, moving the industry from bulk metallurgy toward high-purity chemistry. For high-grade ores, pyrometallurgy retains its economic logic, whereas for low-grade and complex oxide raw materials reductive sulfate leaching with oxalate, sucrose, or biomass reductants achieves manganese recoveries of 94–98%, and sulfur-based reductive roasting at 550 °C extracts 95.6% of Mn. Deep purification stages enable the production of 99.5% pure MnSO₄ crystals and electrolytic manganese metal containing 99.81% Mn. Environmental factors, including electrolytic manganese residue generation of 7–9 tons per ton of metal and the dominant share of electricity in the life cycle impact, have become integral criteria of technology selection. For the low- and medium-grade manganese occurrences of Uzbekistan, hydrometallurgical or combined pyro-hydrometallurgical flowsheets combining beneficiation, selective reductive sulfate leaching, and staged solution purification are recommended as the priority direction.

¹ Vice-Rector for Research and Innovation, Almalyk State Technical Institute, Almalyk, Uzbekistan. s.toshpulatovich@odti.uz; ORCID: 0000-0001-6634-8606

² Associate Professor (PhD), Head of International Cooperation Department, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: 5515414d@gmail.com (corresponding author) ORCID: 0009-0006-1612-7083

³ Assistant of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: nafisamuzafarova1521@gmail.com; ORCID: 0009-0005-7757-3389

Keywords: manganese; manganese-containing raw materials; hydrometallurgy; reductive sulfate leaching; reductive roasting; bioleaching; solvent extraction; high-purity manganese sulfate; electrolytic manganese metal; Uzbekistan.

1. Introduction

Manganese is strategically important in two markets simultaneously: the traditional metallurgical market, where it serves desulfurization, deoxidation, and alloying functions in steelmaking, and the rapidly growing market for new energy materials, where demand for manganese sulfate, electrolytic manganese dioxide (EMD), and cathode precursors is expanding. These two vectors determine modern technological choice: pyrometallurgical routes dominate for high-grade ores, while hydrometallurgical routes are increasingly preferred for complex and low-grade raw materials.

Global manganese mine production in 2025 was estimated at 20.0 million tons of contained Mn. South Africa led with 7.6 million tons, followed by Australia (1.6), Brazil (0.8), India (0.79), and China (0.70 million tons) (U.S. Geological Survey [USGS], 2026). However, a high share of ore production does not necessarily imply leadership in high-purity chemicals: although China's ore output is far below South Africa's, China accounts for approximately 90% of the global supply of high-purity manganese (Reuters, 2024).

Uzbekistan possesses more than 30 manganese occurrences and five small deposits. In the Dautash ores, Mn typically ranges from 8 to 35%; in Kyzylbayrak, from 13 to 25%; and in Alysay, MnO₂ varies from 5 to 43%, averaging around 17%. The total forecast resources of the Karatau Mountains are estimated at 8 million tons. A significant part of this raw material base is low- and medium-grade and variable in composition, making it more suitable for selective chemical processing than for direct ferroalloy production.

The aim of this paper is to systematize world practice in manganese extraction and to identify the technological class best suited to the conditions of Uzbekistan.

2. Materials And Methods

The study is based on a comparative analysis of open scientific and industrial sources published between 1994 and 2026, including USGS mineral commodity summaries, peer-reviewed hydrometallurgical literature, life cycle assessment (LCA) studies, and official company and government reports from the leading manganese-producing countries. Five technological blocks were examined: (i) pyrometallurgy; (ii) reductive sulfate hydrometallurgy; (iii) reductive roasting with subsequent leaching; (iv) bioleaching; and (v) deep solution refining. The technologies were compared using six criteria: manganese recovery, energy demand, reagent profile, primary environmental risk, technological maturity, and eligibility for Uzbekistan's raw material base.

3. Results

3.1. Pyrometallurgy

Pyrometallurgy remains the industrial backbone of the ferromanganese and silicomanganese chains. Its strengths are process maturity, high unit capacity, and direct integration with the steel industry; its weaknesses are high consumption of electricity and reductants and a significant carbon footprint. A global estimate recorded approximately 6.0 kg CO₂-eq of cradle-to-gate emissions per kilogram of average manganese alloy (Integrating Process Simulation, 2024). South Africa's Kalahari Basin, hosting around 80% of world manganese resources, and Brazil's Azul mine in the Carajás complex represent the natural strongholds of this route (South32, 2025).

3.2. Reductive Sulfate Leaching

The central chemical problem of dissolving manganese oxide ores in sulfate media is the need to reduce Mn(IV) to soluble Mn(II). Oxalic acid provides very high manganese recovery from low-grade ores through the combined action of reduction and complexation (Sahoo et al., 2001). Leaching with sucrose at 50 °C and 1 M H₂SO₄ yields up to 94% Mn (Vegliò & Toro, 1994), while glucose acts through the formation of formate and other short-chain oxidation products (Furlani et al., 2006). Approximately 98% leaching efficiency has been recorded using banana peel, indicating that agricultural waste can serve as a low-cost, renewable reductant (Ali et al., 2021).

3.3. Reductive Roasting And Bioleaching

For complex oxide ores, reductive roasting followed by sulfate leaching is often the most balanced option. Sulfur-based roasting at 550 °C for 10 minutes extracted 95.6% of Mn while suppressing iron dissolution (Zhang et al., 2013). Bioleaching with *Aspergillus niger* achieved more than 80% Mn recovery within 30 days through a combination of acidolysis, complexolysis, and redoxolysis; however, long process duration and bioreactor management limit its industrial implementation (Keshavarz et al., 2021).

3.4. Solution Purification And Refining

The greatest value addition occurs during post-leaching refining. Using D2EHPA to remove Fe(III) and Cyanex 272 to remove Zn(II), 99.5% pure MnSO₄ crystals were obtained from ferroalloy dust leach solutions (Wen et al., 2023). A Cyanex272–HTTA synergistic system yielded 97.83% Mn extraction with an Mn/Mg separation factor of 81.7 in a single stage, which is particularly important for magnesium-rich solutions (Selective Recovery, 2026). In a "green" electrolytic manganese metal (EMM) process based on neodecanoic acid extraction, 88.87% of Mg was removed and EMM containing 99.81% Mn was produced (A Green Production Process, 2023). Electrodialysis removed

87–97% of heavy metals from manganese residue leachate while recovering 95% of ammonia nitrogen (Simultaneous Recovery, 2023).

4. Discussion

The comparison reveals a clear structural shift: the technological center of manganese extraction is moving from bulk metallurgy toward high-purity chemistry. Country models confirm this divergence — South Africa represents "bulk ore strength," China represents "refined chemistry strength," while Australia and Brazil are transitioning toward combined ore and downstream chemistry models (USGS, 2026; Reuters, 2024).

Environmental performance has become an integral part of technology selection. Approximately 7–9 tons of electrolytic manganese residue are generated per ton of EMM, and accumulated stockpiles have exceeded 50 million tons, growing by about 10 million tons annually (He et al., 2021). LCA results attribute 57.43% of the environmental impact of EMM production to electricity generation (Life Cycle Assessment, 2024). Consequently, the electricity mix and residue management are as decisive as reagent selection.

For Uzbekistan, the justified technological class is a hydrometallurgical or combined pyro-hydrometallurgical scheme: mineralogical typing and beneficiation; direct reductive sulfate leaching for carbonate and easily soluble ores, or reductive roasting followed by leaching for oxide ores with severe Fe/Mg problems; deep purification of Fe, Al, Zn, and Mg; and, finally, MnSO_4 crystallization or EMM/EMD production depending on the target market. The main limitation is the absence of open pilot-scale mass balance data for Uzbek ores, which defines the nearest direction of experimental work.

5. Conclusion

World practice shows that pyrometallurgy retains its economic logic for high-grade ore bases, whereas reductive sulfate hydrometallurgy creates greater value for low-grade and complex oxide raw materials, especially when combined with deep refining. Reductive roasting followed by leaching offers the most practical compromise for raw materials with severe iron and magnesium problems. Environmental sustainability — electricity mix, residue management, and water circulation — has become an integral criterion of technology choice. For Uzbekistan's low- and medium-grade, variable-composition manganese occurrences, hydrometallurgical or combined pyro-hydrometallurgical routes based on selective leaching, solvent extraction, and targeted crystallization or electrolysis offer the best technical and economic prospects.

References

Мирзавалиев Достонбек Баходир Угли, Парманов Сарвар Тошпутович, Улугов Голибжон Давлатович ПЕРЕРАБОТКА ВОЛЬФРАМСОДЕРЖАЩИХ ОТХОДОВ И ПОЛУЧЕНИЕ РАСТВОРА ВОЛЬФРАМАТА НАТРИЯ // Universum: технические науки. 2023. №10-2 (115). URL: <https://cyberleninka.ru/article/n/pererabotka-volframsoderzhaschih-othodov-i-poluchenie-rastvora-volframata-natriya> (дата обращения: 19.07.2026).

Mizavaliyev D., Karshiboyev S. THE MAIN PROBLEMS OF OBTAINING HIGHPURE SELENIUM IN THE INDUSTRY AND WAYS TO SOLVE THEM //Innovations in Technology and Science Education. – 2023. – T. 2. – №. 9. – С. 106-113.

Parmonov, S., Sharipov, K., Mirzavaliyev, D., Makhmudova, F., Askarova, N., Toshkodiroya, R., ... & Kambarov, A. (2024). The Technology of Obtaining Powders Used in the Production of Solid Alloys. *New Materials, Compounds and Applications*, 8(3), 450-458.

Parmonov, S., Sharipov, K., Mirzavaliyev, D., Makhmudova, F., Askarova, N., Toshkodiroya, R., ... & Kambarov, A. (2024). The Technology of Obtaining Powders Used in the Production of Solid Alloys. *New Materials, Compounds and Applications*, 8(3), 450-458.

S. Parmonov, K. Sharipov, A. Kambarov, M. Khoshimkhanova, A. Abdurimov, D. Mirzavaliyev, G. Yusupova, *E3S Web of Conferences*, 498, 03013 (2024)

The Technology Of Obtaining Powders Used In The Production Of Solid Alloys // S. Parmonov, K. Sharipov, D. Mirzavaliyev, et al., *New Mater., Compd. Appl.* 8, 450–458 (2024). <https://doi.org/10.62476/nmca83450>Sahoo, R. N., Naik, P. K., & Das, S. C. (2001). Leaching manganese from low-grade manganese ore using oxalic acid as a reducing agent in sulfuric acid solution. *Hydrometallurgy*, 62(3), 157–163.

System Integration of Resource-Saving Innovative Technologies Alongside Productivity Enhancement of Twin-Shaft Mixers

Bobozhanov M.K.¹, Rismukhamedov D.A.², Tuichiev F.N.³, Rozmetov X.E.⁴

Abstract

The priority task of modern industrial energy is the system integration of resource-saving innovative technologies along with increased productivity. In this context, the problem of designing electromechanical complexes with high energy efficiency and digitally automating their control algorithms remains a key link in the global technological transformation. Two-shaft mixers play a major role in complex technological cycles of the chemical, metallurgical and construction industries, in particular, in the processes of homogenization of refractory and acid-resistant components. However, traditional electric drive systems with single-speed asynchronous motors used in practice have a high coefficient of inertia, which leads to irreversible energy dissipation in transient modes (start and deceleration). This, in turn, reduces the overall efficiency of the system and causes an exponential increase in operating costs. In order to extend the mechanical life of the equipment and optimize the technological regulations, it becomes necessary to introduce contactless switching devices with high functionality. Modernization of existing low-efficiency and inertial drives based on intelligently controlled contactless modules is evaluated as

¹ Doctor of Technical Sciences, Professor of the Department of Electricity Supply at the Tashkent State Technical University named after Islam Karimov. mbobojanov@yahoo.com, ORCID: 0000-0002-0244-2932

² Doctor of Philosophy (PhD), Associate Professor, Department of Electrical Engineering and Electromechanics, Almalyk State Technical Institute. drismuxamedov@gmail.com, [http](http://), ORCID: 0000-0002-9458-0522

³ Doctor of Philosophy (PhD), Associate Professor of the Department of Electricity Supply at the Tashkent State Technical University named after Islam Karimov. tuychievfn@gmail.com, ORCID: 0000-0003-4858-3690

⁴ Senior lecturer, Department of Mining Electromechanics, Almalyk State Technical Institute. xamza@gmail.com, ORCID: 0009-0005-1061-4262

the optimal solution to minimize energy consumption, increase device life and ensure the stability of technological processes. Development and research of a two-speed asynchronous motor (DM) with a PPO for the electric drive of a two-shaft mixer providing a step start, precise stop and increased efficiency of the technological process. The following methods were applied in the work: electromagnetic calculation with the selection of optimal winding parameters for the analysis of DD with PPO at a pole pair ratio of 2:4; computer modeling in the ANSYS Maxwell software environment for magnetic field analysis; development of a contactless starting circuit for two-speed asynchronous motors; experimental studies of a prototype AIR180M8/4 motor with the acquisition of operating, mechanical and starting characteristics under production conditions.

A new pole-switching winding circuit was developed, and the AIR180M8/4 two-speed motor was designed based on it. The motor produces 18.5 kW at 1500 rpm ($p=2$) with 90% efficiency and 13.9 kW at 750 rpm ($p=4$) with 85% efficiency. The implementation of a contactless commutation system ensures long-term, safe, quiet, and reliable operation of the electric drive. Industrial tests at the facilities of Almalyk Mining and Metallurgical Combine JSC showed that the motor's integration into the VL-400-VRU mixer drive reduced the rotation cycle by 420 seconds and increased the daily mix capacity by 580 kg.

Keywords: Electric drive, twin-shaft mixer, pole-switching winding (PSW), two-speed asynchronous motor (AM), energy saving, transient processes, contactless start.

1. Introduction

Twin-shaft mixers of the VL-400-VRU type are critical equipment in industrial processes involving the preparation of special mixtures (refractory, acid-resistant). The specifics of the process—frequency of operation, the need for precise shaft positioning for loading/unloading, and the large inertial mass of the mixture—place stringent demands on the electric drive.



Fig. 1. General view of a twin-shaft mixer.

2. Materials And Methods

Using traditional single-speed asynchronous motors requires multiple short-term switching cycles (7-10 times per revolution), which leads to excessive wear on windings and mechanical transmissions, as well as significant starting currents that negatively impact the grid. This necessitates modernizing the electric drive to reduce dynamic loads, facilitate starting, and improve overall energy efficiency.

The use of two-speed motors allows for step-starting (first at low speed, then at high speed), thereby reducing the process cycle time. However, existing PPO circuits often have design flaws: complex switching, numerous terminals, and imperfect electromagnetic characteristics, which limits their widespread adoption.

The basis of the development is the method of discretely specified spatial functionals (DZSF), which allows for the synthesis of a PPO with a given ratio of pole pairs and high electromagnetic performance. The “Y- Δ /YY” configuration was used as the basic circuit (BC).

Based on the calculated data, an experimental model of a two-speed motor with a developed pole-switching winding for a pole pair ratio of 2/4 according to the BS “Y- Δ /YY” was manufactured at Energy Motors, based on the magnetic circuit of a serial machine of the AIR180M4U3 type with the number of stator slots $Z_1 = 48$ and rotor $Z_2 = 38$, the length of the stator package $l_\delta = 185$ mm.

3. Results

Electromagnetic calculation and selection of parameters: A comparative analysis of five winding options with different numbers of turns, conductor cross-sections and numbers of elementary conductors was carried out.

Table 1 shows that the energy performance of a two-speed electric motor in nominal operation was calculated by varying the number of turns in the winding slots, the conductor diameter, and the number of elementary conductors n . The results obtained suggest a significant impact of these parameters on motor efficiency.

Using a LeCroy WaveRunner 64Xi digital oscilloscope, the starting and gear shifting processes were studied.

Start at $p=4$: Starting current amplitude is 140–150 A ($4.5 I_{\sim nom}$). The mode is established in ~ 1.3 s.

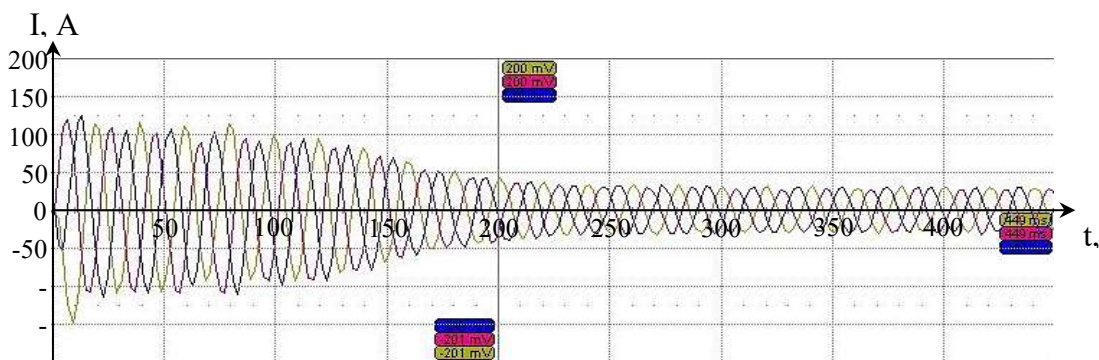


Fig. 2. Curves of change in stator current depending on time during starting from a standstill of an AIR180M8/4 type electric motor at $p2=4$

Start at $p=2$: Starting current amplitude is 280–300 A ($4.5 I_{\sim nom}$). The mode is established in ~ 3.5 s.

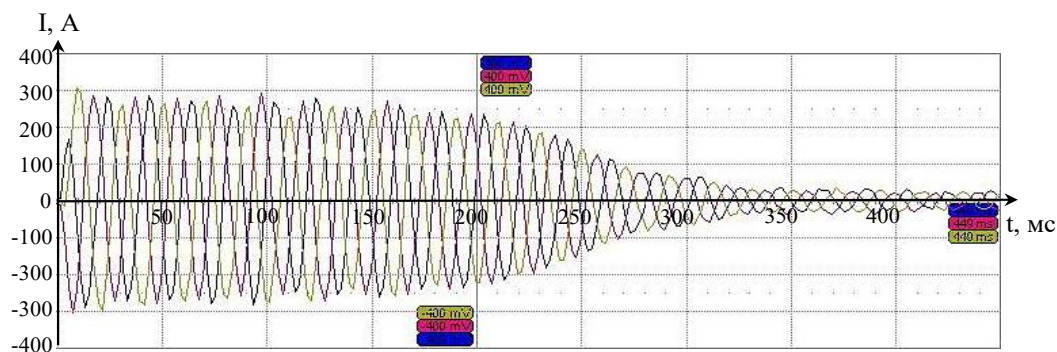


Fig. 3. Curves of change in stator current depending on time when starting from a standstill of an AIR180M8/4 type electric motor at $p2=2$

Switching $p=4 \rightarrow p=2$: The switching process lasts ~ 1.2 s, the currents do not exceed the starting values for the corresponding speed.

The dynamics of starting currents and transient processes are typical for asynchronous motors of this class and are within acceptable limits.

A prototype of the AIR180M8/4 engine was implemented in the drive of the VL-400-VRU two-shaft mixer in workshop No. 35 of NPO Almalyk GMK JSC.

Technological result: The use of a two-speed drive made it possible to implement the following optimal cycle:

Smooth start of the process and mixing at low speed ($p=4$, 750 rpm).

Switch to high speed ($p=2$, 1500 rpm) for the main mixing cycle.

Shift to low speed and stop precisely in a convenient position for unloading and braking.

As a result, the cycle time was reduced to 420 seconds (7 minutes). This allowed for an increase in the number of cycles per shift and an increase in daily production of finished mix by 580 kg.

Economic calculation: The net additional profit from implementing one motor amounted to approximately 37.4 million soums per year. Taking into account the operation of four VL-400-VRU mixers at the plant, the total annual economic benefit from implementing the developed drive is estimated at 149.4 million soums. This calculation includes energy savings due to reduced operating time and the elimination of multiple starts, as well as profit from increased output.

4. Conclusion

The motor's efficient operation in transient conditions (starting, gear shifting) has been experimentally confirmed. Starting currents and dynamic loads comply with standards.

Industrial implementation of the drive on a twin-shaft mixer has proven its technological and economic advantages: a reduction in cycle time by 7 minutes, an increase in daily production volume of the mixture by 580 kg, and an annual economic effect of ~149.4 million soums (12 320\$) for four units of equipment.

Thus, the electric drive developed on the basis of a two-speed motor with a pole-switching winding is an effective solution for the modernization of two-shaft mixers, ensuring significant resource and energy savings, and is recommended for widespread implementation at enterprises of a similar profile.

References

Karimov XG, Bobojanov MK New pole-changing windings for asynchronous motors of mechanisms with severe operating conditions// *Elektr.* - Moscow, 1996. - No. 1 - pp. 27-32 (45)

Bobojanov M. Induction machine with pole-changing winding for turbomechanisms. *Archives of Electrical Engineering*, 2023, Vol. 72, No. 2, P. 415–428. DOI: 10.24425/ae.2023.145417.

Rismuhamedov DA, Yuldoshov XE, Mominov VU, Toychiev FN, Rozmetov XE “Three-phase alternating current generator with a pole ratio of 8/4”. Patent for invention. No. IAP07040, 29.07.2022.

Rismuhamedov DA, To‘ychiev FN, G‘aniyev ST, Raykhonov Sh.Z., Shamsutdinov XF “Three-phase pole-changing motor with a ratio of 8/4”. Patent. No. IAP07210, 30.11.2022.

Rismuhamedov, XF Shamsutdinov, XE Ro'zmetov, SD Rismuhamedov. Improving the electromagnetic properties of pole-changing windings.

DA Rismuhamedov, XE Ro'zmetov, Z. Turg'unboyev. Ways to improve the efficient of electric drives of twin-shaft mixers//Mineral raw materials extraction, processing prospects from the perspective of youth: Sb. proc. republican. scientific-technical. conf. 2024 yil May 15. – Almalyk, 2024 yil, –P.

Developing Innovative Thinking in Engineering Education and Supporting the Potential of Young Researchers

Jasur Xamraboyevich Razzaqov¹

Abstract

Innovation has become one of the principal driving forces of economic development, industrial modernization and technological competitiveness in the twenty-first century. Consequently, engineering education is expected not only to provide students with professional knowledge and technical competencies but also to cultivate innovative thinking, creativity and research capabilities that enable future engineers to solve complex global challenges. Universities therefore play a crucial role in creating educational environments that encourage scientific inquiry, interdisciplinary collaboration and technological innovation from the early stages of academic training.

This paper examines contemporary approaches to developing innovative thinking in engineering education and explores institutional strategies for supporting the scientific potential of young researchers. Particular attention is devoted to student-centered learning, research-based education, interdisciplinary project activities, digital technologies and university-industry collaboration as mechanisms for strengthening innovation competencies. The study also discusses the importance of research mentorship, innovation ecosystems, technology transfer and international academic cooperation in preparing a new generation of engineering researchers capable of contributing to sustainable technological development. The paper concludes that the integration of innovative pedagogy, scientific research and institutional support systems represents a fundamental prerequisite for educating globally competitive engineers and future scientific leaders.

Keywords: Engineering Education, Innovative Thinking, Young Researchers, Research Competence, Innovation Ecosystem, Creativity, Technology Transfer, Higher Education.

¹ Almalyk State Technical Institute, Almalyk, Uzbekistan E-mail: razzaqovjasur@gmail.com, ORCID: 0009-0003-6534-1893

Introduction

The rapid advancement of science and technology has fundamentally transformed the role of engineering education in contemporary society. Modern engineers are no longer expected merely to apply existing technical knowledge; they are increasingly required to generate innovative ideas, design sustainable technological solutions and contribute to scientific advancement through research and development. Consequently, higher education institutions have shifted their educational priorities from knowledge transmission toward the development of creativity, critical thinking and innovation competencies.

The transition toward knowledge-based economies has significantly increased demand for professionals capable of responding effectively to rapidly changing technological environments. Digital transformation, artificial intelligence, automation, renewable energy systems and advanced manufacturing technologies continuously generate new engineering challenges that require original thinking and interdisciplinary problem-solving skills. Universities therefore face the responsibility of preparing graduates who possess not only technical expertise but also entrepreneurial thinking, research competence and innovation-oriented mindsets.

Innovative thinking has emerged as one of the core competencies defining engineering professionals in the twenty-first century. It involves the ability to analyze complex problems, generate creative solutions, evaluate technological alternatives and transform scientific knowledge into practical innovations. These competencies are developed through educational environments that encourage experimentation, collaboration, independent inquiry and continuous learning rather than relying solely on traditional lecture-based instruction.

At the same time, universities have become important centres for identifying, supporting and developing talented young researchers. Early involvement in scientific research enhances students' analytical abilities, strengthens professional motivation and creates pathways toward future academic careers. Participation in research projects, innovation competitions, engineering design challenges and international scientific collaboration enables young researchers to acquire valuable experience while contributing to technological development and institutional research capacity.

International organizations consistently emphasize that universities capable of integrating education, research and innovation achieve higher levels of academic quality and greater societal impact. Consequently, the development of innovative thinking and the systematic support of young researchers should be regarded as strategic priorities

within engineering education. This paper examines contemporary educational approaches that promote innovation competencies while exploring institutional mechanisms for nurturing the scientific potential of future engineering researchers.

Innovative Thinking as a Core Competency in Engineering Education

The transformation of engineering education has significantly altered the competencies expected from engineering graduates. Technical knowledge alone is no longer sufficient for addressing the increasingly complex technological, economic and environmental challenges of the modern world. Contemporary engineers must demonstrate innovative thinking, adaptability, interdisciplinary collaboration and the ability to generate practical solutions for problems that often have no predefined answers. Consequently, innovative thinking has become one of the fundamental competencies within engineering education.

Innovative thinking can be defined as the capacity to generate original ideas, critically evaluate existing approaches and develop practical technological solutions through creative and analytical reasoning. Unlike routine problem-solving, innovative thinking requires engineers to integrate scientific knowledge with imagination, experimentation and strategic decision-making. It combines technical expertise with creativity, enabling professionals to transform theoretical concepts into innovative products, processes and technologies.

Engineering education increasingly recognizes that innovation cannot be taught through traditional lecture-based instruction alone. Instead, universities are adopting active learning methodologies that encourage students to investigate real-world engineering problems, collaborate in multidisciplinary teams and engage directly with industrial challenges. These approaches strengthen independent learning while promoting intellectual curiosity and scientific inquiry.

One of the most influential educational frameworks supporting innovative thinking is the **CDIO (Conceive–Design–Implement–Operate)** model. CDIO emphasizes the complete engineering lifecycle by engaging students in designing, implementing and operating engineering systems rather than merely studying theoretical concepts. This educational philosophy allows learners to connect classroom knowledge with practical engineering applications while strengthening creativity, teamwork and decision-making skills.

Similarly, **Project-Based Learning (PBL)** has become an effective pedagogical approach for developing innovation competencies. Students work collaboratively on authentic engineering projects that require investigation, experimentation and iterative

design. Throughout these projects, learners develop not only technical expertise but also communication, leadership and entrepreneurial skills that are essential for innovation-driven industries.

Problem-Based Learning further strengthens innovative thinking by placing students in situations where solutions are not immediately available. Rather than memorizing predetermined answers, learners analyze complex engineering problems, evaluate alternative approaches and justify their decisions through scientific reasoning. This process develops analytical thinking, research competence and professional confidence while encouraging continuous intellectual development.

The integration of **Design Thinking** into engineering education has also gained increasing international recognition. Design Thinking places human needs at the centre of technological innovation by encouraging empathy, creativity, experimentation and rapid prototyping. Engineering students learn to understand user requirements, generate multiple design alternatives, test prototypes and continuously improve solutions through iterative feedback. This methodology has become particularly valuable in developing technologies that are technically feasible, economically viable and socially beneficial.

Interdisciplinary education further contributes to innovation by integrating engineering sciences with information technology, business, environmental studies and social sciences. Contemporary engineering challenges rarely belong to a single discipline; therefore, universities increasingly encourage students to participate in multidisciplinary research teams where diverse perspectives stimulate creative problem-solving and technological innovation.

Digital technologies have substantially expanded opportunities for cultivating innovative thinking. Artificial intelligence, simulation software, digital twins, virtual laboratories, cloud computing and advanced modelling platforms enable students to explore engineering concepts through interactive experimentation. These technologies reduce the gap between theoretical instruction and industrial practice while allowing learners to evaluate multiple engineering solutions efficiently.

Ultimately, innovative thinking develops most effectively within educational environments that value curiosity, experimentation and constructive failure. Universities should therefore establish academic cultures where students are encouraged to question conventional approaches, explore alternative ideas and transform scientific knowledge into technological innovation. Such environments prepare graduates not only to respond to future engineering challenges but also to become creators of technological progress.

Institutional Strategies for Supporting the Potential of Young Researchers

The sustainable development of engineering science depends largely on the ability of universities to identify, nurture and retain talented young researchers. Early engagement in scientific research enables students to acquire advanced analytical skills, develop scientific independence and contribute to technological innovation before entering professional careers. Consequently, supporting young researchers has become a strategic priority for engineering universities worldwide.

Modern universities increasingly recognize that research competence cannot be developed exclusively at postgraduate level. Instead, undergraduate and master's students should be systematically involved in scientific inquiry through research-oriented curricula, laboratory activities, innovation projects and interdisciplinary engineering competitions. Early exposure to research encourages intellectual curiosity while strengthening students' confidence in conducting independent scientific investigations.

Research mentorship represents one of the most effective mechanisms for developing young scientific talent. Experienced academics play a critical role in guiding students through research design, experimental methodologies, academic writing and ethical scientific practice. Effective mentoring relationships not only improve research quality but also foster professional identity, motivation and long-term commitment to scientific careers.

Participation in university research laboratories significantly enhances students' practical experience. Modern engineering laboratories equipped with advanced technologies allow young researchers to test innovative ideas, conduct experiments and collaborate with academic staff on ongoing scientific projects. These research environments bridge the gap between theoretical education and technological application while strengthening practical engineering competencies.

Innovation competitions, hackathons, engineering design contests and startup incubators have emerged as valuable instruments for identifying talented students and stimulating creative problem-solving. Participation in these activities encourages students to transform research findings into practical innovations while developing entrepreneurial thinking, project management skills and interdisciplinary collaboration. Universities that actively support such initiatives create dynamic innovation ecosystems capable of generating commercially valuable technological solutions.

International academic cooperation further expands opportunities for young researchers. Student participation in international conferences, research internships, exchange programmes and collaborative projects enables future scientists to gain

exposure to global research standards and multicultural academic environments. Such experiences improve scientific communication skills, broaden research perspectives and facilitate future international collaboration.

Scientific publication also constitutes an essential stage in developing research competence. Universities should encourage students to participate in academic writing workshops, research seminars and publication mentoring programmes that familiarize young researchers with international publishing standards. Early publication experience strengthens analytical thinking while enhancing institutional research productivity and global academic visibility.

Moreover, universities should establish comprehensive support systems that include research grants for students, seed funding for innovative projects, access to digital scientific databases, intellectual property guidance and opportunities for collaboration with industry. Such institutional mechanisms create favourable conditions for transforming promising ideas into impactful scientific and technological outcomes.

The development of young researchers should therefore be viewed as a long-term investment in national scientific capacity and technological competitiveness. By integrating education, research and innovation within a supportive academic environment, engineering universities cultivate future scientists capable of leading technological progress, generating new knowledge and contributing to sustainable socio-economic development.

Building an Innovation Ecosystem in Engineering Universities

Developing innovative thinking among engineering students requires more than the implementation of modern teaching methods. Sustainable innovation emerges within an institutional ecosystem that integrates education, scientific research, technological development, entrepreneurship and industrial collaboration. Universities should therefore establish comprehensive innovation ecosystems capable of supporting students and young researchers throughout every stage of the innovation process—from generating original ideas to commercializing technological solutions.

An effective innovation ecosystem is built upon close interaction between higher education institutions, industry, research organizations, government agencies and society. This collaborative model, commonly referred to as the **Triple Helix**, has become one of the most influential frameworks for fostering innovation and technological advancement. Within engineering education, the Triple Helix promotes continuous cooperation among universities, industrial enterprises and public institutions to accelerate knowledge creation, technology transfer and economic development.

Engineering universities play a central role in this ecosystem by serving not only as educational institutions but also as centres of scientific discovery and technological innovation. Modern universities increasingly establish innovation centres, technology transfer offices, engineering design studios, startup incubators and business accelerators that provide students with opportunities to transform research outcomes into practical engineering applications. These structures encourage entrepreneurial activity while strengthening the commercialization of scientific knowledge.

The integration of education with industrial practice is another essential component of innovation ecosystems. Collaborative research projects, industrial internships, dual education models and participation of industry experts in curriculum development enable students to understand real engineering challenges while applying theoretical knowledge in professional environments. Such cooperation improves graduate employability and ensures that engineering education remains aligned with technological developments and labour market demands.

Digital transformation has further expanded the capabilities of university innovation ecosystems. Artificial intelligence, big data analytics, cloud computing, digital twins and virtual laboratories provide students with powerful tools for conducting research, testing engineering solutions and optimizing technological processes. These technologies accelerate innovation by reducing development time, improving experimental accuracy and facilitating interdisciplinary collaboration across geographical boundaries.

Innovation ecosystems also depend upon institutional cultures that encourage creativity, experimentation and responsible risk-taking. Students should be provided with opportunities to develop original engineering solutions without fear of failure. Constructive evaluation, continuous mentoring and interdisciplinary teamwork contribute to the development of resilience, adaptability and lifelong learning—qualities that characterize successful innovators and scientific leaders.

Universities should additionally promote intellectual property awareness and innovation management. Young researchers need to understand patent procedures, technology licensing, research ethics and innovation commercialization in order to maximize the societal impact of their scientific achievements. Integrating these competencies into engineering education enables graduates to become not only skilled engineers but also innovators capable of creating competitive technologies and establishing technology-based enterprises.

The development of sustainable innovation ecosystems ultimately strengthens the international competitiveness of engineering universities. Institutions capable of integrating education, research, entrepreneurship and industrial cooperation create favourable environments for scientific excellence while contributing directly to national technological modernization and economic growth.

Future Perspectives for Engineering Education and Young Researchers

The future of engineering education will be shaped by rapid technological advancement, global scientific collaboration and the continuous evolution of industrial innovation. Emerging technologies such as artificial intelligence, robotics, quantum computing, advanced manufacturing, biotechnology and sustainable energy systems are transforming both engineering practice and engineering education. Universities must therefore continuously modernize their educational strategies to prepare graduates capable of responding to these technological changes.

One of the most important future priorities is the transition toward personalized and competency-based learning. Artificial intelligence will increasingly support individualized educational pathways by analyzing students' learning progress, identifying strengths and recommending adaptive instructional strategies. Personalized learning environments will enable engineering students to acquire professional competencies more efficiently while encouraging independent research and creative problem-solving.

International scientific collaboration will become even more significant as global engineering challenges continue to expand. Climate change, resource sustainability, digital security and infrastructure resilience require coordinated research efforts involving universities, governments and industrial partners across different countries. Young researchers will therefore need strong intercultural communication skills, interdisciplinary knowledge and experience working within multinational research teams.

Lifelong learning will also become an essential characteristic of engineering careers. Technological knowledge rapidly becomes outdated, making continuous professional development indispensable. Universities should provide flexible educational opportunities, micro-credentials, online certification programmes and professional development courses that enable engineers to update their competencies throughout their careers.

Entrepreneurship education is expected to play an increasingly important role within engineering programmes. Future engineers should possess not only technical expertise but also the ability to identify market opportunities, develop innovative business models and commercialize scientific discoveries. Strengthening entrepreneurial

competencies among young researchers will contribute to the establishment of technology-based startups and innovation-driven economic growth.

Another important direction involves expanding interdisciplinary collaboration. Future technological breakthroughs will increasingly emerge at the intersection of engineering, computer science, environmental studies, economics, medicine and social sciences. Universities should therefore encourage interdisciplinary research environments where young researchers develop comprehensive solutions to complex global problems.

Finally, universities should continue strengthening international academic partnerships that support collaborative research, joint doctoral supervision, researcher mobility and participation in global innovation networks. Such cooperation enhances scientific quality while preparing young researchers to become active contributors to the international scientific community.

The future success of engineering education will depend not only on technological modernization but also on universities' ability to cultivate creative, responsible and globally minded researchers capable of transforming scientific knowledge into sustainable technological innovation. By investing in innovative thinking, research competence and international collaboration, engineering universities create the intellectual foundation necessary for addressing the technological challenges of the twenty-first century.

Conclusion

The continuous evolution of science, technology and industrial innovation has fundamentally reshaped the mission of engineering universities worldwide. Modern engineering education is expected not only to prepare technically competent professionals but also to cultivate innovative thinkers, creative problem-solvers and future scientific leaders capable of contributing to sustainable technological development. Consequently, the development of innovative thinking and the systematic support of young researchers have become strategic priorities for higher education institutions seeking to strengthen their academic excellence and global competitiveness.

This study has demonstrated that innovative thinking is a multidimensional competence integrating creativity, critical analysis, interdisciplinary collaboration and scientific inquiry. Contemporary pedagogical approaches—including Project-Based Learning, Problem-Based Learning, CDIO, Design Thinking and research-oriented education—provide effective mechanisms for developing these competencies. When supported by modern digital technologies, active learning environments and close

collaboration with industry, these approaches significantly enhance students' ability to generate innovative engineering solutions.

Supporting young researchers requires comprehensive institutional policies extending beyond traditional academic instruction. Research mentorship, participation in scientific laboratories, innovation competitions, startup incubation, interdisciplinary collaboration and international research mobility collectively contribute to developing scientific independence and professional confidence. Universities that establish favourable research environments enable talented students to transform theoretical knowledge into practical technological innovations while strengthening institutional research capacity.

The establishment of sustainable innovation ecosystems further enhances the effectiveness of engineering education. Close cooperation among universities, industrial enterprises, research institutions and governmental organizations accelerates technology transfer, promotes entrepreneurship and facilitates the commercialization of scientific achievements. Such ecosystems encourage continuous interaction between education, research and innovation, thereby creating favourable conditions for technological modernization and economic development.

Digital transformation has emerged as another essential driver of innovation in engineering education. Artificial intelligence, virtual laboratories, digital twins, cloud-based research platforms and advanced simulation technologies have expanded opportunities for scientific experimentation, collaborative learning and international research cooperation. These technologies not only improve educational quality but also prepare young researchers to work effectively within increasingly digitalized scientific and industrial environments.

International cooperation remains an indispensable component of developing future engineering researchers. Participation in multinational research projects, academic mobility programmes, joint publications and global scientific networks broadens research perspectives, strengthens intercultural competence and enhances institutional visibility within the international academic community. Engineering universities that actively participate in global knowledge networks are better positioned to respond to rapidly changing technological challenges while contributing to scientific advancement at both national and international levels.

Looking forward, engineering education should continue evolving toward flexible, interdisciplinary and innovation-oriented models that integrate scientific research, entrepreneurial thinking and digital technologies into every stage of academic

preparation. Universities should create institutional cultures that encourage creativity, lifelong learning, responsible experimentation and collaborative problem-solving while providing young researchers with sufficient academic, technological and financial support to realize their scientific potential.

In conclusion, investing in innovative thinking and supporting young researchers represents a strategic investment in the future of engineering, science and society. Universities capable of integrating education, research, innovation and international cooperation into a coherent institutional strategy will play a decisive role in preparing the next generation of engineers and scientists who will lead technological progress, strengthen industrial competitiveness and contribute to sustainable global development.

References

- Altbach, P. G., & de Wit, H. (2021). *International Higher Education: Reflections on Policy and Practice*. Boston College Center for International Higher Education.
- Biggs, J., & Tang, C. (2011). *Teaching for Quality Learning at University* (4th ed.). McGraw-Hill Education.
- Brennan, J., & Teichler, U. (2008). The future of higher education and of higher education research. *Higher Education*, 56(3), 259–264.
- Crawley, E. F., Malmqvist, J., Östlund, S., Brodeur, D. R., & Edström, K. (2014). *Rethinking Engineering Education: The CDIO Approach* (2nd ed.). Springer.
- European Commission. (2022). *A European Strategy for Universities*. Brussels: European Commission.
- European University Association. (2021). *Universities without Walls: A Vision for 2030*. Brussels: EUA.
- Knight, J. (2015). Updated definition of internationalization. *International Higher Education*, 33, 2–3.
- OECD. (2023). *Education at a Glance 2023: OECD Indicators*. Paris: OECD Publishing.
- Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons and research bases. *Journal of Engineering Education*, 95(2), 123–138.
- Schwab, K. (2024). *The Global Competitiveness Report*. World Economic Forum.
- UNESCO. (2021). *UNESCO Recommendation on Open Science*. Paris: UNESCO.
- UNESCO. (2024). *Global Education Monitoring Report 2024*. Paris: UNESCO Publishing.
- World Bank. (2024). *Higher Education and Skills for Economic Transformation*. Washington, DC: World Bank.
- World Economic Forum. (2025). *The Future of Jobs Report 2025*. Geneva: World Economic Forum.

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Wulf, W. A., & Fisher, G. M. C. (2002). *A Makeover for Engineering Education*. National Academy of Engineering.

The Strategic Significance of Metallurgy and The Copper Mining Industry in The Economic and Industrial Development of Uzbekistan

Munis Ilkhom o'gli Shonazarov¹ Sarvar Mavlon o'gli Yuldoshev² Ahmad Sherali o'gli Omonov³

Abstract

Metallurgy has historically played a significant role in the economic and industrial development of Uzbekistan and remains one of the strategically important sectors of the national economy. The country possesses considerable mineral resources and significant industrial potential for the extraction and processing of gold, copper, lead, zinc, and other strategically important metals. Among these sectors, the copper industry has become one of the most dynamically developing areas of Uzbekistan's mining and metallurgical complex.

The purpose of this paper is to examine the historical development and contemporary strategic significance of metallurgy in Uzbekistan, with particular emphasis on the copper mining industry and its contribution to industrial modernization and economic growth. The study is based on the analysis of scientific publications, official information, and publicly available data concerning the development of Uzbekistan's mining and metallurgical industry.

The analysis demonstrates that the expansion of copper production, the modernization of mining and processing facilities, the introduction of advanced technologies, and the development of high-value-added products are creating new opportunities for the diversification of

¹ Assistant, Department of Metallurgy, Navoi University of Innovation and Technology; munisshonazarov@mail.ru; ORCID: 0009-0002-1530-4886

² Assistant, Department of Metallurgy, Navoi University of Innovation and Technology; sarvarbek5775@gmail.com; ORCID: 0009-0007-4762-926X

³ Department of Metallurgy, Almalyk State Technical Institute; omonovahmad77@gmail.com; ORCID: 0009-0007-3690-0675

Uzbekistan's industrial economy. The development of the Yoshlik-I deposit and the expansion of production capacities at the Almalyk Mining and Metallurgical Complex represent important elements of this transformation. The further development of copper-based value chains may strengthen the country's export potential, stimulate related industries, create new employment opportunities, and contribute to sustainable long-term economic growth.

Keywords: metallurgy, copper mining industry, Uzbekistan, mining and metallurgical complex, copper production, economic development, industrial modernization, value-added production.

1. Introduction

Metallurgy has played an important role in the economic and technological development of the territory of modern Uzbekistan for centuries. Historical evidence indicates that metalworking and the production of metal tools, weapons, and other products were important components of the economic activity of ancient Central Asian societies. Cities such as Samarkand and other major urban centers historically served as important centers of craftsmanship, trade, and metal processing [1].

The historical development of metalworking created important technological traditions and practical knowledge that subsequently contributed to the formation of modern industrial metallurgy. Today, Uzbekistan possesses a developed mining and metallurgical sector based on substantial reserves of non-ferrous and precious metals.

The modern mining and metallurgical complex is of particular importance to the national economy because it contributes to industrial production, export revenues, investment attraction, technological modernization, and employment generation. The sector also serves as a foundation for the development of related industries, including mechanical engineering, electrical engineering, electronics, construction, chemical production, and energy.

Within this system, the copper industry occupies a particularly important position. The increasing global demand for copper, driven by the development of electric power systems, renewable energy, electric vehicles, digital technologies, and advanced manufacturing, creates favorable conditions for the further development of copper production and processing in Uzbekistan.

2. Materials And Methods

This study applies a descriptive and analytical research approach. The research is based on the analysis of scientific publications, official government information, publicly

available data from Uzbekistan's mining and metallurgical enterprises, and materials related to the development of the country's copper industry.

The analysis focuses on several key aspects: the historical role of metallurgy, the current development of the mining and metallurgical sector, the strategic importance of copper production, the modernization of production capacities, investment projects, and the development of value-added processing.

A comparative and qualitative analysis was used to identify the principal factors influencing the development of the copper industry and its potential contribution to the industrial and economic development of Uzbekistan.

3. The Current Role Of Metallurgy In Uzbekistan

Uzbekistan possesses significant mineral resources and production capacities for the extraction and processing of gold, copper, lead, zinc, and other mineral resources. These metals are essential for a wide range of industrial sectors, including construction, electric power generation, mechanical engineering, electronics, transport, and infrastructure development.

The mining and metallurgical industries make a substantial contribution to the national economy by generating export revenues, creating employment opportunities, attracting investment, and stimulating industrial growth. The development of these industries also promotes the establishment of new production chains and contributes to the expansion of domestic industrial capabilities.

Modern metallurgy is increasingly characterized by technological modernization, automation, digitalization, efficient use of natural resources, and the implementation of environmentally responsible production methods. Consequently, the future competitiveness of the sector depends not only on the volume of extracted raw materials but also on the ability to process them efficiently and produce products with higher added value.

4. The Development Of Uzbekistan's Copper Industry

The copper industry is one of the most promising sectors of Uzbekistan's mining and metallurgical complex. Copper is widely used in electrical engineering, electronics, construction, mechanical engineering, energy, transport, and modern digital technologies.

The development of the copper industry in Uzbekistan has been supported by the expansion of mining operations, the modernization of production facilities, the implementation of large-scale investment projects, and the development of processing

capacities. National industrial policy has increasingly emphasized the need to expand copper production and establish a more complete value chain based on domestic mineral resources.

In 2021, Uzbekistan identified the development of a copper industry cluster as a strategic priority. At that time, the country's copper production had reached approximately 148 thousand tons in 2020, while a significant proportion of copper was still exported in the form of raw materials. The development of high-value-added products was therefore identified as an important direction for increasing the economic efficiency of the industry [2].

The development of copper-based production chains can create favorable conditions for the expansion of electrical engineering, electronics, machinery manufacturing, and other related industries. This approach makes it possible to move gradually from the export of raw materials toward the production of technologically advanced goods with higher added value.

5. The Almalyk Mining And Metallurgical Complex And The Yoshlik-I Deposit

The Almalyk Mining and Metallurgical Complex (AMMC) is one of the key enterprises in Uzbekistan's non-ferrous metallurgy and copper industry. The complex plays an important role in the extraction and processing of copper-bearing ores and in the production of copper and other valuable metals.

One of the most significant investment projects in the development of Uzbekistan's copper industry is the development of the Yoshlik-I deposit in the Tashkent Region. The project is aimed at expanding the country's raw material base, increasing ore processing capacity, modernizing production infrastructure, and strengthening the production of copper and other valuable metals [3].

A major stage in this development was the construction and commissioning of Copper Processing Plant No. 3. In March 2026, the first phase of the plant was officially launched. At full design capacity, the plant is expected to process up to 60 million tons of ore annually and produce approximately 900 thousand tons of copper concentrate per year. The project is considered an important element in the development of a modern copper production cluster in Uzbekistan [3, 4].

The project also incorporates modern technologies, digital control systems, automation, and advanced equipment. These technological solutions are intended to improve production efficiency, increase labor productivity, reduce resource consumption, and strengthen the competitiveness of Uzbekistan's mining and metallurgical industry [4].

The development of the Yoshlik-I deposit and related production facilities is also expected to stimulate the development of related industries and create new employment opportunities. As a result, the project has significance not only for the mining and metallurgical sector but also for the broader industrial development of the country.

6. Economic And Industrial Significance Of The Copper Industry

The development of the copper industry can contribute significantly to Uzbekistan's economic growth and industrial modernization. Copper production generates export revenues and creates demand for services, technologies, equipment, transport, engineering, and other related sectors.

According to official information published in 2021, revenues associated with Uzbekistan's copper industry amounted to approximately US\$2.5 billion at that time. It was also estimated that increasing copper production and developing related industries could significantly increase the overall economic impact of the sector. This figure should be understood as a historical estimate associated with the period in which it was announced rather than as a current annual indicator [2].

The development of copper processing and the production of copper-based goods with higher added value may increase the economic efficiency of the industry. Such development can support the growth of electrical engineering, electronics, machinery manufacturing, construction materials, chemical production, and other sectors.

The copper industry also has the potential to contribute to employment generation and human capital development. Modern mining and metallurgical enterprises require specialists in mining engineering, metallurgy, automation, information technologies, environmental protection, energy systems, and industrial management.

7. Technological Modernization And Sustainable Development

The future development of metallurgy in Uzbekistan depends increasingly on the introduction of advanced technologies and sustainable production practices. Modern mining and processing enterprises require efficient resource management, automation, digital monitoring, energy-efficient equipment, and improved environmental protection systems.

The development of new processing facilities provides opportunities for the introduction of modern technologies throughout the production cycle. These technologies can improve the efficiency of ore processing, reduce production losses, optimize energy consumption, and improve operational control.

Environmental sustainability is also becoming increasingly important. The responsible development of mineral resources requires effective management of waste, water, energy, and other production resources. The use of recirculating water systems, digital monitoring, and advanced processing technologies can contribute to more efficient and environmentally responsible industrial production.

The combination of technological modernization and efficient resource use is therefore essential for ensuring the long-term competitiveness and sustainability of Uzbekistan's mining and metallurgical industry.

8. Discussion

The development of Uzbekistan's copper industry demonstrates the importance of integrating mineral resources, investment, modern technologies, industrial policy, and human capital. The expansion of mining and processing capacities creates opportunities for economic growth, but the long-term effectiveness of the sector will depend increasingly on the development of complete industrial value chains.

The transition from the export of raw materials toward the production of high-value-added products is particularly important. Such a transition can increase the economic return from mineral resources and stimulate the development of technologically advanced sectors.

The development of copper-based industrial clusters may also strengthen cooperation between mining enterprises, manufacturing companies, research institutions, and higher education institutions. This cooperation can support innovation, the development of new technologies, and the training of highly qualified specialists.

At the same time, the expansion of mining and metallurgical production requires careful attention to environmental sustainability, efficient use of water and energy resources, occupational safety, and the long-term development of mining regions.

Therefore, the future development of Uzbekistan's copper industry should be based on a balanced combination of increased production, technological modernization, deeper processing, environmental responsibility, and the development of human capital.

9. Conclusion

Metallurgy, and particularly the copper mining and processing industry, has strategic importance for the economic and industrial development of Uzbekistan. The country possesses significant mineral resources, an established industrial base, and

substantial potential for the further development of mining, metallurgy, and related processing industries.

The development of the copper industry is supported by the modernization of existing enterprises, the implementation of large-scale investment projects, the development of the Yoshlik-I deposit, and the expansion of copper processing capacities. The commissioning of new production facilities represents an important step toward the modernization of Uzbekistan's mining and metallurgical complex [3, 4].

The further development of copper-based value chains can contribute to export growth, industrial diversification, technological advancement, employment creation, and the development of related high-tech industries.

The long-term success of the sector will depend on the effective combination of mineral resources, advanced technologies, investment, scientific research, environmental responsibility, and highly qualified human resources. Therefore, the development of metallurgy and the copper industry should remain one of the important strategic directions of Uzbekistan's industrial development.

References

- 1- Shonazarov, M. I., Yuldoshev, S. M., & Omonov, A. S. (2023). Selection and characterization of raw materials for the production of sorbents used in the recovery of rare metals from local raw materials. *Universum Journal*, 7-2(112), 35–39.
- 2- President of the Republic of Uzbekistan. (2021). A copper industry cluster to be established. Official website of the President of the Republic of Uzbekistan.
- 3- President of the Republic of Uzbekistan. (2026). First stage of the new Copper Processing Plant launched in Almalyk. Official website of the President of the Republic of Uzbekistan.
- 4- Almalyk Mining and Metallurgical Complex. (2026). Information on the development of the Yoshlik-I deposit and Copper Processing Plant No. 3.

Mechanism of H₂S Corrosion in Absorption and Recycling Processes

Pulatov Golibjon Murodovich¹ Yusupov Farkhod Makkamovich²

Abstract

In this scientific article, the fundamental electrochemical and physico-chemical mechanisms of corrosion of metals and alloys in highly aggressive technological environments containing hydrogen sulfide (H₂S) are deeply analyzed.

The main focus of the research is on the destructive changes that occur in combined absorption amine treatment devices (desulfurization processes involving alkanolamines) with the most responsible and severe operating conditions of oil and gas refineries. Under rapid mass exchange and high temperature kinetics, alkanolamines interact with hydrosulfide ions and dramatically increase the speed of electrochemical anode and cathode processes on the metal surface. The kinetics of the formation of the most dangerous types of destruction of the metal base under the influence of H₂S - sulphide corrosion, internal hydrogen embrittlement caused by cathodic hydrogen adsorption, and the formation of a chemically unstable iron sulfide (FeS) layer on the metal surface were considered spatially and microstructurally.

It is worth noting that, although the FeS film initially seems to perform a protective function, it is easily corroded under the influence of mechanical currents and creates galvano-pair centers that further deepen local pitting corrosion. Atomic hydrogen diffused into the crystal lattice leads to the loss of plastic properties of the metal and premature brittle fracture. In order to

¹ Almalyk State Technical Institute, e-mail: raxmonjongolibjon2017@mail.ru, ORCID-0009-0004-8634-0256

² Institute of General and Inorganic Chemistry; f.yusupov@yandex.ru; ORCID: 0000-0002-6758-3445

eliminate these problems, the article systematizes modern engineering and technological methods for minimizing the corrosion rate.

In particular, the use of highly effective film-forming chemical inhibitors specially synthesized for amine environments, the criteria for the variable selection of hydrogen-resistant alloyed steels and special alloys in the design of equipment are highlighted. Also, conceptual methodological recommendations and practical models are proposed for extending the service life of equipment by optimizing technological parameters such as hydrodynamic flow rate, amine concentration and temperature in the process.

Keywords: H₂S, corrosion, absorption, amine solutions, concentration, crystal lattice, diffusion hydrogen embrittlement, atomic hydrogen, inhibitors.

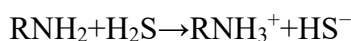
1. Introduction

Corrosion of metal structures under the influence of technological environments containing hydrogen sulfide in hydrocarbon extraction and transportation systems is one of the fundamental engineering problems of the oil and gas industry. This toxic component dissociates when it comes into contact with the aqueous phase, reducing the hydrogen index (pH) of the environment and creating acidic aggressive conditions. As a result, a complex of electrochemical reactions with a high kinetic rate is activated on the metal surface. The basis of this heterogeneous process is the sub-reactions of anodic dissolution of iron ($\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$) and cathodic reduction of hydrogen ions.

The final product of this anode-cathode coordination is the formation of a heterogeneous iron sulfide (FeS) coating on the metal surface. However, this chemical compound layer is often characterized by a high degree of porosity, defects in the crystal lattice, and low adhesion strength to the metal substrate.

Such a porous and destructive morphology cannot limit the diffusion of aggressive ions (especially HS⁻ and H⁺) that cause corrosion into the inner layers, and as a result, it cannot fully fulfill its passivation function and creates the basis for the consistent continuation of local and pitting corrosion degradation.

The amine absorption process selectively absorbs hydrogen sulfide present in a gas using amine solutions. During this process, a chemical reaction occurs between the amine (RNH₂) and H₂S, resulting in the formation of protonated amine and hydrosulfide ions:



As a result of these reactions, the concentration of acidic components in the solution increases, which leads to a decrease in the overall pH of the environment.

In alkanolamine absorption devices, the absorption of H_2S gas, along with gas purification, is the main factor that creates an acidic environment and rapidly activates electrochemical corrosion of technological equipment. The corrosion processes in these absorption systems are multifactorial in nature, and their kinetic rate increases sharply in a nonlinear manner due to high temperature, the presence of a mixture of CO_2 gas and oxygen in the environment, and the structural decomposition of amine solutions.

Mechanical degradation of metals in an H_2S environment is characterized by hydrogen embrittlement and sulfide corrosion stress (SSC) phenomena resulting from the diffusion of atomic hydrogen into the crystal lattice.

These processes, which occur under the synergistic influence of external mechanical stress and an acidic aggressive environment, form microcracks in high-strength steels, leading to sudden brittle fracture of structures and sharply reducing the operational reliability of technological systems.

To minimize these destructive processes, the system of using highly effective organic inhibitors (amines, phosphates and complex compounds) that form a film on the metal surface and slow down the anode-cathode reactions is considered effective. The comprehensive combination of inhibitory metal protection measures with the targeted selection of corrosion-resistant alloys and optimization of technological parameters, such as neutralizing the pH of the environment, reducing the operating temperature and minimizing the oxygen content in the system, is the fundamental basis for extending the service life of equipment and ensuring production stability.

2. Materials And Methods

Control of technological parameters is one of the main control factors in reducing the intensity of corrosion processes. In practical industrial systems, in particular in amine absorption plants, the operating temperature is usually maintained in the range of 40–60°C. An increase in temperature by 10°C can increase the corrosion rate by about 1.5–2 times, therefore it is important to maintain a stable thermal regime. Also, the pH value of the medium is usually controlled in the range of 7.5–9.5, since below pH 7, the corrosion rate increases sharply.

In addition, controlling the concentration of H_2S and CO_2 in the gas is also an important technological parameter. In industrial practice, if the amount of H_2S exceeds 0.5–2.0 mol%, the risk of corrosion increases significantly. And the presence of CO_2 can

increase the overall corrosion rate by 20–40%. Therefore, the gas content in the process systems is constantly monitored, and if necessary, the dose of inhibitors is applied in the range of 50–200 ppm, and the corrosion rate is reduced to 60–80%. As a result, operational reliability of technological equipment increases and service life is significantly extended.

The presence of oxygen in the process medium is one of the main factors significantly accelerating corrosion processes. In industrial systems, especially in amine absorption processes, when the dissolved oxygen content exceeds 0.1–2.0 mg/l, oxidation reactions on metal surfaces are activated, and the overall corrosion rate can increase by 2–5 times.

Therefore, limiting the entry of oxygen into the system and maintaining its concentration at a minimum is an important technological requirement.

3. Results

According to model calculations, the average consumption of processed natural gas is 1,000,000 Nm³/day. Assuming a H₂S content of 1.5% (volume fraction) in this stream, the total substance amount is 44,643 kmol/day, of which the H₂S fraction is 669 kmol/day. In terms of mass, this value is approximately 22.8 tons/day of H₂S, which indicates that the system operates in a high corrosion risk zone. According to the model results, the intensity of the corrosion process directly depends on the operating temperature and H₂S concentration. At a temperature of 45°C and 1.5% H₂S, the total corrosion rate was estimated to be 0.18 mm/year. When the temperature is increased by 10°C, this indicator increases by approximately 1.6–1.8 times, which confirms the exponential nature of the process.

According to the results of practical modeling, the operational resource of the pipeline system in the absence of protective measures is limited to an average of 10–15 years. However, when corrosion inhibitors are used (60–80% efficiency), the corrosion rate decreases from 0.18 mm/year to 0.05–0.07 mm/year, which results in an extended service life of up to 30–40 years. This significantly increases the reliability of the technological system.

4. Conclusion

Corrosion processes involving H₂S are a complex natural-chemical system, characterized by the interaction of electrochemical reactions, diffusion phenomena and mechanical stresses. As a result of this process, the formation of iron sulfide on metal surfaces, the penetration of hydrogen into the material and structural damage are observed.

To reduce the intensity of corrosion, not just one method, but a comprehensive approach is needed. This should include a combination of chemical protection (inhibitors), optimization of technological parameters (temperature, pH, gas composition) and the use of corrosion-resistant materials. In general, the management of H₂S corrosion requires a systematic and multifactorial approach. When this set of measures is implemented, the service life of technological equipment is extended, the risk of accidents is reduced, and the stability and economic efficiency of industrial processes are significantly increased.

References

- Revie, R.W., Uhlig, H.H. Corrosion and Corrosion Control. Wiley-Interscience, 2008.
- Uhlig, H.H., Revie, R.W. Corrosion Handbook. Wiley, 2000.
- Nešić, S. Key Issues Related to Modeling of Internal Corrosion of Oil and Gas Pipelines. Journal of Corrosion Science, 2007.
- G.M. Pulatov, F.M. Yusupov, G.M. Bekturdiev. Svoystva sulfida natriya poluchennogo iz otkhodov proizvodstva // Central Asian Journal Of The Theoretical And Applied Sciences. May 2021. C 174-178.

Development of an Eco-Friendly and Highly Efficient Process For the Selective Recovery of Valuable Metal Ions From Zinc and Cadmium Cakes Generated at the Zinc Plant of Jsc “Almalyk Mining and Metallurgical Complex” Using Immobilized Organic Reagents

Rustamjon Mirzaxmedov¹, Doniyor Kholiqulov², Nazira Madusmanova³,
Farxod Jo‘rayev⁴

Abstract

The research focused on zinc cake, copper–cadmium cake, cobalt- and nickel-bearing technogenic intermediate products generated during the zinc production process at the Zinc Plant of JSC Almalyk Mining and Metallurgical Complex (AMMC). In addition, technological wastewater from the plant and water samples collected from surrounding environmental sites were investigated. To achieve the selective, sensitive, and rapid determination of Zn (II), Cd (II), Co (II), and Ni (II) ions in these complex matrices, polymer-supported immobilized organic analytical reagents were employed as the working sorbent-reagents. The immobilization of organic reagents on a polymer matrix enhanced their physicochemical stability, sorption efficiency, and complex-forming ability while enabling repeated use and significantly reducing the consumption of organic solvents, thereby improving the environmental sustainability of the analytical procedure. The analytical performance of the immobilized reagents was systematically

¹ Almalyk Branch of Tashkent State Technical University, rustam.mirzaxmedov23@mail.ru; ORCID: 0000-0002-4445-0631

² Almalyk State Technical Institute, doniyor_xb@mail.ru; ORCID: 0000-0001-6968-9297

³ Almalyk State Technical University, nazira.imomova@mail.ru; ORCID: 0000-0002-9926-7666

⁴ Academic Lyceum of Tashkent Medical Academy, farhodjurayev0@gmail.com; ORCID: 0009-0004-1157-0444

evaluated by investigating the complexation mechanism with target metal ions, the influence of solution pH, contact time, maximum analytical signal intensity, and selectivity toward individual metal ions. Experimental conditions were optimized to maximize sensitivity and reproducibility while minimizing interference from coexisting ions commonly present in technogenic waste and industrial wastewater. The proposed method demonstrated high accuracy, precision, reproducibility, and reliability in the analysis of complex industrial samples.

Keywords: technogenic waste, immobilized organic analytical reagents, Zn(II), Cd(II), Co(II), Ni(II), technological wastewater, sorption–photometric analysis, environmental monitoring, complex formation.

1. Introduction

The global demand for certain transition (d-block) metals is increasing every year. To meet this demand, these metals are mainly recovered using pyrometallurgical and hydrometallurgical methods. In addition, leading countries are conducting extensive research on the development of rapid processing methods for mineral raw materials and ores, the complete recovery of cobalt and nickel from these resources, increasing production capacity, and the implementation of low-waste and waste-free technologies. At present, numerous methods have been developed and implemented on an industrial scale for the recovery of certain heavy metal ions belonging to the d-block from industrial wastewater [1].

According to the authors in the physicochemical characteristics of zinc, cadmium, nickel, and cobalt ions in industrial waste were investigated using Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). The obtained results showed that the percentages of zinc, cadmium, nickel, and cobalt ions in the analyzed samples reached $78.70 \pm 1.02\%$ and $76.53 \pm 1.21\%$, respectively. Furthermore, the analytical method was evaluated over a pH range of 1–9, where the standard deviation did not exceed $S_r = 0.05$, demonstrating satisfactory analytical precision [2].

Hydrometallurgical (electrolytic) processing has been widely employed for the recovery of metallic zinc from zinc-bearing raw materials. In this process, the calcine obtained after oxidative roasting is leached with sulfuric acid, and metallic zinc is subsequently recovered from the resulting zinc sulfate solution by electrolytic deposition [3–4].

The Zinc Plant is one of the major production facilities of JSC Almalyk Mining and Metallurgical Complex (AMMC). The plant commenced operation on 13 September 1970, and the first cathode zinc was produced on 30 September 1970 [5–6]. Since then,

the plant has produced more than 4.3 million tonnes of metallic zinc, approximately 5.5 million tonnes of sulfuric acid, and 23 thousand tonnes of metallic cadmium. Since 2018, continuous modernization and reconstruction of the plant's technological equipment have been carried out to improve production efficiency and environmental performance [7–8]. For the first time in the plant's operational history, a three-stage zinc solution purification process was introduced, enabling the production of high-purity zinc electrolyte. As a result, both the quality of cathode zinc and the recovery rates of zinc and cadmium have been significantly improved [9–10].

During zinc production, several types of process cakes are generated, including:

- Copper–cadmium cake: Cd (2.5–8%), Co (0.02–0.06%), Cu (3.5–10%), Ni (0.02–0.04%), Zn (36–45%), and Sb (0.10–0.15%).
- Zinc cake: total Zn (<21%), acid-soluble Zn ($\leq 12.0\%$), Cd (0.2–0.3%), Pb (2–6%), and sulfide sulfur ($\leq 1.5\%$).

The determination of cobalt(II) and nickel(II) ions in these process cakes is of considerable importance because of their economic value and environmental significance [11–12].

2. Materials and Methods

2.1. Preparation of the Working Solution of 2-Nitroso-1-Naphthol-3,6-Disulfonic Acid

1. A 0.1% (w/v) solution of 2-nitroso-1-naphthol-3,6-disulfonic acid was prepared by accurately weighing 0.01 g of the reagent using an analytical balance and dissolving it in 10 ml of 96% ethanol. Owing to its high solubility in ethanol, a clear and stable solution was obtained and stored for subsequent experiments.

2. A $1.0 \times 10^{-1} \text{ mol l}^{-1}$ hydrochloric acid (HCl) solution was prepared by appropriate dilution of concentrated hydrochloric acid with distilled water and used throughout the experimental work.

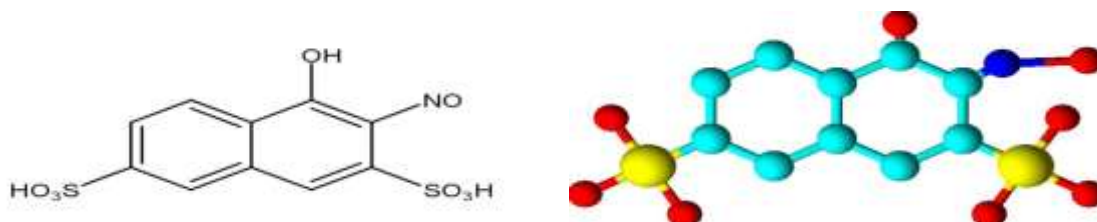


Figure 1. Molecular structure of the organic reagent 2-nitroso-1-naphthol-3,6-disulfonic acid.

2.2. Preparation of the working solution of thymol blue organic reagent

1. A 0.01% (w/v) working solution of thymol blue (thymol sulfonephthalein) was prepared by accurately weighing 0.01 g of the reagent using an analytical balance and dissolving it in 10 ml of 96% ethanol. The resulting solution was transferred quantitatively into a 100 ml volumetric flask and diluted to the calibration mark with distilled water. The prepared working solution was further diluted as required and used for subsequent experimental analyses.

2. A $1.0 \times 10^{-1} \text{ mol/l}^{-1}$ hydrochloric acid (HCl) solution was prepared by diluting concentrated hydrochloric acid with distilled water and used throughout the experimental work.

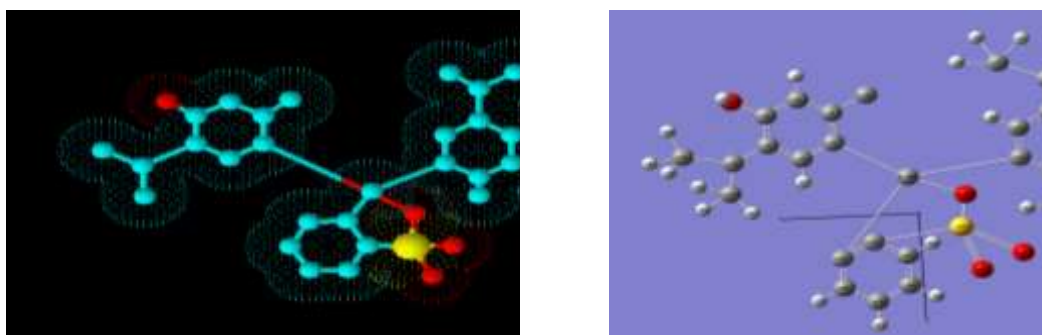


Figure 2. Molecular structure of the analytical reagent thymol blue (thymol sulfonephthalein).

2.3. Preparation of the standard cobalt (II) solution

A standard Co (II) solution with a concentration of 1 mg ml^{-1} was prepared by accurately weighing 0.10 g of cobalt sulfate (CoSO_4) and transferring it into a 100 ml volumetric flask. Subsequently, 2 ml of sulfuric acid (H_2SO_4) was added, and the solution was diluted to the calibration mark with distilled water. The prepared standard solution was used in all subsequent experiments.

To determine Co (II) ions experimentally, X-ray fluorescence (XRF) spectroscopy was employed. As a result, the analytical spectral lines corresponding to Co^{2+} were obtained at the characteristic wavelengths shown in figure 3.

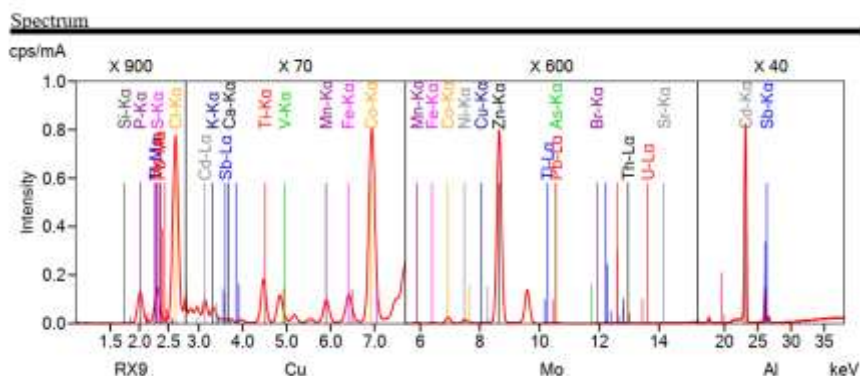


Figure 3. X-ray fluorescence (XRF) spectrum of the standard cobalt (II) sample.

As shown in Figure 3, the X-ray fluorescence (XRF) spectrum of the standard cobalt(II) sample was obtained and compared with the reference spectrum. The experimental results demonstrated that the characteristic spectral peak of Co^{2+} exhibited high maximum intensity, confirming the reliability of the standard sample for subsequent analytical measurements.

2.4. Preparation of the standard nickel (II) solution

A standard Ni (II) solution with a concentration of 1 mg ml^{-1} was prepared by accurately weighing 0.50 g of $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, transferring it into a 100 ml volumetric flask, adding 2 ml of sulfuric acid (H_2SO_4), and diluting to the calibration mark with distilled water. The prepared solution was used in all subsequent experiments. As a result, the analytical spectral lines corresponding to Ni^{2+} were obtained at the characteristic wavelengths presented in Figure 4.

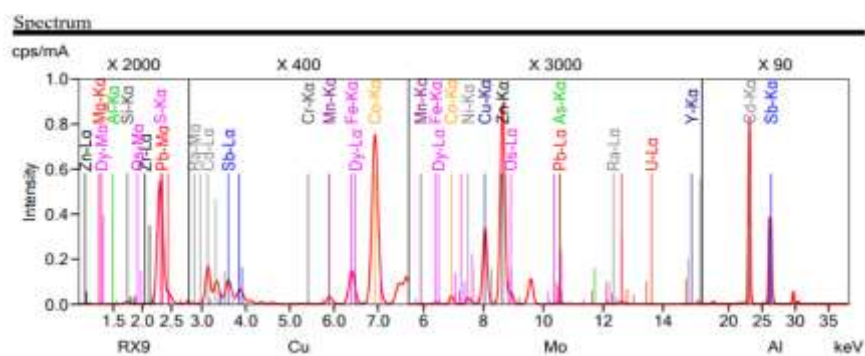


Figure 4. X-ray fluorescence (XRF) spectrum of the standard nickel (II) sample.

Reaction conditions: temperature 373 K , $[\text{PEPA}] = 50\%$, reaction time 3 h , and bath modulus $1:40$. An ion-exchange sorbent with a static exchange capacity (SEC) of 5.3 meq g^{-1} was synthesized, and the molecular structure of the optimal support material was characterized by FTIR spectroscopy.

As shown in the table, the complex formation of Ni(II) and Co(II) ions with the immobilized organic reagent occurs predominantly through the –OH and –N– analytical functional groups. The immobilization of the reagent onto the polymer fiber is primarily achieved through the –O–SO₃ and –N=N– functional groups.

3. Results and Discussion.

3.1. Optimization of the complex formation conditions of nickel (II) and cobalt (II) ions with thymol blue and 2-nitroso-1-naphthol-3,6-disulfonic acid reagents

The complex formation of Ni(II) and Co(II) ions with the selected reagents was investigated by evaluating the absorbance intensity at the characteristic wavelength using UV–Vis spectrophotometry. The effects of solution pH, buffer composition, organic solvent composition, reagent concentration, and reagent addition sequence on complex formation were systematically studied. The analytical reaction mechanisms of Ni (II) and Co (II) ions with thymol blue and 2-nitroso-1-naphthol-3,6-disulfonic acid were also investigated. The corresponding results are presented in Figures 5.

The changes observed in the diffuse reflectance spectra of the Ni(II) complex indicated that the complex formed between thymol blue immobilized on the PAN–TEA fiber and Ni(II) exhibited a maximum spectral response at a wavelength of 560 nm. Accordingly, the spectral contrast was determined to be $\Delta\lambda = 110$ nm.

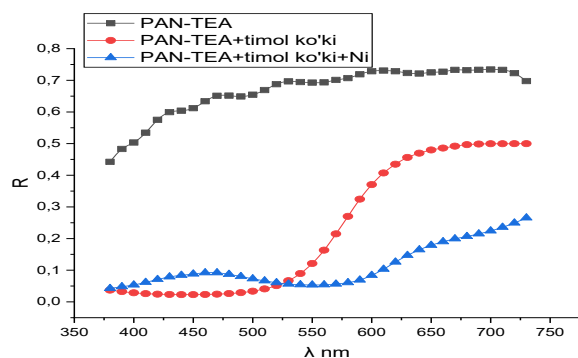


Figure 5. Diffuse reflectance spectra of the PAN–TEA support sorbent, thymol blue immobilized on the PAN–TEA support, and the resulting Ni (II) complex.

3.2. Spectral characterization of the complex formation between Co (II) ions and immobilized 2-nitroso-1-naphthol-3,6-disulfonic acid

The PAN–TEA sorbent, 2-nitroso-1-naphthol-3,6-disulfonic acid immobilized on the sorbent, and its complex with Co (II) ions were analyzed by diffuse reflectance spectrophotometry (Figures 8). The results showed that the maximum analytical signal for the complex formed between the immobilized reagent and Co (II) ions was observed

at 550 nm, while the immobilized reagent exhibited a maximum at 420 nm. The spectral contrast of the reaction was determined to be $\Delta\lambda = 130$ nm.

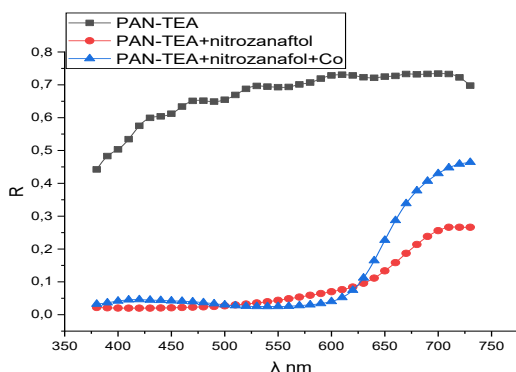


Figure 6. Diffuse reflectance spectra of the PAN-TEA support sorbent, 2-nitroso-1-naphthol-3,6-disulfonic acid immobilized on the PAN-TEA support, and the resulting Co (II) complex.

The results demonstrated that the complexes formed between thymol blue and 2-nitroso-1-naphthol-3,6-disulfonic acid organic reagents with Ni (II) and Co (II) ions exhibited maximum optical density at the optimal wavelengths of $\lambda_R = 450$ and 420 nm, respectively.

The FTIR spectroscopic investigation of the complex structure and the study of the complex formation mechanism demonstrated that, for the thymol blue reagent, the functional groups O–Me, –N=O, and –SO₄^{2–} exhibited high complexation activity. The highest intensity of complex formation was observed in the spectral regions at 454.9 cm^{-1} , 578.11 cm^{-1} , 613.20 cm^{-1} , and 850.65 cm^{-1} . Based on these results, this reagent was selected for further studies.

4. Discussion

The results of this study demonstrated that thymol blue and 2-nitroso-1-naphthol-3,6-disulfonic acid reagents immobilized on a PAN-TEA polymer support exhibit high analytical performance for the determination of Ni (II) and Co (II) ions.

The spectrophotometric studies revealed that the maximum analytical signal was observed at 450 nm for the Ni (II)–thymol blue complex and at 420 nm for the Co (II)–2-nitroso-1-naphthol-3,6-disulfonic acid complex. The Kubelka–Munk function and FT-IR spectroscopy results confirmed the active involvement of hydroxyl and nitrogen-containing functional groups in the complex formation process.

Optimization of the process parameters established that the optimum medium was pH 6 for Ni(II) and pH 4 for Co(II). The immobilization time was 17 min for thymol blue and 13 min for 2-nitroso-1-naphthol-3,6-disulfonic acid. The Beer's law linearity range was 8.1–42 µg/25 mL for Ni(II) and 6.3–54 µg/25 mL for Co(II), indicating the wide linear working range of the proposed method.

5. Conclusion.

In this study, a novel sorption–photometric method based on thymol blue and 2-nitroso-1-naphthol-3,6-disulfonic acid reagents immobilized on a PAN–TEA polymer support was developed for the determination of Ni (II) and Co (II) metal ions in technogenic wastes and technological wastewater generated by JSC “Almalyk Mining and Metallurgical Complex”. The obtained results demonstrated that the immobilized reagents exhibited high selectivity, sensitivity, and analytical stability. The optimal analytical conditions were established, including pH = 6 for Ni (II) and pH = 4 for Co (II) ions. The maximum analytical signals were observed at 450 and 420 nm, respectively. FTIR spectroscopic investigations confirmed the mechanism of complex formation and the successful interaction of metal ions with functional groups on the sorbent surface. The proposed method is considered scientifically and practically promising for the rapid determination of heavy metal ions in industrial wastewater and technogenic wastes, environmental monitoring, and control of hydrometallurgical processing operations.

References

1. Рузикулов К.М., Бекбутаев А.Н., Хаджаев А.Р. Реконструкция и модернизация производственных мощностей Цинкового завода АО «Алмалыкский ГМК» **Цветные металлы. 2024. №9.**
2. Marchenko N.V. Metallurgiya tyazelykh svetnykh metallov // [Elektronnyy resurs]: elektron. ucheb. posobie. – Krasnoyarsk, –2009. –402 s.
3. Romanteev YU.P., Byistrov S.V. Metallurgiya tyazelykh svetnykh metallov. Svinets. Sink. Kadmiy // M.: Izdatelskiy dom MISiS, –2010. –S. 324-339.
4. Gidrometallurgiya sinka (ochistka rastvorov i elektroliz) / L.A.Kazanbaev, P.A.Kozlov, V.L.Kubasov [i dr.]. – M. : Ruda i metall, 2006. – 176 s.
5. Tarasov, A.V. Obshchaya metallurgiya / A.V.Tarasov, N.I.Utkin. – M. : Metallurgiya, 1997. – 592 s.
6. Kholikulov D.B., Ruzikulov Q.M., Khaidaraliev K.R. Improvng the technology of waelzaton of zinc cakes. Gornyy Jurnal Kazaxstana. 2022. №6, Pp. 23-28. <https://doi.org/10.48498/MINMAG.2022.206.6.003>.
7. Mirzakhmedov R.M., Madusmanova N.K., Usmonaliev J.U., Rakhmonqulov R., Mirusmanova F.B., Mirusmanova P.B., and Kayumova N.K., Sorption-spectroscopic of Rhenium ion production of detection methods // E3S Web of Conferences. 2024, Vol.524, P.1-8. (scopus).

8. Makhmudova G. U., Mirzakhmedov R. M., Madusmanova N. K., Rhenium ionnini sorbtionspectroscopic creation of detection technology // Eurasian Research Bulletin. 2023 g. T. 1. № 2. P. 296-299.
9. Mirzakhmedov R.M., Jumayev M.N., Imomnazarova K.A., Sorbtion-photometric determination of zinc ion from the composition of industrial cake of non-ferrous metallurgical enterprises // Scholar's Digest- Journal of Multidisciplinary Studies. 2023 g. T.4. № 2. P. 40-44.
10. Mirzaxmedov R.M. Sanoat chiqindi keklari tarkibidan qo'rg'oshin (II) ionni sorbsion-fotometrik aniqlash usulini ishlab chiqish // Journal of new century innovations. T.38 – № 2. S. 45-48.
11. Tursunbayeva A., Mirzakhmedov R. M., Jumayev M. N., Imomnazarova K. Sorbtion-photometric determination of zinc ion from the composition of industrial cake of non-ferrous metallurgical enterprises // Scholar's Digest- Journal of Multidisciplinary Studies T.4 – № 2. S. 40-44.

Using Digital Technologies and Artificial Intelligence in Chemical Engineering Education: A Case Study on the Selective Recovery of Rhenium from Industrial Solutions

Kholida Mumin kizi Azizova¹, Nuritdin Turayevich Kattaev²

Abstract

Digital technologies and artificial intelligence are transforming the content of engineering education, teaching methods, and the professional competencies expected from future engineers. This paper proposes a digital case-study model for chemical engineering education based on the selective recovery of rhenium from a sulfuric acid industrial solution containing rhenium and molybdenum using ion-exchange sorbents. The case integrates a real technological problem with chemical analysis, sorbent selection, mathematical processing of kinetic and dynamic data, graphical interpretation, and AI-assisted evaluation of alternative solutions. Its educational objective is to develop students' skills in handling industrial data, interpreting calculation results on the basis of physicochemical principles, making evidence-based decisions, and using digital tools responsibly. Within the proposed model, students are regarded not as passive recipients of ready-made answers, but as active participants who analyse data, verify calculations, and justify engineering decisions. Artificial intelligence is used as a supporting tool for structuring data, comparing models, and developing technological scenarios; however, its conclusions must be verified through material balances, chemical principles, and experimental results. The case also addresses ethical issues, including the confidentiality of industrial data, academic integrity, correct citation practices, and human responsibility for final engineering decisions. The proposed approach may contribute to integrating theory, experimentation, and industrial practice in chemical and metallurgical engineering education.

¹ PhD in Chemistry, Associate Professor, Almalyk State Technical Institute, Almalyk, Uzbekistan. E-mail: azizovakholid@gmail.com; ORCID: 0000-0003-4406-5941.

² National University of Uzbekistan named after Mirzo Ulugbek (O'zbekiston Milliy Universiteti), Physical Chemistry Department; a.kattaev@nuu.uz; ORCID: 0000-0002-0276-2717

Keywords: chemical engineering education, digital technologies, artificial intelligence, case-study method, rhenium, ion exchange, sorption, industrial solution.

1. Introduction

The digitalisation of industrial technologies requires modern engineers to possess not only fundamental scientific knowledge, but also the ability to analyse large datasets, identify relationships between process parameters, and make well-founded decisions under conditions of uncertainty. Therefore, integrating traditional lectures and laboratory classes with real industrial data, digital modelling, problem-based learning, and artificial intelligence tools has become an important task in contemporary engineering education.

According to the concept of experiential learning, knowledge is acquired more effectively through the process of solving practical problems than through the passive reception of ready-made information [1]. Active-learning methods in engineering education have also been reported to support the development of analytical thinking, questioning skills, and independent decision-making [2]. Artificial intelligence can further assist this process by organising data, explaining calculation algorithms, identifying trends in graphical results, and comparing alternative technological solutions.

However, artificial intelligence should not be regarded as a source of automatically correct and final answers. Its application in engineering education must be based on the verification of results, critical evaluation of sources, compliance with ethical principles, and preservation of human responsibility for final decisions [3].

The recovery of rare metals from technogenic and industrial solutions is a complex engineering problem involving several interrelated factors. In particular, the relatively low concentration of rhenium, the considerably higher concentration of molybdenum, the strong acidity of the solution, and the presence of competing ions make the selection of a selective sorbent difficult. This process provides an opportunity to study chemical equilibrium, ion exchange, mass transfer, sorption kinetics, and column hydrodynamics within a single integrated engineering problem.

The aim of this study is to develop a digital case-study model enriched with artificial intelligence tools for chemical engineering education, using real research data on the selective recovery of rhenium from sulfuric acid industrial solutions.

2. Materials and Methods

The case study was developed using laboratory and dynamic experimental data obtained during the treatment of sulfuric acid process solutions containing rhenium and

molybdenum with ion-exchange sorbents. To protect industrial confidentiality, the name of the enterprise, certain technological stages, and identifying production details were generalised.

The initial engineering situation considered in the case involves a strongly acidic solution containing approximately 0.5–0.7 g/L rhenium and more than 15 g/L molybdenum. Students are required to select a sorbent that provides a high degree of rhenium uptake, sufficient selectivity in relation to molybdenum and other components, effective regeneration, and operational stability under dynamic conditions.

The digital case consists of seven interconnected stages:

1. analysis of the chemical composition and acidity of the process solution;
2. assessment of the probable ionic forms of rhenium and molybdenum;
3. comparison of gel-type and macroporous ion exchangers according to their functional groups, porous structure, and stability in acidic media;
4. digital processing of static sorption data;
5. comparison of kinetic and diffusion models;
6. analysis of dynamic column breakthrough curves;
7. justification of the technological decision according to technical, environmental, and ethical criteria.

Using spreadsheet software or mathematical data-processing programs, students calculate sorption capacity, recovery efficiency, and relative concentration. The kinetic data are analysed using pseudo-first-order and pseudo-second-order models, the Weber–Morris intraparticle diffusion model, and the Boyd approach.

Based on dynamic experimental data, the relationship between the relative concentration and treated bed volumes, expressed as C/C_0 versus BV, is constructed. This relationship is used to estimate the working sorption capacity, the breakthrough point of rhenium, and the appropriate time for transferring the column to the regeneration stage.

Artificial intelligence tools may be assigned tasks such as organising experimental data into tables, explaining the sequence of calculations, interpreting trends in graphs, and generating alternative technological scenarios. Nevertheless, every AI-generated response must be verified by the student using the original data, material balances,

measurement units, and physicochemical principles. In this way, artificial intelligence is positioned as a tool supporting analysis rather than as a system that independently produces the final answer.

3. Results and Discussion

The developed case-study model integrates the content of several chemical engineering disciplines within a single industrial problem. At the first stage, students analyse the behaviour of rhenium in a strongly acidic medium, where it is mainly present as the perrhenate ion, ReO_4^- . Molybdenum may exist in different oxoanion and polymeric forms depending on the composition and acidity of the solution. This situation demonstrates that sorbent selectivity depends not only on ionic charge, but also on ion size, degree of hydration, the nature of functional groups, and the porous structure of the sorbent.

At the sorbent-comparison stage, students are encouraged to reconsider the simplified assumption that the material with the highest sorption capacity is necessarily the best industrial sorbent. Under industrial conditions, sorption rate, selectivity for rhenium over molybdenum, mechanical strength, desorption conditions, regeneration performance, and resistance to aggressive solution components are also important. Thus, the case directs students to evaluate sorbents using several technological criteria rather than a single parameter.

During the digital processing of kinetic data, students learn that selecting a model solely on the basis of its correlation coefficient is not sufficient. For example, a high fit of the pseudo-second-order model does not automatically prove that the process is governed exclusively by chemisorption. Such a conclusion must be supported by diffusion models, sorbent structure, experimental duration, and external mass-transfer conditions. This approach connects numerical results with their actual physicochemical meaning.

At the dynamic stage, the C/C_0 versus BV breakthrough curve provides a visual representation of column performance. The curve can be used to assess not only the total amount of rhenium retained, but also the working sorption capacity, breakthrough point, mass-transfer zone, and appropriate regeneration time. This stage is important for understanding the difference between laboratory batch experiments and the behaviour of a continuous industrial process.

The artificial intelligence component of the case demonstrates that the same dataset may be interpreted differently depending on how the prompt is formulated. The accuracy

of the prompt, completeness of the input data, and correctness of measurement units directly influence the quality of the generated result. When an AI-generated model or conclusion contradicts experimental evidence, priority must be given to verified experimental data and established physicochemical principles.

The ethical and legal component is also an essential part of the proposed case. When industrial data are used for educational purposes, the confidentiality of the enterprise must be protected, sensitive information must be anonymised, sources must be cited correctly, and intellectual property rights must be respected. The uncritical use of AI-generated texts, calculations, or bibliographic references is inconsistent with the principles of academic integrity.

For this reason, the central principle of the case is that artificial intelligence may support analysis, but responsibility for the final engineering decision and its possible consequences remains with the human decision-maker. This principle is especially important in chemical and metallurgical processes, where incorrect technological decisions may result in material losses, environmental impacts, or safety risks.

The proposed model has not yet been evaluated through a pedagogical experiment involving students. Therefore, its educational effectiveness is not presented as a proven result. Instead, it is regarded as a digital case-study model developed for further implementation and testing in chemical and metallurgical engineering courses. This limitation defines the actual scientific status of the study and provides a basis for planning subsequent research.

4. Conclusion

The digital case developed on the basis of the selective recovery of rhenium from industrial solutions integrates theoretical knowledge, experimental data, mathematical modelling, and industrial practice within a single educational task. The case includes analysis of solution composition, selection of an ion-exchange sorbent, digital processing of kinetic and dynamic results, interpretation of graphs, and multi-criteria justification of a technological decision.

Artificial intelligence can serve as an effective supporting tool for organising data and analysing alternative technological solutions. However, each AI-generated conclusion must be verified using experimental evidence, material balances, measurement units, and physicochemical principles. Digital technologies should therefore not replace students' independent thinking, but should support and strengthen their analytical and research activities.

The proposed approach may be applied in courses related to chemistry, metallurgy, ion-exchange technology, and chemical process engineering. At the next stage, the case should be tested with students in chemical and metallurgical engineering programmes. Its influence on digital literacy, analytical thinking, research skills, and engineering decision-making competencies should then be evaluated using appropriate pedagogical assessment methods.

References

- Kolb, D. A. *Experiential Learning: Experience as the Source of Learning and Development*. Prentice-Hall, 1984.
- Prince, M. “Does Active Learning Work? A Review of the Research.” *Journal of Engineering Education*, 2004, 93(3), 223–231.
- UNESCO. *Guidance for Generative AI in Education and Research*. Paris: UNESCO, 2023.
- Felder, R. M., and Brent, R. “Designing and Teaching Courses to Satisfy the ABET Engineering Criteria.” *Journal of Engineering Education*, 2003, 92(1), 7–25.
- Zawacki-Richter, O., Marín, V. I., Bond, M., and Gouverneur, F. “Systematic Review of Research on Artificial Intelligence Applications in Higher Education: Where Are the Educators?” *International Journal of Educational Technology in Higher Education*, 2019, 16, 39.

Legal-Regulatory Implications of AI and Automation in Hydrometallurgical Zinc Residue Processing: Occupational Safety and Workforce Transition

Khaydaraliev Kholbay Rustam ugli¹, Kholikulov Doniyor Baxtiyorovich²,
Shodiyev Mekhriddin Tojiddinzoda³.

Abstract

Hydrometallurgical processing of zinc calcine generates hazardous zinc residue (zinc cake) rich in valuable metals such as zinc, lead, and indium. AI, the Internet of Things (IoT), and robotic automation have improved metal recovery and process stability while reducing workers' exposure to hazardous conditions. However, these technologies also create legal challenges related to occupational health and safety (OHS), liability, and workforce displacement. This paper examines automated zinc cake processing through technical and comparative legal analysis, highlighting regulatory gaps in algorithmic liability, sensor failure, and worker retraining. It also emphasizes the need for engineering curricula integrating hydrometallurgy, AI ethics, and industrial safety law.

Keywords: Zinc residue processing, Hydrometallurgy, Artificial Intelligence, Industrial automation, Occupational safety law, Workforce displacement.

¹ Senior Lecturer, Department of Metallurgy; Almalyk State Technical Institute, Almalyk, Uzbekistan, E-mail: xolboyxaydaraliyev@gmail.com ORCID: 0000-0002-6953-6490

² Professor (DSc), Head of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: Kholikulov.d@odti.uz6, ORCID: 0000-0001-6968-9297

³ Student. Department of Metallurgy; Almalyk State Technical Institute, Almalyk, Uzbekistan; mehridinshodiev17@gmail.com; ORCID: 0009-0003-0921-1947

1. Introduction

Hydrometallurgical extraction of zinc produces substantial volumes of leaching residue, commonly designated as zinc cake or zinc residue. This solid waste stream contains significant concentrations of zinc (Zn), lead (Pb), and indium (In), alongside hazardous heavy metals and residual free acids [1]. The comprehensive recovery and clean utilization of zinc cake represent a critical imperative for both environmental stewardship and economic efficiency within the circular economy [1]. In facilities such as the Almalyk Mining and Metallurgical Complex (AMMC), the mineralogical complexity of zinc residues requires sophisticated hydrometallurgical leaching schemes to optimize valuable metal extraction and stabilize toxic components [2,3].

To overcome the non-linear dynamics and harsh operating environments inherent in heavy hydrometallurgy, industrial facilities are increasingly deploying automated process monitoring, machine learning (ML) algorithms, and robotic systems [5, 6]. AI-driven software sensors, automated chemical dosing, and IoT monitoring frameworks allow precise operational control, minimizing chemical waste and reducing major spill risks [7].

However, rapid technological integration has exposed a significant gap between industrial capabilities and existing legal-regulatory frameworks. Traditional Occupational Health and Safety (OHS) statutes and labor codes were constructed around direct human supervision and manual labor paradigms [8]. As algorithmic decision-making replaces human intervention in hazardous zones, fundamental questions arise regarding statutory employer liabilities, automated system accountability, and the legal obligations surrounding workforce displacement [8–10].

This paper investigates the intersection of hydrometallurgical automation and industrial law. Its main objectives are to:

1. Analyze technical trends in automated zinc cake processing.
2. Evaluate shifts in OHS metrics and legal liability allocation when control is delegated to AI systems.
3. Formulate regulatory recommendations for workforce retraining, statutory compliance, and engineering curriculum modernization.

2. Methods

This research utilizes an interdisciplinary methodology combining process engineering analysis, case study examination, and comparative legal analysis. The technical baseline evaluates hydrometallurgical zinc cake processing, drawing on empirical and mineralogical data from global operations as well as specific processing routes developed for AMMC zinc residues [4].

By synthesizing process dynamics with statutory analyses, this study identifies structural friction points between technical capabilities and regulatory compliance.

3. Results

3.1. Technical Architecture of AI-Driven Zinc Cake Processing

Hydrometallurgical extraction from zinc residue involves multi-stage pressure leaching, neutral and acid wash cycles, and solid-liquid separation. Historically, manual monitoring of slurry density, free acid concentrations, and autoclave pressure introduced operational variances and exposed personnel to toxic emissions.

Modern processing lines employ IoT-driven smart sensing arrays combined with machine learning control systems [5, 7]. Advanced soft sensors continuously track pulp density and acid reactivity, feeding real-time data to neural network controllers that automatically adjust reagent dosages and thermal inputs [5, 7]. Furthermore, automated high-pressure leaching reactors and robotic manipulators handle hazardous cake filter presses, effectively isolating human operators from harsh chemical environments [1, 6].

3.2. Impact on Workplace Safety and Liability Allocation

Implementing AI-driven control systems significantly improves quantitative health and safety metrics. Automated fault detection algorithms and robotic material handling drastically reduce acute chemical exposures, acid burns, and manual handling injuries [6, 7]. When an algorithmic control failure causes a pressure excursion or slurry overflow, establishing legal fault under traditional OHS legislation becomes complex [8, 11]. Standard frameworks assume human negligence or mechanical fatigue; they are ill-equipped to apportion liability between plant operators and third-party software developers when automated control loops fail [8, 11].

3.3. Workforce Restructuring and Job Displacement

Automation in zinc residue processing shifts job roles across the facility:

Low-Skilled (Eliminated)	Manual Roles	Data-Literate Engineering Roles (Demand Created)
- Filter press manual cleaning - Manual chemical sampling - Basic cake transport		- AI system maintenance & supervision - IoT sensor calibration - Process data analytics

Manual tasks such as cake handling, hazardous sampling, and filter press operation are increasingly automated. In contrast, demand is growing for data-skilled technicians, control engineers, and mechatronics specialists [9]. Without statutory reskilling measures, this transition may lead to structural displacement of low-skilled metallurgical workers [12].

4. Discussion and Recommendations

4.1. Adequacy of Existing Statutory Frameworks

Current labor and environmental statutes remain largely reactive. Standard OHS laws rely on physical safety barriers and manual inspection protocols, offering few guidelines for algorithmic safety verification, software audits, or sensor redundancy mandates in heavy industry [8].

4.2. Comparative International Insights

International regulatory bodies are beginning to address these gaps. Frameworks like the European Union's Artificial Intelligence Act and updated directives on machinery safety attempt to classify high-risk industrial AI, assigning strict product liability to software developers while maintaining employer duty-of-care obligations [10].

4.3. Strategic and Legal Recommendations

To align technological progress with worker safety and employment stability, regulatory bodies and industrial operators should implement three main initiatives:

1. **Updated OHS Standards for Algorithmic Safety:** Industrial safety codes must incorporate specific regulations for autonomous systems, including mandatory dual-redundant IoT sensor arrays, periodic AI audit protocols, and clearly defined legal indemnification boundaries between software providers and plant operators [8, 11].
2. **Statutory Transition and Retraining Retainers:** Labor legislation should require industrial enterprises undertaking major automation projects to fund structured re-skilling programs. Employer tax incentives should be tied directly to internal workforce retraining success rates [9, 12].
3. **Algorithmic Transparency and Worker Involvement:** Plant management should establish joint worker-management safety committees to review automated monitoring deployments, ensuring algorithmic management practices remain transparent and fair [10].

4.4. Implications for Engineering Education

The shift toward AI-controlled hydrometallurgy requires updating academic curricula. Engineering institutions must break down traditional silos between metallurgy, computer science, and jurisprudence. Future metallurgical engineers need technical competence in chemical kinetics and hydrometallurgical recovery [1–4], alongside working knowledge of process control algorithms, industrial IoT architecture, and OHS law [5, 8, 11].

Integrating these disciplines ensures future plant managers can design efficient recovery circuits while maintaining regulatory compliance and upholding worker safety [8, 11, 12].

References

- 1- L. Zhang, Y. Wang, and R. Liu, "Comprehensive recovery and clean utilization of zinc residue from hydrometallurgical zinc extraction: A critical review," *Journal of Cleaner Production*, vol. 340, p. 130789, 2022. <https://doi.org/10.1016/j.jclepro.2022.130789>
- 2- D. B. Xolikulov, X. R. o'g'li Xaydaraliev, and H. K. Qarshiyev, "OLMALIQ KMK" AJ RUX ISHLAB CHIQRISH ZAVODI SHAROITIDA RUX KEKLARINI GIDROMETALLURGIK QAYTA ISHLASH IMKONIYATLARINI TAHLIL QILISH," *Journal of Advances in Engineering Technology*, vol. 2, pp. 54–58, 2020. <https://doi.org/10.24412/2181-1431-2020-2-54-58>
- 3- D. B. Kholikulov, Kh. R. Khaydaraliev, and Sh. T. Khojiev, "Mineralogical investigation of zinc cake generated in Almalyk zinc production," in *Proceedings of the International Conference on Integrated Innovative Development of Zarafshan Region: Achievements, Challenges and Prospects*, Navoi, 2025, pp. 401–402.
- 4- Kh. R. Khaydaraliev, M. M. Yakubov, D. B. Kholikulov, and O. M. Yokubov, "Development of effective technology for hydrometallurgical processing of zinc cakes of JSC 'Almalyk MMC'," *Non-Ferrous Metals*, no. 2, pp. 33–40, 2025.
- 5- M. Akkaya and S. Sundaram, "Machine learning applications for process control and optimization in heavy hydrometallurgical industries," *Minerals Engineering*, vol. 195, p. 108012, 2023. <https://doi.org/10.1016/j.mineng.2023.108012>
- 6- C. Ribeiro, F. Silva, and M. Santos, "Robotics and automated systems in metal recovery and waste recycling: Current trends and future directions," *Resources, Conservation and Recycling*, vol. 174, p. 105820, 2021. <https://doi.org/10.1016/j.resconrec.2021.105820>
- 7- H. Li, J. Xu, and X. Chen, "Smart monitoring systems for hazardous liquid effluent control in heavy metal extraction plants," *Computers & Chemical Engineering*, vol. 181, p. 108540, 2024. <https://doi.org/10.1016/j.compchemeng.2024.108540>
- 8- P. Korhonen and J. Alitalo, "Occupational health and safety in the age of industrial automation: A legal and regulatory assessment in high-risk sectors," *Safety Science*, vol. 152, p. 105789, 2022. <https://doi.org/10.1016/j.ssci.2022.105789>
- 9- O. Frey and H. Bakhshi, "Job displacement, reskilling, and the AI transition in heavy manufacturing and recycling sectors," *Journal of Industrial Relations*, vol. 65, no. 4, pp. 412–431, 2023. <https://doi.org/10.1177/00221856231178901>
- 10- V. De Stefano and S. Taes, "AI, robotics, and worker rights: Regulatory frameworks for the automated workplace," *European Labour Law Journal*, vol. 12, no. 3, pp. 298–315, 2021. <https://doi.org/10.1177/20319525211012345>
- 11- R. Srinivasan and P. Kumar, "Industrial safety, legal liability, and automation in chemical and metallurgical processing," *Journal of Loss Prevention in the Process Industries*, vol. 87, p. 105210, 2024. <https://doi.org/10.1016/j.jlp.2024.105210>

12-- E. Martinez and C. Lawson, "The legal implications of AI-driven automation in resource recovery and heavy manufacturing," *International Journal of Law and Management*, vol. 67, no. 1, pp. 88–104, 2025. <https://doi.org/10.1108/IJLM-05-2024-0210>

Production of Copper(I) Phosphide (Cu_3P) From Copper-Bearing Raw Materials Using Digitally Automated, Environmentally Safe Technologies: Research Directions and Prospects

Doniyor Bakhtiyorovich Kholikulov¹, Durdona Yo‘ldosh qizi Sharopova²

Abstract

Copper(I) phosphide (Cu_3P) has attracted considerable attention in materials science in recent years because of its semiconducting, electrocatalytic, and energy-storage properties. Conventional synthesis methods require high temperatures, toxic phosphorus precursors (such as white phosphorus or phosphine gas), and substantial energy input, which limits their industrial-scale application. This study aims to develop a technology for synthesizing Cu_3P nanomaterials from local copper-bearing raw materials and industrial waste using environmentally safe and resource-efficient methods, including low-temperature hydrothermal and mechanochemical routes and biogenic phosphorus sources. Digital modelling and machine-learning methods will also be used to optimize the synthesis parameters, making the study particularly relevant to the integration of digital technologies into engineering practice. The phase composition, morphology, and physicochemical properties of the resulting nanomaterials will be analysed by XRD,

¹ Doctor of Technical Sciences (DSc), Professor; E-mail: Kholikulov.d@tdtuof.uz; ORCID: 0000-0001-6968-9297

² Doctoral Researcher, Department of Metallurgy; E-mail: durdonasharopova9@gmail.com; ORCID: 0009-0005-1781-3483

DOI: <https://doi.org/10.5281/zenodo.22023688>

SEM/TEM, EDX, and UV–Vis spectroscopy. The expected results will contribute to establishing a new, environmentally friendly raw-material base for Cu₃P-based energy-storage devices and catalytic systems.

Keywords: copper(I) phosphide, Cu₃P, environmentally safe synthesis, nanomaterials, resource-efficient technology, digital process automation, copper-bearing raw materials

1. Introduction

Over the past decade, transition-metal phosphides, particularly copper(I) phosphide (Cu₃P), have attracted the attention of materials scientists because of their distinctive electronic structure, high electrical conductivity, and catalytic activity. Cu₃P is considered a promising anode material for lithium-ion and sodium-ion batteries, an electrocatalyst for water electrolysis and hydrogen production, and an active component in photocatalytic systems.

However, existing methods for producing Cu₃P—including high-temperature solid-state reactions and the use of highly toxic precursors such as white phosphorus or phosphine gas—have serious environmental and process-safety limitations and require high energy consumption, which conflicts with the principles of resource efficiency and sustainable development.

To address this problem, the present study aims to develop a technology for synthesizing Cu₃P nanomaterials from local copper-bearing raw materials, including mining and metallurgical waste, using low-temperature, energy-efficient processes and environmentally safer precursors. Another important aspect of the study is to investigate opportunities for the digital modelling and automation of the synthesis process, including the use of machine-learning algorithms to predict relationships between synthesis parameters and material properties, as well as real-time sensor monitoring. This aspect is directly related to the influence of technological innovation on engineering education and practice and reflects the transformation of materials-science research in the digital age.

The authors' previous research on Cu₃P—including studies of alloying components [7], the anticorrosion properties of Cu₃(PO₄)₂ [8], and a comparative review of synthesis methods [9]—provides the methodological and theoretical foundation for the present study.

2. Literature Review

The review conducted by Kholikulov and Sharopova (2026) provides an important methodological basis for assessing recent developments in the synthesis, properties, and applications of Cu₃P. Drawing on more than twenty sources, the authors comparatively analysed six Cu₃P production routes: ionothermal, hydrothermal/solvothermal,

mechanochemical, colloidal, vapour-phase phosphorization, and pyrometallurgical processing [9].

According to the review, ionothermal and solvothermal methods provide high phase purity and enable control over copper vacancies, whereas mechanochemical synthesis produces nanocrystalline particles approximately 20 nm in size and enhances electrochemical activity through structural defects [2]. In vapour-phase phosphorization, Cu_3P nanostructures are formed on conductive copper substrates, resulting in high electrical conductivity [3]. Alloys produced from industrial waste by a pyrometallurgical route at 1,110°C contain 7.62–8.00% phosphorus [9].

In terms of electrochemical performance, conventional Cu_3P electrodes exhibit capacities of 180–420 mAh g⁻¹, whereas graphene-decorated $\text{Cu}_3\text{P}@3\text{DG}$ hybrid electrodes deliver a capacity of 440 mAh g⁻¹ and retain more than 88% of their capacity after 50 cycles [4]. Cu_3P nanobush structures exhibit overpotentials of 120 mV for the hydrogen evolution reaction (HER) and 380 mV for the oxygen evolution reaction (OER) during water electrolysis [3]. $\text{Cu}_3(\text{PO}_4)_2$ pigments have also been shown to reduce the corrosion current density from 12.1 to 0.018 $\mu\text{A cm}^{-2}$, corresponding to an approximately 65-fold improvement [7, 8].

Although individual Cu_3P production methods have been studied in depth, systematic research aimed at developing an integrated, environmentally safe, digitally controlled technology based on local raw materials remains insufficient. Addressing this gap constitutes the scientific novelty of the present study.

3. Research Methodology

The study is planned in two main stages. In the first stage, the chemical and mineralogical composition of copper-bearing raw materials and industrial waste will be examined using X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses. In the second stage, the following environmentally safer methods for synthesizing Cu_3P nanomaterials from the selected raw materials will be compared: (i) low-temperature hydrothermal/solvothermal synthesis using aqueous or bio-based solvents; (ii) mechanochemical synthesis under solvent-free conditions; and (iii) synthesis using biogenic or low-toxicity phosphorus sources, such as sodium hypophosphite or phytic-acid derivatives.

The phase composition and crystal structure of the synthesized samples will be analysed by XRD; their morphology and particle size by scanning and transmission electron microscopy (SEM/TEM); their elemental composition by energy-dispersive X-ray spectroscopy (EDX); and their surface chemical states by X-ray photoelectron spectroscopy (XPS). Optical properties will be determined by UV–Vis spectroscopy, and the specific surface area will be measured using the BET method.

Digital control and automation of the synthesis process constitute a separate research direction. Reactor temperature, pH, and reagent flow rates will be recorded in real time by sensors and transmitted to a PLC/SCADA system, enabling the process parameters to be maintained accurately and reproducibly with minimal human intervention. Using the collected data, machine-learning models based on regression and neural networks will identify relationships between synthesis parameters and material properties. Based on the digital-twin concept, this approach will enable the optimal operating conditions to be predicted while reducing the number of experimental trials.

4. Expected Results

Based on the literature review and preliminary theoretical calculations, the selected environmentally safe methods are expected to yield Cu_3P with high phase purity at relatively low temperatures (200–350°C). The mechanochemical route is also expected to outperform conventional high-temperature methods in terms of energy consumption and processing time.

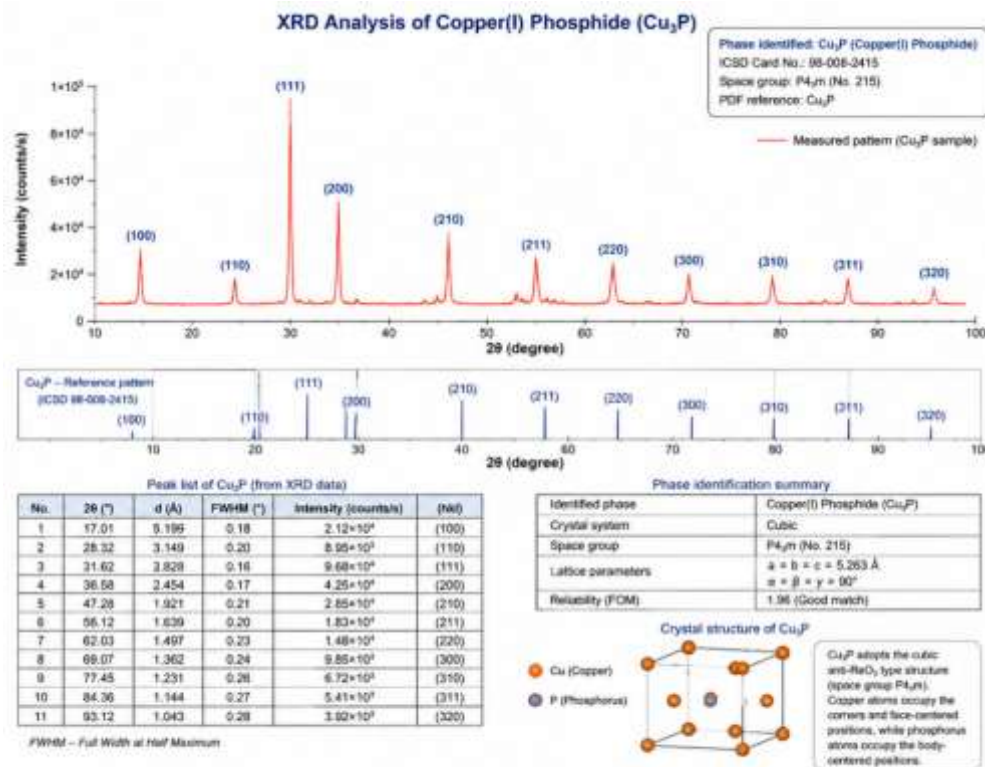


Figure. XRD pattern and phase identification of synthesized copper(I) phosphide (Cu_3P).

Figure 1. XRD pattern and phase identification of the synthesized copper(I) phosphide (Cu_3P) sample.

The phase composition of a sample obtained in preliminary synthesis experiments conducted within this study was confirmed by X-ray diffraction (XRD). The principal diffraction peaks were indexed to the (100), (110), (111), (200), (210), (211), (220), (300),

(310), (311), and (320) planes and showed close agreement with the reference Cu_3P phase in ICSD card No. 98-008-2415, with a figure of merit (FOM) of 1.96. The sample was assigned to a cubic crystal system with the $P4_3m$ space group (No. 215) and lattice parameters $a = b = c = 5.263 \text{ \AA}$, consistent with the anti- ReO_3 -type crystal structure characteristic of Cu_3P , in which copper atoms occupy the corners and faces and phosphorus atoms occupy the body-centred positions. The most intense (111) peak was observed at 31.62° , confirming the predominance of the principal phase. These results demonstrate that the synthesized material is high-phase-purity Cu_3P and support the suitability of the selected synthesis method (Figure 1).

5. Discussion

The proposed approach offers several advantages: eliminating toxic precursors improves worker safety and environmental protection; using local raw materials and industrial waste is consistent with circular-economy principles; and digital process automation with real-time monitoring reduces the influence of human factors and substantially improves efficiency.

Automating the synthesis process through sensors, SCADA systems, and machine learning is not merely a technical solution; it also clearly demonstrates how technological innovation intersects with law and engineering education. Industrial-scale implementation of automated production processes requires the development of appropriate technical regulations, data-security requirements, and quality-control standards, as well as the adaptation of the existing legal and regulatory framework to digital forms of production. This further strengthens the need to integrate competencies in digital control, automation, and data-driven decision-making into engineering curricula—an aspect that directly aligns with the central theme of the symposium.

6. Conclusion

Developing an environmentally safe, resource-efficient, and digitally controlled technology for producing Cu_3P nanomaterials from copper-bearing raw materials has not only scientific and practical significance for materials science but also value as an innovative solution aligned with the principles of sustainable development and industrial digitalization. The findings are expected to be published in reputable international journals indexed in Scopus and Web of Science and to strengthen Uzbekistan's scientific capacity in materials science. Future research will focus on practical testing of the synthesized nanomaterials and the industrial-scale implementation of automated control systems.

References

Aitken, J. A., Ganzha-Hazen, V., & Brock, S. L. (2005). Solvothermal syntheses of Cu_3P via reactions of amorphous red phosphorus with a variety of copper sources. *Journal of Solid State Chemistry*, 178(4), 970–975.

Wolff, A., Doert, T., Hummel, F., Schmidt, P., & Ruck, M. (2016). Resource-efficient high-yield ionothermal synthesis of microcrystalline Cu_{3-x}P . *Inorganic Chemistry*, 55(11), 4991–4998.

Wei, S., Wang, T., Sun, Z., et al. (2017). One-step synthesis of a self-supported copper phosphide nanobush for overall water splitting. *ACS Applied Materials & Interfaces*, 9(3), 2305–2313.

Kumar, S., et al. (2020). Three-dimensional graphene-decorated copper-phosphide ($\text{Cu}_3\text{P}@3\text{DG}$) heterostructure as an effective electrode for a supercapacitor. *Frontiers in Materials*, 7, 30.

Bi, M., Yang, F., Wang, T., & Guo, Z. (2023). Controllable synthesis and super electrochemical stability of copper phosphide (Cu_3P) nanosheet catalysts in nearly neutral electrolyte. *Materials Chemistry and Physics*, 307, 128013.

Ma, X., Huang, X., & Lachgar, A. (2024). Direct synthesis of CuP_2 and Cu_3P and their performance as electrocatalysts for hydrogen evolution, oxygen evolution, and oxygen reduction reactions. *Solids*, 5(1), 140–150.

Yakubov, M. M., Kholikulov, D. B., Sharopova, D. Y., & Boltayev, O. N. (2022). Technology for obtaining copper phosphide (Cu_3P) in the form of solders and an alloying component of copper-based alloys. *Composite Materials*, 2, 165–166.

Sharopova, D. Y. (2025). Anti-corrosive properties of copper phosphide / copper phosphate ($\text{Cu}_3(\text{PO}_4)_2$) derived from spent copper plating electrolytes. *Universum: Technical Sciences*, 9(138), 62–66.

Kholikulov, D. B., & Sharopova, D. Y. (2026). Copper phosphide (Cu_3P): A modern review of synthesis methods, electrochemical properties, and anticorrosion applications. *Digital Technologies in Industry*, 4(2). <https://doi.org/10.70769/3030-3214.SRT.4.2.2026.29>

Determination of the Toxicity of Phenyl-2-Chloropropionate and 4-Hydroxyphenyl-2-Chloropropionate

Ochilov Mansur¹, Abdushukurov Anvar Kabirovich² Mamatkulov Nematillo Narzullaevich³

Abstract

In this study, the acute toxicity of phenol, phenyl-2-chloropropionate, 2-chloropropionyl chloride, and 4-hydroxyphenyl-2-chloropropionate compounds was evaluated using the QSAR approach based on the GUSAR program. The LD₅₀ values of the compounds following IP, IV, oral, and SC administration routes, as well as their toxicity classes according to OECD classification, were comparatively analyzed. The results demonstrated that toxicity levels depend on the route of administration, with higher toxicity observed for IV and IP routes and lower toxicity for oral administration. According to OECD classification, phenyl-2-chloropropionate and 4-hydroxyphenyl-2-chloropropionate mainly belong to Class 4 (low toxicity), while 2-chloropropionyl chloride was classified as Class 3 (moderate toxicity) for some administration routes. The toxicity order was determined as follows: 2-chloropropionyl chloride > phenyl-2-chloropropionate > 4-hydroxyphenyl-2-chloropropionate. The obtained results confirm the effectiveness of the QSAR approach in assessing the safety of organic compounds and optimizing toxicological studies.

Keywords: GUSAR, toxicity, LD₅₀, chloropropionate, phenyl-2-chloropropionate, QSAR, OECD.

¹Senior Lecturer, Almalyk State Technical Institute, Almalyk, Republic of Uzbekistan; mansurochilov2003@gmail.com ORCID ID 0009-0009-4247-3694.

² Doctor of Chemistry, Professor, Faculty of Chemistry, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Republic of Uzbekistan; abdushukurov-ximik@mail.ru; ORCID: 0000-0003-0879-9614

³ Doctor of Chemistry (DSc) Associate Professor, Faculty of Chemistry, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Republic of Uzbekistan; nematillomamatkulov767@gmail.com; ORCID ID 0009-0000-2728-4507

1. Introduction

Phenyl-2-chloropropionate and 4-hydroxyphenyl-2-chloropropionate are important chemical compounds widely used in industry and agriculture. Therefore, a comprehensive and systematic investigation of their toxicological properties is considered one of the relevant scientific challenges in modern chemistry and pharmaceutical research [1].

The assessment of acute toxicity parameters, particularly the determination of LD₅₀ values, plays an important role in evaluating the biological activity and safety of chemical substances. Along with traditional *in vivo* experiments, the increasing application of QSAR (Quantitative Structure–Activity Relationship) approaches in recent years has enabled reliable prediction of the toxicity of compounds. This approach contributes to reducing the volume of experimental studies, saving time and resources, and decreasing the number of animal-based experiments [2,3].

2. Materials and Methods

In this study, the acute toxicity of the above-mentioned compounds was evaluated using the GUSAR software, considering different routes of administration (oral, dermal, inhalation, and others), and their potential hazard levels were analyzed. Phenyl-2-chloropropionate was synthesized, and its toxicity classification was determined based on the obtained data presented in the table.

Table 1

Parameter type	IP (Intraperitoneal)	IV (Intravenous)	Oral (Oral administration)	SC (Subcutaneous)
LD ₅₀ Log ₁₀ (mmol/kg)	0,125	-0,662	1055	0,743

Acute toxicity classification of chemicals in rodents according to the OECD project

- Rat IP LD₅₀ classification: Class 4
- Rat IV LD₅₀ classification: Class 4
- Rat Oral LD₅₀ classification: Class 5
- Rat SC LD₅₀ classification: Class 5

2-Chloropropionyl chloride toxicity classification

Table 2

Parameter type	IP (Intraperitoneal)	IV (Intravenous)	Oral (Oral administration)	SC (Subcutaneous)
LD ₅₀ Log ₁₀ (mmol/kg)	-0,581	-1151	0,938	-0,721
LD ₅₀ (mg/kg)	33290	8967	1100000	24 140

OECD acute toxicity classification of chemicals in rodents

- Rat IP LD₅₀ classification: Class 3
- Rat IV LD₅₀ classification: Class 3
- Rat Oral LD₅₀ classification: Class 4
- Rat SC LD₅₀ classification: Class 3

The LD₅₀ values of 4-hydroxyphenyl-2-chloropropionate in rats were determined for different routes of administration, and the obtained results are presented as follows:

Table 3

Parameter type	IP (Intraperitoneal)	IV (Intravenous)	Oral (Oral administration)	SC (Subcutaneous)
LD ₅₀ Log ₁₀ (mmol/kg)	0,114	-0,582	0,711	0,506
LD ₅₀ (mg/kg)	242600	48900	959,400	598,800

OECD acute toxicity classification of chemicals in rodents

Rat IP LD₅₀ classification: Class 4

-Rat IV LD₅₀ classification: Class 4

-Rat Oral LD₅₀ classification: Class 4

-Rat SC LD₅₀ classification: Class 4

3. Obtained Results

Based on the provided data, a comparative analysis of the toxicity indicators obtained using the GUSAR program for phenol and its derivatives was carried out as follows. Firstly, the calculated LD₅₀ values for phenol and its derivatives (phenyl-2-chloropropionate, 2-chloropropionyl chloride, and 4-hydroxyphenyl-2-chloropropionate) show significant differences depending on the route of administration. In particular, toxicity is relatively higher when administered intravenously (IV) and intraperitoneally (IP) (lower LD₅₀ values), whereas considerably lower toxicity is observed through oral administration. This difference is associated with the biological availability and metabolism of the compounds.

The acute toxicity of the studied compound, phenyl-2-chloropropionate, presented in Table 1, was evaluated in mice using different routes of administration. According to the experimental data, the LD₅₀ values were determined as follows: 246 mg/kg for intraperitoneal (IP) administration, 40,250 mg/kg for intravenous (IV) administration, 2,096,000 mg/kg for oral administration, and 1,021,000 mg/kg for subcutaneous (SC) administration. According to the OECD toxicity classification system, the compound is classified as low toxic (Class 4) for all routes of administration. Oral toxicity was found to be almost minimal, indicating a high safety profile of the compound for both humans and animals.

The significant differences in LD₅₀ values depending on the route of administration may be associated with the biological mechanism of action and absorption characteristics of phenyl-2-chloropropionate. For example, the relatively low oral toxicity suggests limited absorption of the compound through the gastrointestinal tract or its possible biotransformation before reaching systemic circulation. At the same time, the comparatively lower LD₅₀ values observed following intraperitoneal and subcutaneous administration reflect the compound's systemic effects and its easier penetration into the organism.

The LD₅₀ graph presented on a logarithmic scale visually demonstrates the differences in toxicity levels among various administration routes, serving as an important tool in safety assessment. These findings provide a scientific basis for evaluating the toxicological risks of phenyl-2-chloropropionate, determining appropriate safety measures, and supporting its potential use under laboratory conditions.

The compound demonstrates the highest toxicity when administered intravenously (IV) and subcutaneously (SC). Administration via the intraperitoneal (IP) route shows a moderate level of risk, whereas oral administration (Oral) exhibits minimal risk and is considered practically safe. According to the OECD classification, the IV, IP, and SC routes correspond to Class 3 (moderately toxic), while the oral route belongs to Class 4 (low toxicity).

The acute toxicity of 4-hydroxyphenyl-2-chloropropionate in rats was evaluated through different routes of administration. The LD₅₀ values (mg/kg) were determined as follows: IP – 242,600; IV – 48,900; Oral – 959,400; SC – 598,800. According to the OECD standards, all administration routes fall into Class 4 (low toxicity).

The analysis indicates that the compound exhibits the highest toxicity when administered intravenously (IV), while the lowest risk is observed through oral administration (Oral). Administration via intraperitoneal (IP) and subcutaneous (SC) routes demonstrates a minimal level of risk, and the compound can be considered practically safe under these conditions. Therefore, 4-hydroxyphenyl-2-chloropropionate is classified as a low-toxic compound, and standard precautionary measures are considered sufficient during handling.

Within the scope of this study, a comparative analysis of the acute toxicity (LD₅₀) of four main compounds — phenol, phenyl-2-chloropropionate, 2-chloropropionyl chloride, and 4-hydroxyphenyl-2-chloropropionate — was performed in rodents using different routes of administration (IP, IV, Oral, and SC).

The hazard levels of the compounds were classified based on their lowest LD₅₀ values and the standards of the OECD (Organisation for Economic Co-operation and Development) as follows:

Indicators of the hazard levels of the compounds

Table 4

№	Compound name	Lowest LD ₅₀ (mg/kg)	OECD Class	Hazard level
I	2-Chloropropionyl chloride	8,967 (IV)	Class 3	Highest (Toxic)
II	Phenyl-2-chloropropionate	40,250 (IV)	Class 4	Low Hazard
III	4-Hydroxyphenyl-2-chloropropionate	48,900 (IV)	Class 3	Least Toxic

4. Conclusion

In this study, the acute toxicity of phenol, phenyl-2-chloropropionate, 2-chloropropionyl chloride, and 4-hydroxyphenyl-2-chloropropionate compounds was predicted using the GUSAR software and comparatively analyzed according to different routes of administration (IP, IV, oral, and SC). The results demonstrated that the toxicity level of all compounds was significantly dependent on the route of administration. Higher toxicity was observed following intravenous (IV) and intraperitoneal (IP) administration, whereas oral administration showed the lowest toxicity. This difference can be explained by variations in biological availability and metabolic transformations of the compounds. According to the OECD classification, the majority of the studied compounds belong to Class 4 (low toxicity), while 2-chloropropionyl chloride was classified as Class 3 (moderately toxic) for certain routes of administration.

Based on the comparative analysis, the toxicity levels of the compounds were found to decrease in the following order:

2-chloropropionyl chloride > phenyl-2-chloropropionate > 4-hydroxyphenyl-2-chloropropionate

The obtained results confirm the effectiveness of the QSAR approach in evaluating the biological activity and safety profiles of newly synthesized organic compounds and demonstrate its importance for optimizing experimental studies.

References

- Raies, A. B., Bajic, V. B. In silico toxicology: Computational methods for the prediction of chemical toxicity. WIREs Computational Molecular Science, 2016. 6(2), 147–172.
- Ballabio, D., Grisoni, F., Consonni, V., Todeschini, R. (2019). Integrated QSAR Models to Predict Acute Oral Systemic Toxicity. Molecular Informatics, 38 (1–2), 1800124.
- Graham, J. C., Rodas, M., Hillegass, J., Schulze, G. (2021). The performance, reliability and potential application of in silico models for predicting the acute oral toxicity of pharmaceutical compounds. Regulatory Toxicology and Pharmacology, 119, 104816.

Optimization of Copper Smelting Processes Using Artificial Intelligence and In-Situ Alkali Modification for Recovery of Iron and Valuable Metals

Mutalibkhonov Saidalokhon Saidolimkhonovich¹, Doniyor Bakhtiyorovich Kholikulov²

Abstract

Copper smelting is an energy-intensive process in which furnace stability directly affects metal recovery, slag quality, refractory life, and production costs. Although modern technologies have improved smelting efficiency, copper slag still contains recoverable iron, copper, and trace precious metals, representing an important secondary resource. This study proposes an integrated concept combining artificial intelligence (AI)-assisted optimization of sulfide copper smelting with in-situ alkali modification of molten copper slag during pouring into the bowl. AI is used to analyze real-time process parameters and optimize furnace operation to reduce valuable metal losses, improve energy efficiency, and stabilize the smelting process. Simultaneously, an alkali modifier is introduced into molten slag during tapping, utilizing its intrinsic thermal energy to initiate structural modification of the fayalite matrix before solidification without external heating. The proposed methodology is expected to improve downstream recovery of iron and residual valuable metals while supporting sustainable copper production and circular economy principles.

Keywords: Artificial Intelligence; sulfide copper smelting; copper slag; in-situ alkali modification; fayalite, iron extraction, DRI, copper

¹ PhD student of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: mutalibkhonov1990@gmail.com (corresponding author), ORCID: 0009-0003-1300-3411

² Professor (DSc), Head of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: kholikulov.d@odti.uz, ORCID: 0000-0001-6968-9297

Introduction

The growing demand for copper and other critical metals has increased the need for more efficient and sustainable metallurgical technologies. Sulfide copper smelting remains the principal industrial process for copper production because of its high productivity and reliability [1]. However, significant challenges remain, including high energy consumption, refractory wear, process instability, and losses of valuable metals into the slag phase.

Copper slag is mainly composed of fayalite (Fe_2SiO_4), iron oxides, and silicate phases. Besides being a by-product, it contains recoverable amounts of iron, copper, gold, silver, and other valuable elements. The stable structure of fayalite limits the efficiency of conventional beneficiation and hydrometallurgical recovery methods, making slag utilization an important research topic.

Recent developments in artificial intelligence (AI), machine learning, and digital process control have created new opportunities for improving metallurgical operations. AI can continuously analyze process data and optimize furnace temperature, oxygen supply, charge composition, and slag chemistry, resulting in improved process stability, lower energy consumption, and reduced metal losses [2]

Most previous studies have investigated either AI-based smelting optimization or copper slag treatment separately. Limited attention has been given to combining intelligent furnace control with modification of molten slag immediately after tapping [3].

Therefore, this study proposes an integrated technological concept that combines AI-assisted smelting optimization with in-situ alkali modification of molten copper slag. The proposed approach utilizes the intrinsic thermal energy of molten slag during tapping to initiate structural modification of the fayalite matrix before solidification. This strategy is expected to improve the recovery of iron and residual valuable metals while reducing additional energy requirements and supporting sustainable copper production [4].

Materials and Methods

This study presents a conceptual process integrating AI-assisted sulfide copper smelting with in-situ alkali modification of molten copper slag during tapping. The proposed methodology consists of two interconnected stages [5].

In the first stage, AI functions as a decision-support system by analyzing real-time operational data collected from industrial sensors, including furnace temperature, oxygen-to-charge ratio, concentrate composition, matte grade, slag chemistry, and off-gas characteristics. Machine learning algorithms evaluate these data to recommend operating conditions that improve process stability, reduce copper losses to slag, decrease energy consumption, and extend refractory service life [6].

In the second stage, molten slag discharged from the furnace is transferred into a steel slag pot. During slag pouring, an alkali-based modifier is introduced under controlled mixing conditions while utilizing the intrinsic thermal energy of the molten slag. This approach avoids additional heating and is expected to promote partial modification of the fayalite-rich structure before solidification, improving the liberation of iron-bearing phases and entrapped valuable metals [7].

The proposed concept may be evaluated using X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy with energy-dispersive spectroscopy (SEM–EDS). Process performance can be assessed by measuring copper losses to slag, matte grade, slag composition, iron recovery, energy consumption, furnace productivity, and refractory campaign life [8].

Results

The proposed methodology integrates AI-assisted smelting optimization with in-situ alkali modification of molten copper slag, creating a unified technological approach for improving both primary copper production and secondary resource recovery [9]. Unlike conventional practice, where furnace optimization and slag treatment are performed independently, the proposed concept establishes a direct connection between process control and slag conditioning.

AI is expected to improve furnace performance through continuous analysis of key operating variables, including furnace temperature, oxygen-to-charge ratio, concentrate composition, matte grade, slag chemistry, and off-gas characteristics. By adapting operating conditions to changing process parameters, AI can maintain stable smelting conditions, reduce copper losses to slag, improve matte quality, decrease specific energy consumption, and reduce thermal fluctuations that accelerate refractory wear. Consequently, improved operational stability and longer furnace campaign life are anticipated [10].

A distinguishing feature of the proposed methodology is the utilization of the intrinsic thermal energy of molten slag immediately after tapping. Instead of reheating cooled slag, an alkali modifier is introduced while the slag remains molten, allowing structural modification before solidification. This approach eliminates an additional heating stage and therefore has the potential to reduce overall energy consumption and simplify subsequent processing [11].

The elevated temperature of molten slag is expected to facilitate partial modification of the fayalite-rich silicate network, improving the liberation of iron-bearing phases together with entrapped copper and precious metals. Consequently, the conditioned slag may exhibit improved performance during downstream magnetic

separation or hydrometallurgical recovery compared with conventionally solidified slag [12].

From an environmental perspective, the proposed concept supports circular economy principles by reducing valuable metal losses while increasing the utilization of copper slag as a secondary resource. Simultaneously, AI-assisted process control contributes to more efficient use of raw materials and energy, whereas in-situ slag modification minimizes additional thermal treatment. Together, these improvements may reduce waste generation, greenhouse gas emissions, and overall processing costs.

Although the proposed methodology demonstrates considerable potential, further laboratory and industrial investigations are required to validate the thermochemical interactions between the alkali modifier and molten fayalite slag, optimize operating parameters, and quantify improvements in metal recovery and process efficiency. The integration of AI with innovative slag engineering represents a promising direction for developing more sustainable and resource-efficient copper smelting technologies.

Discussion and Conclusions

This study proposes an integrated technological concept that combines artificial intelligence (AI)-assisted optimization of sulfide copper smelting with in-situ alkali modification of molten copper slag during the tapping stage. The proposed methodology aims to improve furnace stability, reduce copper losses to slag, enhance energy efficiency, and extend refractory service life through intelligent process control. Simultaneously, the utilization of the intrinsic thermal energy of molten slag for alkali modification offers a practical approach to altering the fayalite-rich structure before solidification without additional external heating.

This strategy has the potential to improve the subsequent recovery of iron and residual valuable metals while supporting resource conservation and circular economy principles. Although the concept requires experimental validation under laboratory and industrial conditions, it represents a promising direction for developing more efficient, sustainable, and digitally enabled copper smelting technologies. The proposed integration of AI-assisted smelting optimization with in-situ alkali modification of molten copper slag provides a novel framework for simultaneously improving primary copper production and secondary resource recovery.

References

Bekhzod Gayratov, Bobur Gayratov, Labone L. Godirilwe, Sanghee Jeon, Abduqahhor Saynazarov, Saidalokhon Mutalibkhonov, Atsushi Shibayama (2025). Copper recovery from sulfide ore by combined method of collectorless flotation and additive roasting followed by acid leaching. ChemEngineering. 9(6), 117. <https://doi.org/10.3390/chemengineering9060117>

Kholikulov D.B. Mutalibkhonov S.S. Khudoymuratov Sh.J. (2025). Literature review: iron extraction from copper smelting slag and direct reduced iron (DRI/HBI) production. *International Journal of Academic Engineering Research (IJAER)*. 9(11), 53-59.

Mutalibkhonov S.S. Khudoymuratov Sh.J., Riskulov D.D. (2025). Copper Slag Processing and Recycling // *International Journal of Engineering and Information Systems (IJEAIS)*. 9(11), 23-29.

Mutalibkhonov S.S. (2026). Enhanced Metal Recovery from Copper Slag Using a Novel Alkali Activation Method Based on Its Intrinsic Latent Heat. *Scientific publication*. 3, 354-385

Runqing Liu, Qilin Zhai, Chen Wang, Xiong Li, Wei Sun (2020). Optimizing the crystalline state of Cu slag by Na₂CO₃ to improve Cu recovery by floatation. *Minerals*. 10(9), 820, <https://doi.org/10.3390/min10090820>

Hasan Arslanoglu, H. Soner Altundogan, Fikret Tumen. (2022). Extraction of copper, cobalt and Nickel by leaching of iron (III) Sulfate from copper slags. *Transactions of the Indian Institute of Metals*. 75, 1759-1766, <https://doi.org/10.1007/s12666-022-02564-y>

Mutalibkhonov S.S. (2025). Hydrogen-based reduction of fayalite and magnetite in copper slags. *IJAAR*. 9(12), 89-96.

Bulut Sukurov, Sergey Kvyatkovskiy, Sultanbek Kozhakhmetov et al. (2022). Structural changes in copper slags during slow cooling. *Metals*, 14(10), 1187, <https://doi.org/10.3390/met14101187>

Mutalibkhonov S.S., Kholikulov D.B., Khudoymuratov Sh.J., Khushbakov D.T. (2025). Recovery of precious and base metals from copper mining byproducts, tailings, and gangue material. *IJAER*. 9(12), 44-50.

A.S. Khasanov, K.T. Ochildiev, T. Khojiev Sh, S.S Mutalibkhonov (2023). [Determination of the theoretical viscosity of the converter slag and the factors affecting it](#). *Composite materials*. 1(2023), 48-52.

Khojiev Sh.T., Kholikulov D.B., Mutalibkhonov S.S., Shaymanov I.I., Ma G. (2025). Comparative thermodynamic analysis of fluxing additives Na₂O and CaO during the reduction of iron from silicate slags of ferrous metallurgy. *Non-ferrous metals*. 9(1125), 12-18. <https://doi:10.17580/chm.2025.09.02>

Mutalibkhonov S.S. (2026). Thermodynamic factors affecting the matte-slag system. *International Journal of Engineering and Information Systems (IJEAIS)*. 10(6), 75-79.

Google Lookout as an AI-Enabled Assistive Tool for Inclusive Engineering Education: Opportunities, Ethical Risks, and an Implementation Framework

Masidikov Elyar Mirsodikovich¹

Abstract

Engineering education relies extensively on technical drawings, diagrams, and laboratory equipment, making it a demanding learning environment for blind and low-vision students. Existing assistive technologies are typically oriented toward text-based content and do not fully address the visual-spatial materials characteristic of engineering education, creating a distinct barrier for this student group. This paper synthesizes the official capabilities and technical limitations of Google Lookout, an AI-enabled assistive-vision application, with the principles of inclusive education, disability rights, and laboratory safety, to propose a conceptual framework for its use in engineering education. The study adopts a conceptual-design approach based on a targeted review of Google's official documentation, UNESCO and United Nations normative instruments, and selected scholarly sources on assistive artificial intelligence. The analysis suggests that Lookout may support independent access to text and label-based information, but it should not be used without human oversight for complex diagrams or safety-critical laboratory tasks. On this basis, a six-stage implementation framework is proposed, spanning needs assessment through evaluation and refinement. The framework has not yet been tested with actual users, and its practical effectiveness should be evaluated in future pilot research. It may serve as an initial planning tool for instructors, accessibility services, and institutional administrators.

¹ PhD, Associate Professor, Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan. E-mail: masidikovelyor@gmail.com. ORCID: <https://orcid.org/0009-0003-9335-9361>. Corresponding author.

Keywords: artificial intelligence, Google Lookout, inclusive education, engineering education, blind and low-vision students, assistive technology, ethical and legal risk, digital accessibility.

1. Introduction

Higher engineering education increasingly relies on computer modeling, virtual laboratories, and artificial intelligence tools; while this trend can enhance instructional quality, tools that fail to create equal opportunity for all students may deepen existing disparities. Engineering disciplines are particularly visually and spatially demanding, relying on technical diagrams, circuit schematics, and laboratory equipment. For blind and low-vision students, this reliance creates a distinct barrier: conventional screen readers can read digital text but cannot independently recognize physical objects or printed materials.

Under Article 24 of the UN Convention on the Rights of Persons with Disabilities, persons with disabilities have the right to access higher education and vocational training without discrimination, with reasonable accommodation provided as needed (Office of the United Nations High Commissioner for Human Rights, 2006). Integrating assistive AI technologies into engineering education is therefore not only a technical matter but one of legal relevance.

Google Lookout is an Android-based assistive application that uses a smartphone camera and computer-vision technologies to identify text and objects, with certain image-description functions incorporating generative AI (Google LLC, n.d.). The ethics of assistive AI (Morris, 2020) and the factors behind its adoption or abandonment (Barak Ventura et al., 2026) have been discussed in the literature; within the sources reviewed here, however, integrated frameworks linking assistive AI, laboratory risk, accessibility, and institutional governance remain underdeveloped.

This paper proposes a six-stage conceptual framework for integrating Google Lookout's official functions and technical limitations with inclusive-education, disability-rights, and laboratory-safety requirements in engineering education for blind and low-vision students.

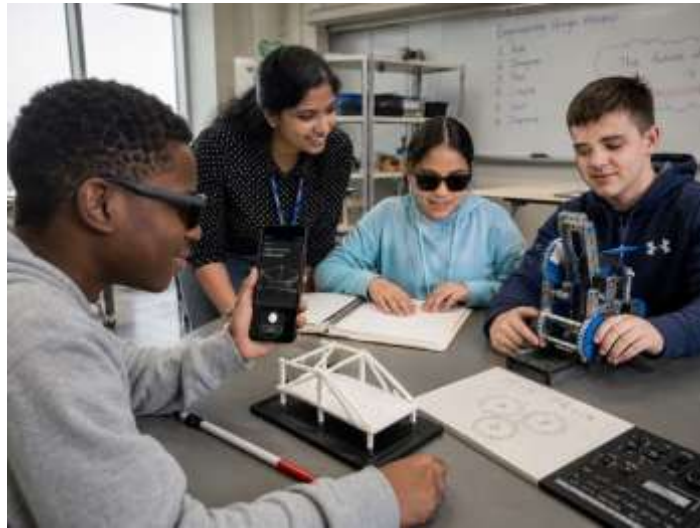


Figure 1. AI-generated conceptual illustration of blind and low-vision students using mobile assistive technology in engineering education. The image was created from the author's design brief and does not depict actual research participants.

2. Research Methodology

The study adopts a conceptual-design approach suitable for an emerging assistive-technology context in which empirical evidence remains limited. The analysis drew on three categories of sources: Google Lookout's official technical documentation (Google LLC, n.d.; Google Accessibility Help, n.d.); UNESCO's recommendations on AI ethics (Miao & Holmes, 2023), the UN Convention on the Rights of Persons with Disabilities (Office of the United Nations High Commissioner for Human Rights, 2006), and W3C's principles for describing visual information (W3C Web Accessibility Initiative, n.d.); and selected publications on assistive AI (Morris, 2020; Barak Ventura et al., 2026; Ahmadi et al., 2024), including the pattern-based approach for accessible STEM materials proposed by Bienhaus and Kreutzer (2026).

No formal systematic database search or predefined review protocol was applied; sources were purposively selected for their direct relevance to Lookout's functional capabilities, the ethical and legal risks of assistive AI, inclusive engineering education, digital accessibility, and laboratory safety -- the study's principal methodological limitation. Lookout's functions were compared with typical engineering-education tasks

and classified into three risk levels, an author-proposed conceptual scheme rather than an official regulatory standard.

3. Results of The Conceptual Analysis

3.1. Opportunities And Limitations of Google Lookout In Engineering Education

As of the time of manuscript preparation, the capabilities most directly applicable to engineering education are the Text and Documents modes: the former reads text aloud in real time, while the latter captures a full page and reads it aloud (Google Accessibility Help, n.d.). These functions may support reading laboratory instructions, identifying equipment and sample labels, and using printed materials. Explore and Find provide general descriptions of surrounding objects, though Explore remains in beta; the follow-up question feature in Images mode currently works only in English (Google Accessibility Help, n.d.).

Applied to metallurgical education, Lookout may assist with reading laboratory sample codes, equipment labels, printed instructions, and large digital displays. It should not, however, be used as an independent decision-making tool for phase diagrams, mineralogical micrographs, process-flow schemes, reagent concentration selection, or furnace control panels; a student should verify such results with an instructor or laboratory specialist.

As of the time of manuscript preparation, Lookout supports more than 30 languages, but Uzbek is not currently included, which constrains recognition of Uzbek-language technical terminology (Google Accessibility Help, n.d.).

3.2. Six-Stage Implementation Framework

Building on the analysis above, a six-stage conceptual framework is proposed, spanning needs assessment through refinement (Table 1), drawing on the normative instruments cited in Section 2 together with the principle of participatory design of assistive technologies (Barak Ventura et al., 2026).

Table 1. *Six-stage framework for implementing Google Lookout in inclusive engineering education*

Stage	Activity	Responsible party	Safety and accessibility requirement	Expected outcome
1. Needs assessment	Consultation with the student, instructor, and	Department and tutor	Respect for individual accessibility needs	Individual accessibility and usage profile

	tutor; identification of complex tasks			
2. Technical preparation	Checking the device, TalkBack, audio, internet access, and language settings	Student and IT support	Stable technical environment	Operationally ready setup
3. Adaptation of learning materials	Preparing documents with clear structure, readable typography, high contrast, and audio descriptions	Instructor	Digital accessibility and alternative-format requirements	Improved access to learning materials
4. Supervised integration	Gradual use in low-risk and subsequently medium-risk tasks	Instructor and tutor	Oversight proportionate to the level of risk	Gradual increase in independent use
5. Ethical, legal, and safety oversight	Establishing consent procedures, privacy rules, and camera-restricted areas	Institutional administration	Data protection, informed consent, and safety control	Safe and accountable use
6. Evaluation and refinement	Measuring time, accuracy, independent task completion, help requests, and errors	Researcher and department	Evidence-based decision-making	Evidence-informed model refinement

Source: Author's own work.

The framework is centered on a human-in-the-loop principle, meaning that safety-critical interpretations and decisions must be verified by an instructor or qualified laboratory specialist. Lookout may be used relatively independently for low-risk tasks, but any decision affecting laboratory safety requires confirmation. As Barak Ventura et al. (2026) note, the sustained adoption of assistive technologies depends substantially on participatory design, a factor reflected in the framework's structure.

3.3. Risk-Based Usage Protocol

The following low-, medium-, and high-risk levels represent an author-proposed conceptual classification, not an official regulatory standard, based on the application's functions and general laboratory practice.

Low-risk tasks include reading room numbers, document text, and equipment labels; the consequence of an error is limited, and the student can verify the result by rescanning. Medium-risk tasks include interpreting simple diagrams, reading instrument displays, and recognizing laboratory layouts; here, Lookout's output should be verified against a second source or by an instructor. High-risk tasks -- selecting reagents, operating electrical panels, using high-temperature or pressurized equipment, and working near moving mechanisms -- are treated separately: Lookout must not be used as an independent safety tool, and qualified human supervision is mandatory.

4. Discussion

Lookout may support independent identification of certain texts, signs, and objects, but it would be inaccurate to regard it as a means of fully comprehending technical drawings or spatial constructions; it is not intended to replace orientation and mobility training, white-cane use, or human assistance. Per W3C recommendations, an alternative description of visual information should encompass not only embedded text but also the objects and relationships necessary for understanding content (W3C Web Accessibility Initiative, n.d.). The most viable approach may therefore be to treat Lookout as part of a broader ecosystem that includes TalkBack, tactile graphics, and instructor supervision.

A key ethical concern is AI output delivered confidently despite being incorrect; as Morris (2020) notes, blind users are often unable to independently verify results, making such errors particularly consequential. A related concern is privacy, since the camera may inadvertently capture other students or confidential laboratory materials. The application may collect certain personal data, with transmission encrypted (Google LLC, n.d.). Institutions should nonetheless establish consent procedures and camera-restricted areas; where minors are involved, separate guardian consent is required.

Digital inequity is a further constraint, since not all students have comparable access to devices, cameras, or internet connections. Barak Ventura et al. (2026) note that abandonment of assistive technologies is often linked to device-infrastructure mismatches and inadequate training, so device model and network quality should be recorded as control variables in future research. Ahmadi et al. (2024) further observe that many publications on AI-based assistive tools do not adequately document error cases, complicating evidence-based safety policy.

Finally, institutional responsibility for harm arising from an incorrect AI description warrants separate consideration. This paper does not analyze Uzbek or other national legislation; liability and usage rules should be developed in accordance with local law and institutional regulations.

5. Conclusion

The conceptual analysis suggests that Google Lookout is most suitable for tasks involving text, documents, and simple labels; it remains insufficient for complex diagrams and safety-critical laboratory work and should be integrated with TalkBack, tactile graphics, and instructor oversight rather than used alone.

The paper's principal conceptual contribution is the six-stage implementation framework, which has not yet been empirically validated with actual users. Future pilot research should evaluate task-completion time, response accuracy, help requests, cognitive load, usability, and safety incidents to determine its practical effectiveness.

References

- Ahmadi, Z., Lewis, P. R., & Sukhai, M. A. (2024). Reporting risks in AI-based assistive technology research: A systematic review [Preprint]. arXiv. <https://arxiv.org/abs/2407.12035>
- Barak Ventura, R., Hamilton-Fletcher, G., & Rizzo, J.-R. (2026). From abandonment to adoption: Advancing assistive technologies for blindness and low vision in the AI era. *Frontiers in Digital Health*, 7, Article 1719746. <https://doi.org/10.3389/fdgth.2025.1719746>
- Bienhaus, D., & Kreutzer, M. (2026). A pattern collection for generating accessible teaching materials for blind and visually impaired students in computer science and electrical engineering. In T. Plummer, D. Dubbert, & C. Preschern (Eds.), *Pattern languages of programs, people and practices: EuroPLOP 2025 (Lecture Notes in Computer Science, Vol. 16494)*. Springer. https://doi.org/10.1007/978-3-032-19157-1_12
- Google LLC. (n.d.). Lookout – Assisted vision [Mobile application]. Google Play. Retrieved July 21, 2026, from <https://play.google.com/store/apps/details?id=com.google.android.apps.accessibility.reveal>
- Google Accessibility Help. (n.d.). Use Lookout to explore your surroundings. Android Accessibility Help. Retrieved July 21, 2026, from <https://support.google.com/accessibility/android/answer/9031274>
- Miao, F., & Holmes, W. (2023). Guidance for generative AI in education and research. UNESCO. <https://www.unesco.org/en/articles/guidance-generative-ai-education-and-research>
- Morris, M. R. (2020). AI and accessibility: A discussion of ethical considerations. *Communications of the ACM*, 63(6), 35–37. <https://doi.org/10.1145/3356727>
- Office of the United Nations High Commissioner for Human Rights. (2006). *Convention on the Rights of Persons with Disabilities*. United Nations. <https://social.desa.un.org/issues/disability/crpd/convention-on-the-rights-of-persons-with-disabilities-crpd>
- W3C Web Accessibility Initiative (WAI). (n.d.). Images tutorial. World Wide Web Consortium. Retrieved July 21, 2026, from <https://www.w3.org/WAI/tutorials/images/>

Effect of the Physicochemical Properties of Molten Gold on Its Recovery during the Pyrometallurgical Processing of Copper Oxide Mineral Raw Materials

M.M. Yakubov¹, J.B. Sunnatov², L.Sh. Samadova³, O.M. Yokubov⁴,
M.S. Maksudkhodjaeva⁵

Abstract

At present, some copper–gold ores are characterized by oxide mineralization, high refractoriness, finely disseminated valuable components, and the presence of a clay-rich matrix. Gold in such ores is mainly present as microscopic inclusions of native gold, which results in its incomplete recovery during mineral processing. Consequently, gold losses in the production of gold-bearing concentrates may reach 15–20%.

This study investigates the possibility of processing refractory gold-bearing ores together with a copper charge consisting of concentrates and fluxes during matte smelting, with the formation of both matte and an iron-based metallic alloy. Matte and the iron-based metallic alloy act as collectors for precious metals. During smelting, complete decomposition of the mineral matrix is achieved, carbon-containing and volatile components are oxidized and removed, and the melt separates into matte, iron-based metallic, and slag phases.

¹ Doctor of Technical Sciences, Professor, National University of Science and Technology MISIS, Almalyk Branch, Almalyk, Uzbekistan. **E-mail:** yakubovmahmud51@gmail.com **ORCID:** <https://orcid.org/0009-0008-8688-7066>

² PhD Candidate, Senior Lecturer, Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan. **E-mail:** jahonuz1987@gmail.com, **ORCID:** <https://orcid.org/0009-0001-4320-6071>

³ Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan Academic Tutor, State Institution *Fan va Taraqqiyot* under Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan. **E-mail:** dildorsamadova3@gmail.com **ORCID:** <https://orcid.org/0009-0004-9168-3800>

⁴ DSc Candidate, technologist at Carbide impex, Uzbekistan. E-mail: lawsecret@mail.ru; **ORCID ID:** <https://orcid.org/0009-0005-5746-1144>

⁵ Candidate of Technical Sciences (PhD), Associate Professor, Almalyk State Technical Institute, Almalyk, Uzbekistan. **E-mail:** mutabar1953uz@gmail.com **ORCID:** <https://orcid.org/0009-0002-3872-7494>

The high recovery of gold is attributed to its thermodynamic and physicochemical properties in the **matte-slag** and **iron-metallic phase** systems. These include its relatively low melting point (1064.18 °C), high boiling point (2856 °C), chemical inertness toward silicate melts, and extremely low solubility in the slag phase. At smelting temperatures of **1280–1300°C**, gold losses due to volatilization are practically negligible. An additional factor contributing to the efficient concentration of gold in the matte is its high density (19.3 g/cm³), which is significantly greater than that of the slag (~3.0 g/cm³). This density difference promotes the rapid settling of gold particles through the slag layer and their accumulation in the matte phase.

Introduction

To date, the accumulated volume of refractory disseminated oxidized copper ores stockpiled in the waste dumps of the Kalmakyr deposit is preliminarily estimated at approximately 136.2 million tonnes. Among the oxidized ores, a significant proportion is represented by ores that are difficult to beneficiate by conventional flotation, resulting in increased losses of valuable metals during mineral processing. This type of ore is commonly referred to as refractory oxidized ore.

The refractory nature of these ores is primarily associated with the presence of copper-bearing minerals such as chrysocolla, turquoise, libethenite, edite, cuprohalloysite, copper-bearing sericite, cuproalunite, and copper-bearing kaolinite. In these minerals, a considerable fraction of copper occurs in a chemically bound and poorly mobile form, making it difficult to recover by conventional beneficiation methods and even challenging to quantify accurately by routine chemical analysis.

The balance waste dumps of the Kalmakyr deposit contain significant amounts of valuable metals, with average grades of 0.9–1.1 wt.% Cu, 1.4–2.1 g/t Au, and 5.0–6.2 g/t Ag. These substantial reserves represent a promising secondary mineral resource and highlight the need for the development of efficient processing technologies capable of recovering copper and precious metals from refractory oxidized ores.

This paper provides a comprehensive review of recent studies on the distribution behavior of precious metals (gold, silver, and platinum group metals) in pyrometallurgical processes. The mechanisms governing the partitioning of these metals among slag, matte, and metallic phases during the high-temperature processing of both primary and secondary raw materials are discussed. Particular attention is paid to the effects of temperature, oxygen partial pressure, slag composition, and sulfur and halogen contents on the distribution coefficients of gold and silver. The authors also examine the application of pyrometallurgical technologies to the recycling of electronic waste and spent catalysts, highlighting their high efficiency in concentrating precious metals in metallic collector phases. Finally, the paper discusses future prospects for the development of precious metal recycling technologies based on pyrometallurgical processing [1].

This paper evaluates gold recovery during the processing of copper sulfide concentrates at modern copper smelters. The authors analyze various copper smelting and converting technologies, examining the distribution of gold among matte, slag, flue dust, and anode slime. The results demonstrate that modern pyrometallurgical processing routes are capable of achieving gold recoveries exceeding **99%**. Most of the gold is concentrated in the anode slime generated during the electrolytic refining of copper, where its concentration may increase by several hundred to several thousand times compared with that in the original concentrate. The study highlights the importance of optimizing and controlling key process parameters to maximize the economic performance of copper smelters through enhanced recovery of precious metals [2].

The paper provides a comprehensive analysis of existing waste processing technologies, including pyrometallurgical, hydrometallurgical, physical, and integrated processing methods. It is shown that pyrometallurgical processes offer high productivity and are well suited for the treatment of large volumes of solid waste. However, they are associated with high energy consumption and require efficient off-gas cleaning systems. In contrast, hydrometallurgical methods provide greater selectivity and process flexibility, enabling high metal recovery at relatively low temperatures. Nevertheless, these methods require the use of chemical reagents and subsequent purification of process solutions [3].

In view of the above, the development of new and innovative technologies for the processing of oxidized and mixed copper ores has become increasingly important. One of the promising approaches for treating oxidized copper ores is **reductive smelting using coke** as the reducing agent [4,5].

Discussion of the Results.

During the smelting process, all charge components are completely melted, thereby eliminating the effects of mineral dissemination. The resulting metallic phase acts as an efficient collector for precious metals, promoting their transfer from the slag into the sulfide melt (matte). One of the key factors responsible for the efficient concentration of gold in the matte is its chemical inertness toward silicate melts and its extremely low solubility in the slag phase. In addition, the high density of molten gold (approximately 17.2 g/cm³) is substantially greater than that of silicate slag (approximately 3.0 g/cm³), allowing gold particles to rapidly settle through the slag and accumulate in the matte phase. Complete melting of the charge eliminates mineral locking and enhances mass transfer, thereby facilitating the efficient recovery and concentration of gold, silver, and copper in the metallic collector phase.

To investigate the effect of temperature on the reduction degree of gold-bearing oxidized copper ores under fixed coke consumption and charge composition, a series of laboratory experiments was conducted in a Nabertherm high-temperature electric furnace (Germany), as shown in Figure 20. The smelting experiments were carried out at 1350 °C with a holding time of 1 h using a 100 g charge.

Table 1. Charge Composition, Charge Weight, and Yields of Smelting Products able.

Experiment No	Crucible No	Charge component	Weight, g	Content, wt. %	Temperature, °C	Metallic phase, g	Metallic phase, %	Slag, g	Slag, %	Flue dust, g	Flue dust, %
1	1	Oxidized ore	50	45,5	1350	9,8	9,10	80,11	72,82	10,09	9,17
	2	Slag	50	45,5							
	3	Coke	10	9							
	4	Total charge	1110	1100							

Table 2. Chemical Composition of Smelting Products

Experiment No.	Smelting Product (Sample No.)	Au (g/t)	Ag (g/t)	Au (%)	Fe (%)	S (%)	C (%)	SiO ₂ (%)	CaO (%)	Al ₂ O ₃ (%)	MgO (%)	B ₂ O ₃ (%)
	Metallic phase	10.18	50.28	2.56	65.43	10.19	6.42	-	-	-	-	-
	Slag	0.10	2.68	0.12	19.49	0.87	0.15	31.9	21.05	9.57	1.34	4.65

Results

According to the experimental results, the recovery into the metallic phase reached 93–95% for copper, 97.67–98.71% for gold, and 89.25–91.0% for silver.

Conclusions

The laboratory investigations demonstrated that the proposed pyrometallurgical technology enables the recovery of up to 95% of copper, 97.67–98.71% of gold, and 89.25–91.0% of silver into the metallic collector phase. These results confirm the high potential of the proposed process for the integrated treatment of mineral and technogenic gold-bearing raw materials in copper smelting operations.

The proposed approach makes it possible to process refractory oxidized gold-bearing ores without prior beneficiation, while simultaneously improving the comprehensive utilization of both mineral and technogenic resources. The high recoveries achieved for copper and precious metals demonstrate the feasibility and industrial potential of the technology for enhancing resource efficiency and increasing the economic performance of copper smelting plants.

References

- Moosavi-Khoonsari E., Tripathi N. (2024). *Gold Recovery from Smelting Copper Sulfide Concentrate*. Processes, 12(12), 2795. <https://doi.org/10.3390/pr12122795>
- He X., Ding Y., Shi Z., Ren J., Zhao B., Zhang C., Zhang S. *A Comprehensive Review on the Distribution Behaviors of Precious Metals Through Pyrometallurgical Processes and Implications for Recycling*. **Minerals Engineering**. 2024. Vol. 219. **Article 108998**. <https://doi.org/10.1016/j.mineng.2024.108998>
- Krishnan S., Zulkapli N.S., Kamyab H. et al. Current technologies for recovery of metals from industrial wastes: An overview // *Environmental Technology & Innovation*. 2021. Vol. 22. Article 101525.
- Kozhakhmetov, S.M., et al.** Reductive Pyrometallurgical Beneficiation of Oxidized and Refractory Gold-Bearing Ores. *Proceedings of the International Scientific and Practical Conference*. Tashkent–Almalyk, Uzbekistan, 2019, pp. 56–58.
- Barbouchi A., Louarrat M., Mikali M., Barfoud L., El Alaoui-Chrifi M.A., Khadiri M., Benzakour J. *Advancements in Improving Gold Recovery from Refractory Gold Ores/Concentrates: A Review* // *Canadian Metallurgical Quarterly*. – 2025. – Vol. 64. – No. 4. – P. 2370–2387. – DOI: 10.1080/00084433.2024.2441548.
- Суннатов, Ж. Б., & Якубов, М. М. (2024). РАЗРАБОТКА ПИРОМЕТАЛЛУРГИЧЕСКОГО МЕТОДА ПЕРЕРАБОТКИ УПОРНЫХ ЗОЛОТО-СОДЕРЖАЩИХ РУД И ОТХОДОВ ОБОГАТИТЕЛЬНЫХ ФАБРИК. *Universum: технические науки*, 3(11 (128)), 51-54.
- Sunnatov, J. B., & Yakubov, M. M. (2024). OLTIN TARKIBLI MURAKKAB VA TEXNOGEN XOMASHYOLARNI QAYTA ISHLASHNING PIROMETALLURGIK USULI. *Journal of Advances in Engineering Technology*, (4), 63-67.
- Sunnatov, J. B., & Saydulloyev, S. S. (2026). Improving the Efficiency of Pyrometallurgical Processing of Gold-Bearing Slag and Man-Made Raw Materials

Automation and AI-Based Control in Metal Recovery from Metallurgical Waste Solutions: Regulatory Implications for Occupational Safety and Labor Displacement

Doniyor Bakhtiyorovich Kholikulov⁶, Shukhratjon Jumaboyevich
Khudoymuratov⁷

Abstract

Metal recovery from metallurgical waste solutions — industrial effluents, e-waste leachates, and acid mine drainage — is increasingly automated. Machine-learning models now guide bioleaching, and robotic arms disassemble electronic waste to recover critical metals. These systems cut worker exposure to toxic reagents and raise recovery efficiency, but they also restructure who works in waste processing: manual sorting and disassembly roles shrink while demand shifts toward digital and supervisory skills. This paper examines where technical automation in metal recovery meets the legal frameworks governing occupational safety and workforce transition. Drawing on a comparative literature review and a robotic e-waste disassembly case study, we find that automation lowers direct chemical exposure but introduces human–robot interaction hazards that current safety codes do not yet address. Labor law aimed at AI-driven displacement remains scattered and reactive rather than systematic — the technology is outpacing the regulation meant to govern its labor consequences. We propose four responses: updated safety standards for adaptive robotic systems, statutory reskilling mechanisms, joint design of circular-economy and labor policy, and curriculum reform in metallurgical engineering education.

Keywords: metal recovery, hydrometallurgy, automation, artificial intelligence, occupational safety, labor law

⁶ Professor (DSc), Head of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: Kholikulov.d@odti.uz, [ORCID: 0000-0001-6968-9297](https://orcid.org/0000-0001-6968-9297)

⁷ PhD student of the Department of Metallurgy, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: shuxrat19890503@gmail.com, [ORCID: 0009-0008-5360-3039](https://orcid.org/0009-0008-5360-3039)

1. Introduction

Industrial wastewater, e-waste leachates, and mine and smelter effluents carry metal concentrations worth recovering — securing critical metal supply while reducing the waste's environmental burden. Conventional hydrometallurgical leaching (strong acids, cyanide) works, but exposes workers to hazardous reagents and leaves behind secondary toxic waste^{8,9}.

Over the past decade, automation and AI-based control have entered nearly every stage of this process. Machine-learning models now select bioleaching parameters^{10,11}. Vision-guided robotic arms disassemble waste electrical and electronic equipment (WEEE) to recover critical metals^{12,13}. Digital-twin data models coordinate standardized robotic "skills" for component sorting¹⁴.

This shift cuts both ways. Fewer workers now handle acidic leachates, heavy-metal dust, or hazardous disassembly tasks directly. At the same time, a large share of manual labor — sorting, disassembly, reagent handling — is disappearing from a sector that has long employed low-skilled workers. And it is disappearing into a regulatory vacuum. Occupational safety codes for industrial robots were written for a different generation of machines, and labor law on AI-driven displacement is still forming, unevenly, across jurisdictions¹⁵.

⁸ Saikat, S. P., Uddin, N., Kawsar, M., Ahmed, S., & Hossain, M. S. (2026). Sustainable metal recovery from e-waste: Exploring greener leachates in hydrometallurgical processes. *MetalMat*, e70041. <https://doi.org/10.1002/metm.70041>

⁹ Khudoymuratov, S. J., & Kholikulov, D. B. (2026). Integrated hydrometallurgical strategies for the valorization of technogenic solutions and waste in copper production. *International Journal of Scientific Bulletin*, 3(01), 48–53. <https://doi.org/10.5281/zenodo.20546948>

¹⁰ Mokarian, P., Bakhshayeshi, I., Taghikhah, F., Boroumand, Y., Erfani, E., & Razmjou, A. (2022). The advanced design of bioleaching process for metal recovery: A machine learning approach. *Separation and Purification Technology*, 291, 120919. <https://doi.org/10.1016/j.seppur.2022.120919>

¹¹ Kholikulov, D. B., Khudoymuratov, Sh. J., Khojiev, Sh. T., Mutalibkhonov, S. S., & Karshiboev, Sh. B. (2026). Sequential hydrometallurgical recovery of Mo, Ni, and Co from technogenic sulfate media. *International Journal of Academic and Applied Research (IJAAAR)*, 10(6), 92–97.

¹² Ricardo, F. A., Muñoz, N., & Gil, J. J. (2025). Robotic system for automated disassembly of electronic waste: Unscrewing. *Robotics and Computer-Integrated Manufacturing*, 95, 103032. <https://doi.org/10.1016/j.rcim.2025.103032>

¹³ Kholikulov, D. B., Sh. J. Khudoymuratov, and S. S. Mutalibkhonov. "Metal Recovery from Copper Industry Waste Solutions Using Carbonate-Bearing Technogenic Solutions: A Literature Review." *International Journal of Academic and Applied Research (IJAAAR)* 9, no. 11 (2025): 205–211.

¹⁴ Saenz, J., Felsch, T., Walter, C., König, T., Poenicke, O., Bayrhammer, E., Vorbröcker, M., Berndt, D., Elkmann, N., & Arlinghaus, J. (2024). Automated disassembly of e-waste—Requirements on modeling of processes and product states. *Frontiers in Robotics and AI*, 11, 1303279. <https://doi.org/10.3389/frobt.2024.1303279>

¹⁵ Kelley, B. J. (2023–2024). Belaboring the algorithm: Artificial intelligence and labor unions. *Yale Journal on Regulation Bulletin*, 41, 88–105.

The question is not whether the technology works — it does — but whether the legal and institutional apparatus has kept up. Three things structure this paper: how far automation and AI control have spread in metal recovery; their effect on hazard exposure and labor demand; and whether existing safety and labor law frameworks are adequate.

2. Materials and Methods

The analysis combines a literature-based technical review with comparative legal analysis. Technical evidence came from peer-reviewed engineering sources covering hydrometallurgical process control, robotic e-waste disassembly, and bioleaching optimization. Regulatory evidence came from labor-law and occupational-safety scholarship on AI-driven displacement and human–robot interaction in manufacturing settings.

One process was selected as an illustrative case: robotic unscrewing and component disassembly of WEEE, as documented by Díaz et al. (2025). It was chosen because it links a specific, well-characterized automation mechanism to concrete safety and labor-market consequences — the kind of connection that broader surveys tend to describe only in the abstract.

3. Results

3.1 Where automation and AI control now sit in the process

Three layers of the recovery process have been automated. At the analytical layer, machine-learning models — random forest regression, in the case reviewed here — predict metal recovery rates in bioleaching from inputs such as pulp density, temperature, and microorganism type. Prediction accuracy reaches around 77%, which cuts the number of laboratory trials needed to tune a process³.

At the physical processing layer, robotic systems combine vision cameras, force-sensing screwdrivers, and collaborative arms. A UR10e robot fitted with an Intel RealSense D405 camera performed automated unscrewing and component extraction on hoverboards in 125 validated operations across several screw types, with high success rates⁵.

At the coordination layer, digital-twin data models and standardized robot "skills" — locate, unscrew, cut — are being formalized so that disassembly cells can reconfigure themselves for different waste streams without redesign⁷.

3.2 Occupational safety outcomes

Automated disassembly and leaching measurably reduce direct worker contact with hazardous solvents, heavy-metal dust, and battery components. This matches the safety rationale that has justified industrial robotics for decades.

But the same systems bring new or altered risks: ergonomic strain from shared human-robot workspaces, cognitive overload for operators monitoring several automated cells at once, and gaps in standards written for fixed, non-collaborative automation rather than AI-supervised, reconfigurable cells¹⁶. General industrial robot standards have not caught up with this configuration.

3.3 Labor displacement and the response so far

A bibliometric review of AI-and-automation-displacement scholarship shows a sharp rise in publication after 2018. The trend tracks a broader recognition: automation is pulling demand away from routine manual tasks — sorting, disassembly, reagent handling — toward digital, supervisory, and maintenance work¹⁷.

Legal scholarship on AI and labor unions describes the regulatory response to this shift as reactive: executive actions, sector-specific agreements, and non-binding proposals, rather than a comprehensive statute⁸. A parallel argument appears in U.S. scholarship on autonomous-vehicle-driven trucker displacement¹⁸, which concludes that mandates forcing human drivers to stay in the loop are counterproductive, and that funded transition assistance works better¹⁹.

4. Discussion and Conclusion

Two speeds are visible here: automation and AI control in metal recovery from waste solutions are mature and spreading fast, while the occupational-safety and labor-law instruments meant to govern their consequences lag behind — generic where they exist, unwritten where they do not. Industrial robot safety standards were built for static, caged machines and have not been reworked for the adaptive, human-collaborative

¹⁶ Lombardi, I., Monaco, M. G. L., & Capece, S. (2024). European data and framework analysis of human-machine interaction in manufacturing 4.0: An update. *Chemical Engineering Transactions*, 111.

¹⁷ Subaveerapandiyani, A., & Shimray, S. R. (2024). The evolution of job displacement in the age of AI and automation: A bibliometric review (1984–2024). *Open Information Science*, 8(1), 20240010. <https://doi.org/10.1515/opis-2024-0010>

¹⁸ Lobel, Orly (2024) "The Future of Work in the Era of AI," *Indiana Law Journal*: Vol. 100: Iss. 1, Article 7. Available at: <https://www.repository.law.indiana.edu/ilj/vol100/iss1/7>

¹⁹ Khudoymuratov, Sh. J. (2026). Artificial intelligence-driven metallurgy: Process modeling, optimization and intelligent production systems. *Nauchno-obrazovatel'nyy elektronnyy zhurnal Obrazovaniye i nauka v XXI veke*, 75-3(1), 6–21.

disassembly cells now used in e-waste and metallurgical recycling. Labor law facing AI-driven displacement shows the same pattern: fragmented, jurisdiction-by-jurisdiction responses rather than a coherent framework⁸.

Two regulatory postures emerge from the comparison. The European Union has tied automation and digitalization directly to material-recovery legislation — the Eco-Design Directive, the Critical Raw Materials Act — folding labor and safety considerations into circular-economy policy from the start. Elsewhere, occupational safety and employment-transition policy are handled as separate questions from industrial automation policy, addressed by different agencies on different timelines.

Four responses follow. First, occupational safety standards must explicitly name AI-supervised, reconfigurable disassembly and leaching systems, including cognitive-load and human-robot interaction risk assessment — legacy fixed-automation codes do not cover this. Second, reskilling and transition-assistance mechanisms should target the roles being displaced: manual sorting, disassembly, and reagent handling. Third, circular-economy legislation and labor-market policy should be designed together, following the EU pattern, rather than sequentially. Fourth, metallurgical engineering curricula should include digital process control, robotic supervision, and the regulatory context these systems operate in.

References

- Saikat, S. P., Uddin, N., Kawsar, M., Ahmed, S., & Hossain, M. S. (2026). Sustainable metal recovery from e-waste: Exploring greener leachates in hydrometallurgical processes. *MetalMat*, e70041. <https://doi.org/10.1002/metm.70041>
- Khudoymuratov, S. J., & Kholikulov, D. B. (2026). Integrated hydrometallurgical strategies for the valorization of technogenic solutions and waste in copper production. *International Journal of Scientific Bulletin*, 3(01), 48–53. <https://doi.org/10.5281/zenodo.20546948>
- Mokarian, P., Bakhshayeshi, I., Taghikhah, F., Boroumand, Y., Erfani, E., & Razmjou, A. (2022). The advanced design of bioleaching process for metal recovery: A machine learning approach. *Separation and Purification Technology*, 291, 120919. <https://doi.org/10.1016/j.seppur.2022.120919>
- Kholikulov, D. B., Khudoymuratov, Sh. J., Khojiev, Sh. T., Mutalibkhonov, S. S., & Karshiboev, Sh. B. (2026). Sequential hydrometallurgical recovery of Mo, Ni, and Co from technogenic sulfate media. *International Journal of Academic and Applied Research (IJAAAR)*, 10(6), 92–97.
- Ricardo, F. A., Muñoz, N., & Gil, J. J. (2025). Robotic system for automated disassembly of electronic waste: Unscrewing. *Robotics and Computer-Integrated Manufacturing*, 95, 103032. <https://doi.org/10.1016/j.rcim.2025.103032>

Kholikulov, D. B., Sh. J. Khudoymuratov, and S. S. Mutalibkhonov. "Metal Recovery from Copper Industry Waste Solutions Using Carbonate-Bearing Technogenic Solutions: A Literature Review." *International Journal of Academic and Applied Research (IJAAAR)* 9, no. 11 (2025): 205–211.

Saenz, J., Felsch, T., Walter, C., König, T., Poenicke, O., Bayrhammer, E., Vorbröcker, M., Berndt, D., Elkmann, N., & Arlinghaus, J. (2024). Automated disassembly of e-waste—Requirements on modeling of processes and product states. *Frontiers in Robotics and AI*, 11, 1303279. <https://doi.org/10.3389/frobt.2024.1303279>

Kelley, B. J. (2023–2024). Belaboring the algorithm: Artificial intelligence and labor unions. *Yale Journal on Regulation Bulletin*, 41, 88–105.

Lombardi, I., Monaco, M. G. L., & Capece, S. (2024). European data and framework analysis of human-machine interaction in manufacturing 4.0: An update. *Chemical Engineering Transactions*, 111.

Subaveerapandiyani, A., & Shimray, S. R. (2024). The evolution of job displacement in the age of AI and automation: A bibliometric review (1984–2024). *Open Information Science*, 8(1), 20240010. <https://doi.org/10.1515/opis-2024-0010>

Lobel, Orly (2024) "The Future of Work in the Era of AI," *Indiana Law Journal*: Vol. 100: Iss. 1, Article 7. Available at: <https://www.repository.law.indiana.edu/ilj/vol100/iss1/7>

Khudoymuratov, Sh. J. (2026). Artificial intelligence-driven metallurgy: Process modeling, optimization and intelligent production systems. *Nauchno-obrazovatel'nyy elektronnyy zhurnal Obrazovaniye i nauka v XXI veke*, 75-3(1), 6–21.

Investigation of Mineralogical Composition and Complex Processing Methods for Out-of-Balance Ores of the Kalmakyr Deposit

Karshiboyev Sherzod¹, Sayfullayeva Dilshoda²

Abstract

This paper examines the technological features, mineralogical composition, and complex processing strategies for out-of-balance ores from the Kalmakyr porphyry copper deposit (Almalyk Mining and Metallurgical Complex). With an estimated reserve of ~115.5 million tons—comprising 72.1% oxidized ores and 27.9% mixed ores containing copper (0.10–0.15%), gold (0.5–0.6 g/t), and silver (3.0–5.0 g/t)—these technogenic deposits represent significant untapped economic potential. Utilizing advanced analytical techniques including XRF, ICP-MS, XRD, and SEM-EDS, the study identifies critical distribution patterns of valuable components across various mineral association phases. The results demonstrate that a combined processing flowsheet—incorporating gravity pre-concentration, flotation, heap leaching, and solvent extraction-electrowin (SX-EW)—is essential to achieve high recovery rates, ensuring sustainable resource utilization and ecological mitigation.

Keywords: Kalmakyr deposit, out-of-balance ores, mineralogical composition, copper, precious metals, complex processing, IMRAD.

¹ Doctor of Philosophy (PhD) in Technical Sciences, Associate Professor, Deputy Dean for Academic Affairs of the Faculty of Metallurgy and Chemical Technologies of the Almalyk State Technical Institute, Almalyk, Uzbekistan; ORCID: 0009-0004-8097-0804

² Basic doctoral student of the Department of Mining Engineering of the Faculty of Mining of the Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: dilshodasayfullayeva197@gmail.com (author-correspondent); ORCID: 0009-0004-2831-501X

1. Introduction

The Kalmakyr deposit is one of the largest porphyry copper deposits in Central Asia and serves as the primary raw material foundation for the Almalyk Mining and Metallurgical Complex (AMMC) in Uzbekistan. Over decades of intensive industrial exploitation, substantial volumes of off-grade and sub-economic mineralized materials—commonly classified as out-of-balance ores—have been systematically deposited into dedicated industrial waste dumps (specifically dumps #2, 7, 8, 9, and 9a). Given the progressive depletion of high-grade primary reserves and advancements in hydrometallurgical and beneficiation technologies, re-evaluating these technogenic formations has become a critical economic and industrial imperative.

The primary objective of this research is to perform a comprehensive technological and mineralogical assessment of the Kalmakyr out-of-balance ores, determining their precise phase distribution, structural associations, and optimal beneficiation pathways. Developing efficient recovery frameworks for these complex ores not only extends the operational lifespan of the mining complex but also significantly alleviates environmental pressures associated with large-scale mining waste accumulation.

2. Materials and Methods

To ensure high statistical representation, composite ore samples totaling 410 kg were collected across 39 distinct sampling points within dump sites #2, 7, 8, 9, and 9a of the Kalmakyr deposit. Sample preparation procedures included primary and secondary crushing via jaw and cone crushers, followed by progressive comminution in rod and ball mills down to particle sizes of -2 mm and 0.074 mm, respectively.

A multi-faceted analytical approach conforming to rigorous scientific standards was employed. Chemical and elemental analysis was conducted using X-ray fluorescence spectrometry (XRF/EDXRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine bulk oxide and trace element concentrations. Precious metal assays, including fire assay and Atomic Absorption Spectrometry (AAS), were utilized for precise quantification of gold and silver content. Furthermore, mineralogical and phase analysis utilized X-ray diffraction (XRD - Empyrean Panalytical) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) to examine microstructural association and mineral species. Finally, beneficiation testing was performed using laboratory-scale flotation machines, centrifugal concentrators, and shaking tables to evaluate gravity and flotation separation efficiency.

3. Results and Discussion

Comprehensive XRF and ICP-MS testing revealed that the Kalmakyr out-of-balance ores possess a complex silicate-iron oxide matrix. The primary bulk oxides identified include SiO₂ (43.7%), Fe₂O₃ (26.0%), Al₂O₃ (7.93%), SO₃ (3.06%), K₂O (2.80%), CaO (1.80%), and TiO₂ (0.538%). Trace elemental analysis indicated significant concentrations of aluminum (65,600 g/t), iron (48,300 g/t), potassium (28,700 g/t), and valuable rare earth elements (Σ REE = 169.2 g/t).

Table 1. Rational phase distribution analysis of gold (Au) and silver (Ag) in Kalmakyr out-of-balance ores

Mineral Association and Binding Form	Gold (Au) g/t	Gold (Au) %	Silver (Ag) g/t	Silver (Ag) %
Free native state and simple chlorides/sulfates	0.44	14.17	3.46	16.06
Bound with acid-soluble Fe and Mn oxides	0.14	22.61	0.31	23.87
Contained within sulfide mineral matrices (HNO ₃ soluble)	0.16	28.48	0.98	31.92
Locked within quartz and aluminosilicate lattices (refractory)	0.12	34.74	0.77	28.15
Total / Weighted Average:	2.48	100.00	8.47	100.00

Granulometric evaluations demonstrated that finer comminution fractions (ranging from -0.125 mm to -0.044 mm) exhibit pronounced enrichment of copper (Cu 0.48%–0.67%) and precious metals. This indicates that intensive grinding effectively liberates finely disseminated mineral grains from the gangue matrix, significantly improving subsequent recovery potential.

4. Conclusions

The evaluation of the Kalmakyr out-of-balance ores confirmed their economic viability as a secondary raw material source. With an aggregate reserve of 115.5 million tons containing copper, gold, silver, molybdenum, and rare earth elements, these materials represent highly valuable resources. Due to the mixed mineralogical forms, including oxidized malachite and azurite alongside refractory silicates and sulfides,

single-stage treatment is inadequate. A combined technological scheme comprising gravity pre-concentration, flotation, sulfuric acid heap leaching, and solvent extraction-electrowinning (SX-EW) delivers maximum extraction efficiency. Implementing this complex processing approach will substantially reinforce AMMC's long-term raw material supply, minimize mining waste footprints, and fulfill sustainable development mandates in metallurgical engineering.

References

- Karshiboyev Sh.B., Sayfullayeva D.A. Processing of off-balance ores: challenges and technological Solutions., June, 2025.
- Karshiboyev Sh.B., Sayfullayeva D.A. Balansdan tashqari rudalarini qayta ishlash texnologiyasini tanlashdagi ahamiyatl. Scientific journal of Construction and Education ISSN 2181-3779, 2025 Maxsus son-3.
- Jia Y., Ruan R., Qu J. et al. Multi-Scale and Trans-Disciplinary Research and Technology Developments of Heap Bioleaching. Minerals, 2024, 14(8), 808. DOI: 10.3390/min14080808.
- Sodikov, F. S., Jeong, Y., Usenov, R. B., Ibragimov, I. S., & Xolmatova, S. U. (2026). Pilot plant tests for acid leaching of low grade copper oxide ores from kalmakyr copper mine. Fars International Journal of Education, Social Science & Humanities., 14(2), 219-226.
- Watling H.R. From Understanding the Rate Limitations of Bioleaching Mechanisms to Improved Bioleach Process Design. Hydrometallurgy, 2023, Vol. 221, 106148. DOI: 10.1016/j.hydromet.2023.106148.
- Tezyapar Kara I., Kremser K., Wagland S.T., Coulon F. Bioleaching Metal-Bearing Wastes and By-Products for Resource Recovery: A Review. Environmental Chemistry Letters, 2023, 21, 3329–3350. DOI: 10.1007/s10311-023-01611-4.
- Latyuk E., Goryachev A., Melamud V., Bulaev A. Hydrometallurgical Processing of a Low-Grade Sulfide Copper–Nickel Ore Containing Pt and Pd. Processes, 2024, 12(6), 1213. DOI: 10.3390/pr12061213.
- Dixon D.G., Petersen J. Heap Leaching of Low-Grade Copper Ores: Current Status and Future Perspectives. Minerals Engineering, 2022, Vol. 182, 107564.

Mineralogical Assessment of Gold Deportment in the Yoshlik I Deposit

Ergashev Makhmud Axbaraliyevich¹ Abdurazakov Ulugbek Mamayusub ugli²
Kulmatov Rustam Baxrambayevich³

Abstract

Low-grade copper-porphyry ores are a major source of by-product gold, yet a significant share of that gold — particularly its free and relatively coarse fraction — is lost to flotation tailings because conventional froth flotation recovers native gold poorly. This paper assesses the material, chemical and mineralogical characteristics of gold-molybdenum copper-porphyry ore from the Yoshlik I deposit (Almalyk mining district, Uzbekistan) in order to establish whether enhanced-gravity (centrifugal) concentration ahead of flotation is technologically justified. The ore was characterised using optical-emission and atomic-absorption spectrometry, X-ray diffraction, automated mineralogy (QEMSCAN), optical and electron microscopy, phase (rational) analysis and fire assay, with mineral liberation measured at two grind sizes. The results reveal a low-grade, high-silica ore (copper $\approx$ 0.3%, gold $\approx$ 0.34 g/t) in which copper occurs almost entirely as well-liberated chalcopyrite. Gold is predominantly native (fineness $\approx$ 890): about 69% of grains fall in the 2–8 μ m range, but particles reach 500 μ m, while 26.6% of the gold is free and 89.9% is cyanidable. This deportment — a substantial free and coarse fraction of high-density native gold combined with highly liberated sulphides — provides a sound basis for an integrated gravity–flotation scheme employing a centrifugal concentrator as a pre-flotation step.

¹ PhD Student, Almalyk State Technical Institute, Almalyk, Uzbekistan; e-mail: mahmude423@gmail.com; ORCID: 0009-0009-3067-0412; Science ID: MTV-0425-0012 (corresponding author).

² Head of the Copper-Molybdenum Ore Beneficiation Department, Center for Development and Implementation of Innovative Technologies, JSC “Almalyk MMC”, Almalyk, Uzbekistan; e-mail: Abdurazoqovulugbek75@gmail.com; ORCID: 0009-0000-3435-9167; Science ID: BTV-0626-0003.

³ Chief Surveyor, Copper Enrichment Plant Project 4, Enter Engineering Pte. Ltd, Almalyk, Uzbekistan; e-mail: r08875397@gmail.com; ORCID: 0009-0008-5558-3940

Keywords: copper-porphyry ore; gold deportment; process mineralogy; enhanced-gravity concentration; Knelson concentrator; gravity-recoverable gold; flotation; Yoshlik I deposit.

1. Introduction

Global demand for copper, gold and silver continues to grow, while the accessible reserves of rich, high-grade ore are being depleted; the industry is therefore compelled to process progressively leaner and mineralogically more complex ores and to recover the associated valuable metals as completely as possible. Uzbekistan holds one of the world's larger copper-porphyry resource bases, centred on the Almalyk Mining and Metallurgical Combine and its Kalmakyr and Yoshlik I deposits, in which the principal metal — copper — is accompanied by economically significant gold, silver and molybdenum (Golovanov et al., 2005). Because these ores are low-grade (copper of the order of 0.4%), recovering the associated precious metals as fully as possible carries substantial economic weight.

In the conventional collective-flotation route applied to such ores, part of the gold — especially its free and comparatively coarse particles — is captured inefficiently and is lost with the tailings. Native gold is very dense (15.6–19.3 g/cm³), which in principle makes it an excellent target for gravity separation; however, the efficiency of traditional gravity devices falls sharply in the fine size range. This limitation is overcome by enhanced-gravity (centrifugal) concentrators such as the Knelson and Falcon units, introduced industrially in the 1980s, which amplify the gravitational field by tens to hundreds of times and thereby recover fine free gold that conventional gravity cannot (Chen et al., 2020). The gravity-recoverable-gold (GRG) test standardised by the McGill school provides a quantitative measure of an ore's amenability to this route (Laplanche et al., 2000).

Installing a centrifugal gravity unit ahead of copper flotation — the “gravity-before-flotation” principle — has been shown to capture otherwise-lost free gold while easing downstream pump and reagent loads (Patchejieff & Lazarov, 1994; Surimbayev et al., 2024). Such integration exemplifies how technological innovation continues to reshape engineering practice in the mining and metallurgical sector, with direct implications for the competencies expected of process engineers and, by extension, for engineering education. The present paper characterises the material, chemical and mineralogical features of the Yoshlik I ore and, on that basis, evaluates the technological rationale for an integrated gravity–flotation beneficiation scheme.

2. Materials and Methods

The object of study was gold-molybdenum copper-porphyry ore from the Yoshlik I deposit, which is geologically an analogue of the neighbouring Kalmakyr deposit. A

representative sample was examined with a complementary suite of analytical methods, so that the limitation of any single technique was offset by the others.

Chemical composition was determined mainly by optical-emission and atomic-absorption spectrometry, with gravimetric, titrimetric and photometric methods used as controls; owing to their low concentrations, gold and silver were assayed directly. Mineral composition was studied by X-ray diffraction, which identifies crystalline phases, together with the QEMSCAN automated mineralogy system, which quantifies mineral proportions, grain size and liberation through mapping. Mineral liberation was measured at 65% and 80% passing 0.074 mm.

Because the mode of occurrence of gold governs the technology required to recover it, the precious metal received particular attention. Gold morphology, particle size and mineral associations were examined by Olympus SZX-7 stereomicroscopy, electron microscopy and the QEMSCAN search mode for precious minerals. The quantitative balance between the different forms of gold was established by phase (rational) analysis: free metallic gold was determined by two-stage amalgamation, surface-exposed gold by sorption cyanidation, and the overall balance was closed by fire assay. Particle-size distribution was obtained by sieve analysis and described analytically using the Rosin–Rammler equation. Gravity beneficiation was studied in laboratory tests on Knelson KC-MD3 and Falcon centrifugal concentrators, in which the centrifugal force, cycle time, fluidising-water pressure and feed density were varied; these tests also served to estimate the gravity-recoverable gold content.

3. Results

3.1. Chemical Composition

The Yoshlik I ore is of the gold-molybdenum copper-porphyry type. Lithophile components make up 83.8–87.7% of its chemical composition and are dominated by silica (SiO_2 51.6–61.2%), whereas the valuable components occur at low levels: copper about 0.3%, molybdenum about 0.005%, gold 0.34 g/t and silver 1.5 g/t. Significantly for downstream processing, 96.7% of the copper is present in sulphide form, which is favourable for flotation.

3.2. Mineral Composition and Liberation

Mineralogically, 92.5–96% of the ore consists of barren host rock. Among the sulphides, chalcopyrite (about 0.8%) is the principal copper mineral, while pyrite accounts for only about 0.7% — roughly six times less than in the Kalmakyr ore. A distinctive feature of the ore is the presence of amphiboles (about 10%) together with anhydrite and gypsum (about 4%). Chalcopyrite is well liberated: its share of free grains reaches 73.4% and its surface exposure 86.4–91.9%, indicating that copper can be

recovered to a high degree; on fine grinding, molybdenite reaches 92.6% free grains and 98.5% surface exposure.

3.3. Gold Deportment

Gold occurs overwhelmingly as native gold, with an average fineness of about 890, and native gold constitutes almost the entire gold mass (99.94%); its principal associated mineral is silver telluride (31.08%). The size distribution is, in practical terms, twofold: the main mass of gold grains (69.1%) lies in the very fine 2–8 μm interval, yet the largest particles reach 500 μm . Phase analysis shows that 89.9% of the gold is cyanidable; of the total, 26.6% is free gold and 63.3% occurs in open, surface-exposed associations, while the QEMSCAN estimate of free and exposed gold by surface liberation is 19.4%.

Taken together, these data define an ore in which a low tenor of copper is carried by highly liberated chalcopyrite and in which the gold, although dominated by ultrafine particles, also contains a substantial free fraction and coarse particles of very high density.

4. Discussion

The characterisation results carry a clear technological implication. The coexistence of a substantial free-gold fraction (26.6%) and coarse free particles (up to 500 μm) with a highly liberated, sulphide-hosted copper mineralogy means that flotation alone is not the optimal route for this ore. Precisely the free and coarse gold that flotation recovers least efficiently is the fraction most amenable to gravity capture, owing to the very high density of native gold; conversely, the fine gold and the copper are well suited to flotation. This complementarity is the physical basis for an integrated, rather than a single-method, flowsheet.

Conventional gravity equipment cannot exploit this opportunity fully, because its efficiency declines steeply for fine particles. Enhanced-gravity centrifugal concentrators remove that barrier, and the international literature — including the direct precedent of a Knelson unit installed ahead of a copper-flotation circuit — confirms that a gravity-before-flotation configuration can recover free gold that would otherwise be lost while reducing reagent and pump loads (Patchejieff & Lazarov, 1994; Surimbayev et al., 2024).

5. Conclusion

It is therefore concluded that the material and mineralogical characteristics of the Yoshlik I ore justify an integrated gravity–flotation beneficiation scheme in which a centrifugal concentrator carries out pre-flotation recovery of free and coarse gold, collective Cu–Mo flotation recovers copper and molybdenum, and control (pyrite) flotation of the tailings recovers additional precious metals. Beyond its site-specific value, the approach illustrates how the adoption of advanced separation technologies is reshaping process-engineering practice and the competencies required of the next

generation of mining and metallurgical engineers. Experimental optimisation of the concentrator regime and semi-industrial validation of the proposed scheme are the subject of subsequent research.

References

- Chen, Q., Yang, H.-Y., Tong, L.-L., Niu, H.-Q., Zhang, F.-S., & Chen, G.-M. (2020). Research and application of a Knelson concentrator: A review. *Minerals Engineering*, 152, 106339. <https://doi.org/10.1016/j.mineng.2020.106339>.
- Golovanov, I. M., Seltmann, R., & Kremenetsky, A. A. (2005). The porphyry Cu-Au/Mo deposits of Central Eurasia: 2. The Almalyk (Kalmakyr-Dalnee) and Saukbulak Cu-Au porphyry systems, Uzbekistan. In *Super porphyry copper and gold deposits: A global perspective* (Vol. 2, pp. 513–523). PGC Publishing.
- Laplante, A. R., Woodcock, F., & Huang, L. (2000). A laboratory procedure to characterise gravity-recoverable gold. *SME Transactions*, 308, 53–59.
- Patchejieff, B., & Lazarov, D. (1994). Opportunities for fine gold recovery from a copper flotation circuit using a Knelson concentrator [Technical note]. *Minerals Engineering*, 7. [https://doi.org/10.1016/0892-6875\(94\)90079-5](https://doi.org/10.1016/0892-6875(94)90079-5).
- Surimbayev, B., Bolotova, L., Akcil, A., Yessengarayev, Y., Khumarbekuly, Y., & Kanaly, Y. (2024). Gravity concentration of gold-bearing ores and processing of concentrates: A review. *Mineral Processing and Extractive Metallurgy Review*. <https://doi.org/10.1080/08827508.2024.2395824>.

SECOND SESSION

THE IMPACT OF TECHNOLOGICAL INNOVATIONS ON LAW IN THE DIGITAL AGE

Lawmaking Engineering in the Digital Age: The Integrated Lawmaking Optimization Model - ILOM

Ayşe Odman Boztosun¹

Abstract

Modern legal systems face an unprecedented regulatory burden driven by complex socio-economic relations, technological disruptions, and globalized dynamics. Traditional lawmaking approaches prioritize the internal dogmatic and doctrinal coherence of statutory norms, frequently failing to quantify their long-term economic, social, and operational impacts. To bridge this analytical gap, this article introduces a novel paradigm, termed “lawmaking engineering” that applies scientific, engineering, and digital approaches to the lawmaking process. An optimization model is proposed to translate this paradigm into a systematic framework for lawmaking. First, the critical role of pure sciences, engineering risk analytics, and big data modeling in formulating empirical, data-driven problem definitions during the initial diagnostic phase of the legislative pipeline is inquired into. Second, the integration of the system optimization, operations research, and process management methodologies of industrial engineering with standard Regulatory Impact Assessment practices is explored. Third, exploitation of data analytics and Artificial Intelligence decision support frameworks is anticipated while addressing technological and ethical vulnerabilities, i.e. hallucination and algorithmic bias, with appropriate safeguards. Fourth, ethical and constitutional principles are embedded as binding constraints within the optimization model, establishing a “justice threshold” beyond which efficiency gains cannot justify violations of fundamental rights. This culminates in a theorized four-stage "Integrated Lawmaking Optimization Model (ILOM)" that optimizes statutes concurrently along the axes of operational efficiency and systemic enforceability, constrained only by a justice threshold.

¹ Prof. Dr., Akdeniz University Faculty of Law, aboztosun@akdeniz.edu.tr, ORCID ID: 0000-0001-5819-1442

Keywords: Lawmaking engineering, scientific analysis and justification, industrial engineering approach, AI deployment with safeguards, justice threshold.

1. Introduction

In modern state structures, dynamic phenomena such as the digital economy, artificial intelligence, climate change, and global supply chains expand the regulatory universe at a geometric rate. This expansion often causes legislative acts to generate unforeseen negative externalities, bureaucratic inertia, or operational bottlenecks within the judicial system. Because traditional lawmaking practice is conducted as a text-oriented, purely normative process, the dynamic effects of enacted laws on socio-economic systems are frequently left unsimulated.

To overcome this deficiency, the lawmaking process must be redefined not as static text drafting, but as a complex system-design problem. The discipline of Industrial Engineering (IE), which specializes in the efficient utilization of resources, process improvement, and optimization of complex systems, holds the potential to provide a methodological foundation for legal science. By applying industrial engineering methodologies to the design, implementation, and impact assessment of laws, supported by AI capabilities and guided by scientific principles, this article introduces a new paradigm in lawmaking: “lawmaking engineering.”² Building on this paradigm, a phased optimization model is developed to translate it into a practical and operational framework.

² The concept “legislation engineering” has been used in the following research proposal to define, “*using advanced analysis and data mining techniques and algorithms in developing laws and legislations.*” Ebaid, Mustafa, Law Informatics - A New Line of Research that is Mixing Law, Mathematics and Computer Sciences (A) Law and Legislation Engineering (B) Law and Legislation Combinatorics (April 07, 2023). Available at SSRN: <https://ssrn.com/abstract=6455699> or <http://dx.doi.org/10.2139/ssrn.6455699>. One year after this paper, a group of authors has introduced the term “legislative engineering” to define, “*examining the common similarities between writing software code and drafting legislation ... to adopt principles from the world of software engineering into the process of drafting legislation.*” Schwartz, Elhanan and Bar-Siman-Tov, Ittai and Gelbard, Roy, When Computers Speak Laws: Legislative Engineering in the Age of Artificial Intelligence (January 17, 2024). Available at SSRN: <https://ssrn.com/abstract=4698512> or <http://dx.doi.org/10.2139/ssrn.4698512>.

In this article, on the other hand, the term “lawmaking engineering” is coined to denote a novel multidisciplinary research framework that integrates systematic scientific analysis, optimization methodologies, and digital technologies into the lawmaking process while remaining firmly anchored in legal theory. Although previous scholarship has explored analogies between law and engineering, systems engineering approaches to legislative design, and AI-assisted legislative drafting, no comprehensive framework has yet integrated industrial engineering methodologies, optimization theory, AI capabilities, and constitutional constraints into a unified model for lawmaking.

2. Phase One: Objective Problem Definition via Pure Sciences, Risk Analytics, and Big Data Modeling

The success of the proposed lawmaking engineering paradigm depends heavily on articulating the problem to be regulated in an empirical, measurable, and objective manner at the very outset. While legislative processes are traditionally triggered by political reflexes or abstract normative arguments, the lawmaking engineering approach utilizes the epistemological outputs of pure sciences (physics, chemistry, biology, mathematics), engineering risk analytics, and big data modeling to diagnose the root cause of systemic issues that require regulating.

2.1. Natural Constraints and Thresholds Provided by Pure Sciences

Basic sciences present the legislator with the boundaries of physical reality within which social and economic systems must operate. For instance, when designing an optimization model for a law restricting carbon emissions in environmental and energy law, the problem parameters are defined by the laws of thermodynamics and chemistry rather than abstract political targets. The theoretical maximum efficiency and minimum emission limits of an industrial plant are established by chemical and physical sciences. Similarly, in agricultural and health law, the regulation of chemical additives or pesticides relies on laboratory-level bio-accumulation data from biology and toxicology, forming the non-negotiable constraints of the legal model.

2.2. Mathematical Modeling, Chaos, and Probability Theory

Mathematics uncovers hidden patterns and systemic risks behind complex socio-economic systems. In financial and tax law regulations, market manipulation or systemic collapse risks are formulated through probability theory and stochastic processes. In cyber law and data protection regulations, the propagation patterns of disinformation or systemic cyber threats are structuralized via nodes and links within graph theory. Applying the principles of network science³, the statutory corpus itself can be modeled as a complex directed graph. By mapping legal cross-references, structural amendments, and constitutional hierarchies as topological networks, lawmaking engineering can mathematically simulate how a change or repeal in one legal node propagates across the entire system, preventing cascading regulatory failures. Consequently, the problem is rescued from subjective assertions and transformed into an empirical optimization problem.

³ Barabási, A. L. (2016). *Network Science*. Cambridge University Press.

2.3. The Contribution of Big Data Modeling and Management

The efficacy of these mathematical frameworks is fundamentally contingent upon the integration of big data modeling and management. By processing high-velocity, heterogeneous data streams through structured ingestion pipelines, regulatory models can transition from static, sampled assumptions to real-time empirical probability distributions. As theorized in foundational big data paradigms⁴, this comprehensive transition to massive datasets where $N=\text{all}$ enables the continuous 'datafication' of socio-economic behaviors. Consequently, big data architectures enable the micro-segmentation of systemic risk parameters via advanced clustering techniques, while streaming data analytics dynamically recalibrate random variables as these behaviors adapt. Through continuous feedback, the optimization model mitigates parameter obsolescence by regularly updating its underlying assumptions, thereby adapting to evolving legal, economic, and societal conditions.

2.4. Failure and Reliability Analyses of Engineering Disciplines

Engineering disciplines verify why existing systems fail using empirical data. In occupational health and safety regulations, the problem definition leverages reliability engineering methods, Fault Tree Analysis, and ergonomics. In zoning and urban planning law, seismic analyses, soil liquefaction coefficients, and structural mechanics, data from geological and civil engineering serve as objective problem parameters that directly dictate building height or zoning restrictions. By structuralizing these mechanical and human-factor vulnerabilities, systemic points of failure within regulatory frameworks can be diagnosed before drafting new statutes. As established in classical risk assessment frameworks⁵, the mathematical formalization of these failure rates enables the calculation of system reliability coefficients, ensuring that legislative interventions are directed precisely at the root, i.e. structural weaknesses of the regulated environment.

3. Phase Two: Integration of IE Methods and Regulatory Impact Assessment

Following the empirical definition of the problem, the process management and optimization tools of IE may be systematically integrated with standard Regulatory Impact Assessment (RIA) practices. This integration transforms RIA from a qualitative, bureaucratic checklist into a quantitative, predictive evaluation framework designed to assess alternative policy options before a new legal regulation is implemented. In

⁴ Mayer-Schönberger, V., & Cukier, K. (2013). *Big data: A revolution that will transform how we live, work, and think*. Houghton Mifflin Harcourt.

⁵ Modarres, M., Kaminskiy, M., & Krivtsov, V. (2016). *Reliability engineering and risk analysis: A practical guide* (3rd ed.). CRC Press.

alignment with established international protocols for public policy assessment⁶, this integration provides a rigorous methodology for evaluating ex-ante choices. When the legal system is modeled as a macro-level service system, three core operational methodologies come to the forefront to operationalize RIA parameters:

3.1. Process Modeling, Simulation, and Bottleneck Analysis for Administrative Burden Estimation

A core mandate of modern RIA is the ex-ante estimation of compliance costs and administrative burdens imposed on citizens and businesses. Before enactment, the anticipated workflows and interactions among public institutions, private actors, and citizens may be modeled using process modelling techniques, such as Business Process Model and Notation, and discrete-event simulation tools to evaluate the operational feasibility and potential impacts of the proposed law. As structuralized in standard process engineering paradigms⁷, the simulation of transactional volume, average processing durations, and resource constraints allows institutional bottlenecks and operational delays within the judicial or administrative machinery to be mathematically identified. Consequently, the regulatory burden is optimized, and systemic friction is eliminated before the statutory text enters into force.

3.2. Operations Research and Constrained Resource Allocation in Cost-Benefit Analysis

Standard RIA guidelines dictate that regulatory alternatives must be subjected to a rigorous Cost-Benefit Analysis to ensure public utility is maximized. The distribution of public resources—such as enforcement budgets, municipal infrastructure, and regulatory personnel—required to implement laws constitutes a classic constrained resource optimization problem. Through the application of Operations Research and Game Theory models, the direct enforcement costs borne by the state and the compliance benefits accrued by society are simultaneously optimized using standard resource allocation algorithms⁸. For example, determining fine rates and audit frequencies in competition law regulations can be mathematically balanced to maximize net social benefits while minimizing both state regulatory expenditures and corporate non-compliance tendencies.

⁶ OECD. (2020). *Regulatory Impact Assessment*. OECD Best Practice Principles for Regulatory Policy, OECD Publishing. <https://doi.org/10.1787/7a9638cb-en>

⁷ Dumas, M., La Rosa, M., Mendling, J., & Reijers, H. A. (2018). *Fundamentals of business process management* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-662-56509-4>

⁸ Hillier, F. S., & Lieberman, G. J. (2021). *Introduction to operations research* (11th ed.). McGraw-Hill.

3.3. System Dynamics Models and Dynamic Feedback Loops for Long-Term Multi-Sector Impact

The societal impacts of laws are non-linear and develop complex, counter-intuitive behaviors over time due to systemic feedback loops—a phenomenon frequently overlooked by traditional, static RIA methods. As conceptualized in foundational systems engineering literature⁹, the System Dynamics approach enables the multi-sectoral simulation of how a regulation enacted in environmental, trade, or tax law propagates through the broader economy, tracking long-term shifts in investment decisions and macroeconomic balances over 5, 10, or 20-year horizons. By coupling these dynamic simulations with engineering economics methods and Multi-Criteria Decision-Making (MCDM) techniques such as Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)¹⁰, conflicting qualitative and quantitative policy targets within the RIA framework are assessed objectively, preventing long-term regulatory lag and unintended structural externalities.

While these system dynamics and operations research methods optimize macroscopic allocations and long-term socio-economic flows, the operational throughput of the legislative pipeline is fundamentally constrained by the capacity to digest textual complexity. To operationalize these continuous feedback loops and process optimizations at scale, the massive informational volumes inherent in modern legal corpuses must be analyzed rapidly and precisely. Consequently, the structural optimization of the lawmaking engineering paradigm necessitates a transition from traditional manual workflows to automated analytical processing systems.

4. Phase Three: Data Analytics and Artificial Intelligence Integration with Safeguards

As established in early conceptualizations of machine learning applications within legal frameworks¹¹, the capacity of algorithmic systems to identify underlying patterns and predict regulatory outcomes offers unprecedented efficiency gains. Moreover, advanced data analytics and Large Language Models, i.e. AI, possess the capacity to drastically accelerate comparative law research, conduct stakeholder analysis, and automatically audit terminological consistency across thousands of pages of drafts. Such

⁹ Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill.

¹⁰ Triantaphyllou, E. (2000). *Multi-criteria decision making methods: A comparative study*. Springer. <https://doi.org/10.1007/978-1-4757-3262-7>

¹¹ Surden, H. (2014). Machine learning and law. *Washington Law Review*, 89, 87.

use however comes with twofold risks, hallucination and bias. These risks may be managed within their specific realms:

4.1. Preventing the Risk of Hallucination

The risk of AI generating fabricated data or sources that appear plausible (ie. AI hallucination) requires zero tolerance in legislation. To manage and eliminate this risk, a multi-layered security architecture may be implemented:

Retrieval-Augmented Generation (RAG) Approach: The model is restricted from generating content freely using open, unverified web data. Instead, it is anchored to a restricted knowledge base (Vector Database) consisting solely of official statutes, constitutional court rulings, and supreme court jurisprudence via a specialized architecture optimized for knowledge-intensive processing.¹²

Traceability Guardrails: The AI model is constrained to provide verifiable, open legislative references for every analysis and recommendation it produces. Any output whose source cannot be matched is automatically filtered out by the system.

Cross-Model Validation: Critical analysis or scenario outputs are tested simultaneously across independently trained, distinct AI architectures (e.g., different base LLMs), and a variance analysis is performed by mathematically comparing the consistency rates between the models.

Temporal and Version Control: Since law is a dynamic structure, the exact date and enforcement status of the legislation referenced by the AI model during its analysis are recorded at the metadata level to prevent the utilization of repealed laws.

4.2. Preventing the Risk of Bias

Hallucination concerns may be offset by technological tools, but there is more to use of data analytics and AI than that: To prevent automated systems from reinforcing systemic inequities, the computational tools must be explicitly engineered to account for the inherent discrepancies of historical datasets. Decision support algorithms must be constructed according to "Explainable AI" (XAI) principles¹³ to mitigate the algorithmic

¹² Lewis, P., Perez, E., Piktus, A., Petroni, F., Lewis, M., Riedel, S., ... & Kiela, D. (2020). Retrieval-augmented generation for knowledge-intensive NLP tasks. *Advances in Neural Information Processing Systems*, 33, 9459-9474.

¹³ For an explanation of XAI principles, see Phillips, P. , Hahn, C. , Fontana, P. , Yates, A. , Greene, K. , Broniatowski, D. and Przybocki, M. (2021), Four Principles of Explainable Artificial Intelligence, NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, [online], <https://doi.org/10.6028/NIST.IR.8312>,

amplification of historical data bias and systemic discrimination¹⁴. By forcing the logical chain of algorithmic recommendations to remain fully transparent and traceable, the model must ensure strict adherence to broader ethical governance models¹⁵. The entire pipeline must remain strictly subject to final human validation (Human-in-the-Loop), guaranteeing that technological efficiency serves rather than supplants equally available human freedom and fundamental rights. In a domain directly tied to sovereign rights and social order, AI must be configured strictly as a Decision Support System (DSS) rather than an automated decision-maker.¹⁶

5. Phase Four: Ethical and Constitutional Boundaries Optimization

Traditional optimization models in IE are generally built upon minimizing costs or maximizing profits. However, a pure pursuit of mathematical efficiency or economic efficacy in the legal arena can damage constitutional freedoms, fundamental rights and social justice.¹⁷ For example, shortening defense periods to speed up judicial processes might make the system operationally efficient, but it violates foundational principles of equity. To resolve this methodological dilemma, a customised optimization approach is proposed: Universal legal values such as the principle of equality, non-discrimination, proportionality, legal certainty, and accountability are defined directly as integral components of the objective function of the law and as hard mathematical constraints.

This optimization model anchors its structural equity parameters in classical political philosophy, ensuring that inequalities are permissible only if they maximize the welfare of the least advantaged segments of society¹⁸. Consequently, no matter how much a regulatory alternative reduces economic costs or increases administrative efficiency, if it violates core constitutional rights, that option is mathematically unacceptable and is immediately eliminated from the design space. Optimization can only be executed within

https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933399 and also Principle 1.3 “Transparency and Explainability” of OECD AI Principles, the first intergovernmental standard on AI; OECD, Recommendation of the Council on Artificial Intelligence, OECD/LEGAL/0449 (adopted 22 May 2019, amended 3 May 2024), Principle 1.3, “Transparency and Explainability.” <https://oecd.ai/en/dashboards/ai-principles/P7> (Accessed September 7, 2026)

¹⁴ Barocas, S., Hardt, M., & Narayanan, A. (2023). *Fairness and machine learning: Limitations and opportunities*. MIT Press.

¹⁵ Cath, C. (2018). Governing artificial intelligence: ethical, legal and technical opportunities and challenges. *Philosophical Transactions of the Royal Society A*, 376(2128), 20180080.

¹⁶ Ashley, K. D. (2017). *Artificial intelligence and legal analytics: New tools for law practice in the digital age*. Cambridge University Press.

¹⁷ Tribe, L. H. (1985). Constitutional Calculus: Equal Justice or Economic Efficiency? *Harvard Law Review*, 98(4), 592–621.

¹⁸ Rawls, J. (1971). *A Theory of Justice*. Harvard University Press.

the legitimate feasible region permitted by these rigid ethical and constitutional boundaries, which may collectively be entitled “justice threshold”. Hence $F(x) \geq$ Justice Threshold.

6. The Four-Stage Integrated Lawmaking Optimization Model

As a synthesis of this study, a four-stage Integrated Lawmaking Optimization Model (ILOM) is theorized, merging technical efficiency and accuracy with ethical values and legal legitimacy:

Stage 1: Problem Definition (Empirical Diagnostics): The social, economic, or administrative problem to be regulated is formulated through empirical data. The root cause of the problem is objectively measured using physical natural constraints, probability theory, graph theory, ergonomics, reliability engineering fault analyses, and big data streams.

Stage 2: Process & Impact Optimization (RIA and IE Integration): Alternative policies are evaluated based on cost-benefit and administrative burden analyses. Alternative legal scenarios are mathematically tested through process modeling, queueing theory, system dynamics simulations, and MCDM methods.

Stage 3: Algocentric Analysis & Safeguards (Data Analytics and AI Deployment): Comparative law reviews, terminological consistency checks, and automated text audits are conducted utilizing secure RAG and cross-model architectures to eliminate hallucinations. Transparent and traceable use of data analytics and AI, complemented with Human-In-the-Loop practices are adhered to.

Stage 4: Ethical & Legal Validation (Multi-Objective Synthesis): The final decision-making phase is executed based on human rights, constitutional constraints, Pareto-optimal balances, and the public interest, ensuring that efficiency maximization never breaches absolute justice thresholds.

7. Conclusion

In a globalizing world, lawmaking has transformed into an activity too complex, dynamic, and data-intensive to be managed solely by classical legal methodology and dogmatic text analysis. Anticipating the long-term effects of laws on societal systems mandates the integration of the theoretical and empirical capacity of pure sciences, the analytical tools of engineering vision, the systematic approach of RIA, and the high computational power of artificial intelligence supported by data analytics into lawmaking processes.

Crucially, this model rejects the pure pursuit of mathematical efficiency or unconstrained economic maximization; instead, it establishes universal values of constitutional freedoms, fundamental rights and equality before law as rigid mathematical constraints that define a strict justice threshold that only allows for positive discrimination for the least advantaged segments of the society. Technical firewalls developed against hallucination, transparency, traceability and Human-in-the-Loop safeguards adopted against algorithmic bias risks, combined with this uncompromising threshold, remain the fundamental pillars guaranteeing the reliability of these technologies. It is highly probable that lawmaking engineering—as articulated in this article—which unifies the normative depth of jurists, the objective and verified knowledge of scientists, the optimization capabilities of industrial engineers, and the data processing power of artificial intelligence within the framework of constitutional principles, will design the legal order of the future.

Declaration of Use of AI in the Writing Process

During the preparation of this manuscript, the author utilized ChatGPT and Gemini to assist in the argument development, and conceptual mapping of the interdisciplinary framework (specifically regarding the use of mathematical modeling and IE methodologies). These AI tools were also used to assist in the research and integration of standard references across the relevant domains.

Following the iterative generation of structural outlines, argument expansions, and text drafts, the author critically reviewed, heavily edited, and systematically validated all content to ensure alignment with the overarching academic thesis. The author maintains ultimate accountability and full responsibility for the theoretical validity, accuracy, integrity, and scholarly conclusions of the final text.

References

- Ashley, K. D. (2017). *Artificial intelligence and legal analytics: New tools for law practice in the digital age*. Cambridge University Press.
- Barabási, A. L. (2016). *Network Science*. Cambridge University Press.
- Barocas, S., Hardt, M., & Narayanan, A. (2023). *Fairness and machine learning: Limitations and opportunities*. MIT Press.
- Cath, C. (2018). Governing artificial intelligence: ethical, legal and technical opportunities and challenges. *Philosophical Transactions of the Royal Society A*, 376(2128), 20180080.
- Dumas, M., La Rosa, M., Mendling, J., & Reijers, H. A. (2018). *Fundamentals of business process management* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-662-56509-4>
- Hillier, F. S., & Lieberman, G. J. (2021). *Introduction to operations research* (11th ed.). McGraw-Hill.

Lewis, P., Perez, E., Piktus, A., Petroni, F., Lewis, M., Riedel, S., ... & Kiela, D. (2020). Retrieval-augmented generation for knowledge-intensive NLP tasks. *Advances in Neural Information Processing Systems*, 33, 9459-9474.

Mayer-Schönberger, V., & Cukier, K. (2013). *Big data: A revolution that will transform how we live, work, and think*. Houghton Mifflin Harcourt.

Modarres, M., Kaminskiy, M., & Krivtsov, V. (2016). *Reliability engineering and risk analysis: A practical guide* (3rd ed.). CRC Press.

OECD. (2020). *Regulatory Impact Assessment*. OECD Best Practice Principles for Regulatory Policy, OECD Publishing. <https://doi.org/10.1787/7a9638cb-en>

OECD, Recommendation of the Council on Artificial Intelligence, OECD/LEGAL/0449 (2019, updated 2024), Principle 1.3, “Transparency and Explainability.” <https://oecd.ai/en/dashboards/ai-principles/P7>

Phillips, P. , Hahn, C. , Fontana, P. , Yates, A. , Greene, K. , Broniatowski, D. and Przybocki, M. (2021). Four Principles of Explainable Artificial Intelligence, NIST Interagency/Internal Report (NISTIR), National Institute of Standards and Technology, Gaithersburg, MD, [online], <https://doi.org/10.6028/NIST.IR.8312>, https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933399

Rawls, J. (1971). *A Theory of Justice*. Harvard University Press.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill.

Surden, H. (2014). Machine learning and law. *Washington Law Review*, 89, 87.

Triantaphyllou, E. (2000). *Multi-criteria decision making methods: A comparative study*. Springer. <https://doi.org/10.1007/978-1-4757-3262-7>

Tribe, L. H. (1985). Constitutional Calculus: Equal Justice or Economic Efficiency? *Harvard Law Review*, 98(4), 592–621.

Bridging Explainable AI and Legal Accountability in Financial Fraud Detection through Neural–Symbolic Compliance

Akmalbek Abdusalomov¹, Mukhriddin Mukhiddinov², Sunnat Makhmudov³,
Dildora Bazarova⁴ and Cüneyt Şamil Oğurlu⁵

Abstract

The rapid digital transformation of financial services has significantly increased the volume and complexity of electronic transactions, creating new opportunities for cyber-enabled financial fraud while simultaneously introducing substantial legal, regulatory, and governance challenges. Although conventional artificial intelligence (AI) models have achieved remarkable predictive performance, their limited explainability, insufficient regulatory compliance, and lack of auditability continue to restrict their practical adoption in highly regulated financial environments. This study explores how neural–symbolic compliance can bridge explainable AI and legal accountability in AI-assisted financial fraud detection. Rather than proposing a new fraud

¹ Department of Computer Engineering, Balikesir University, Balikesir 10145, Türkiye; Research Professor Dr., Department of Computer Engineering, Gachon University Sujeong-Gu, Seongnam-si 13120, Gyeonggi-Do, Korea; Professor, Department of Artificial Intelligence, Tashkent University of Information Technologies Named after Muhammad Al-Khwarizmi, Tashkent 100200 akmaljon@gachon.ac.kr (A.A), ORCID id: 0000-0001-5923-8695

² Department of Artificial Intelligence, Tashkent University of Information Technologies Named after Muhammad Al-Khwarizmi, Tashkent 100200, Uzbekistan. mukhiddinov18@gachon.ac.kr (M.M), ORCID id: 0000-0002-1424-0799

³ Department of Criminal Procedural Law, Tashkent State University of Law, Tashkent 100047, Uzbekistan. sunnat010995@gmail.com (S.M), ORCID id: 0000-0002-5397-4736

⁴ Faculty of Criminal Justice, Tashkent State University of Law, Tashkent 100047, Uzbekistan. d.bazarova@tsul.uz (D.B), ORCID id: 0000-0002-6833-9508

⁵ Phd in Law, Criminal Law Specialist, Department of Law, Istanbul Chamber of Commerce, Istanbul, Türkiye, cuneyt.ogurlu@ito.org.tr, ORCID id: 0009-0003-3708-755X

detection algorithm, the paper examines how integrating neural learning, symbolic reasoning, compliance verification, and human oversight can support transparent, auditable, and legally defensible decision-making. It further argues that AI-generated outputs should be interpreted as structured risk indicators rather than legally binding evidence, ensuring that final legal responsibility remains with qualified human professionals. By aligning technological innovation with legal and regulatory requirements, the proposed approach strengthens institutional accountability, enhances procedural fairness, and promotes responsible AI governance. The study demonstrates that neural-symbolic compliance provides a practical foundation for developing trustworthy AI systems capable of supporting financial institutions, regulators, and investigators in combating cyber-enabled financial fraud while maintaining transparency, accountability, and compliance with applicable legal standards.

Keywords: Neural-Symbolic Artificial Intelligence; Financial Fraud Detection; Explainable AI; Regulatory Compliance; Digital Banking; Cybercrime; Financial Technology.

1. Introduction

The rapid digital transformation of financial services has fundamentally reshaped the global banking ecosystem by enabling real-time payment processing, digital banking platforms, mobile financial services, and cross-border electronic transactions. While these technological advances have significantly improved operational efficiency and financial inclusion, they have simultaneously increased the exposure of financial institutions to sophisticated cyber-enabled fraud. The growing volume, velocity, and complexity of digital transactions have rendered traditional manual monitoring approaches increasingly ineffective, creating an urgent demand for intelligent fraud detection systems capable of identifying suspicious activities in real time. According to recent studies, financial fraud has evolved into one of the most significant cybersecurity threats affecting digital financial infrastructures, posing substantial economic, operational, and societal risks to financial institutions and their customers (Chen et al., 2025; Motie & Raahemi, 2024; ENISA, 2024).

Recent advances in artificial intelligence have substantially improved the ability to detect complex fraud patterns through machine learning, deep learning, graph neural networks, and Transformer-based architectures. These approaches have demonstrated remarkable performance in modeling temporal transaction behavior, relational dependencies, and anomalous financial activities that are often difficult to identify using conventional rule-based systems (Wang et al., 2023; Yu et al., 2024; Lin et al., 2024). At the same time, explainable artificial intelligence (XAI) has emerged as an important research direction aimed at improving transparency and user confidence in automated fraud detection systems by making model decisions more interpretable and

understandable (Psychoula et al., 2021; Ojo & Tomy, 2025). Nevertheless, despite their impressive predictive capabilities, many state-of-the-art AI models continue to function as black-box systems whose internal reasoning processes remain insufficiently transparent for regulatory supervision, legal review, and institutional accountability, as shown in Figure 1.

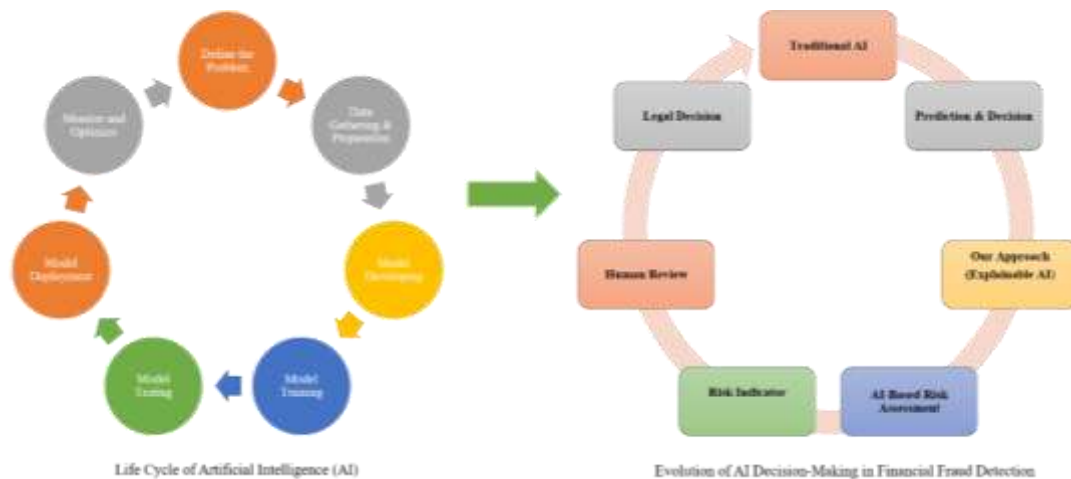


Figure 1. Evolution of Artificial Intelligence in Financial Fraud Detection from Conventional Prediction Models to Explainable and Legally Accountable Decision-Making.

The rapid adoption of AI within financial services has therefore shifted research priorities beyond prediction accuracy toward the development of trustworthy AI that satisfies legal, ethical, and regulatory requirements. Contemporary regulatory frameworks—including the European Union Artificial Intelligence Act (AI Act), the Digital Operational Resilience Act (DORA), the General Data Protection Regulation (GDPR), and the Financial Action Task Force (FATF) risk-based approach—emphasize that AI systems deployed in high-risk financial environments should ensure explainability, transparency, human oversight, accountability, and auditable decision-making throughout their operational lifecycle. From a legal perspective, AI-generated outputs should support regulatory and investigative decision-making rather than replace human judgment, thereby preserving procedural fairness and ensuring compliance with applicable legal standards (FATF, 2023; Regulation (EU) 2024/1689; Regulation (EU) 2022/2554; Oğurlu, 2024).

Building upon our previously proposed compliance-aware neural–symbolic architecture for real-time fraud detection, which integrated explainability, symbolic reasoning, and audit-oriented decision support, this study further extends the discussion toward the broader legal and governance dimensions of AI-assisted fraud detection. Rather than introducing another fraud detection algorithm, this paper examines how neural–symbolic artificial intelligence can systematically align predictive analytics with

regulatory compliance, human oversight, digital evidence, and institutional accountability within regulated financial systems. Accordingly, this study argues that future fraud detection systems should be evaluated not only by their predictive performance but also by their ability to produce transparent, explainable, and legally defensible decisions capable of strengthening trust in modern digital financial ecosystems.

Methodology

This study adopts a conceptual neural–symbolic methodology to investigate how artificial intelligence can support explainable, legally compliant, and trustworthy fraud detection in regulated financial systems. Rather than proposing a completely new prediction algorithm, the study extends a previously developed compliance-aware neural–symbolic framework by integrating machine learning outputs with symbolic reasoning, regulatory verification, and governance-oriented decision support. This methodological approach aims to bridge the gap between high predictive performance and legal accountability by ensuring that AI-generated outcomes remain transparent, interpretable, and suitable for regulatory assessment (Abdusalomov et al., 2026; Oğurlu, 2024).

The proposed approach is organized into four interconnected functional layers, as shown in Figure 2. The first layer performs real-time transaction analysis, where artificial intelligence models continuously monitor financial transactions and identify anomalous behavioural patterns associated with potential fraud. The second layer implements neural–symbolic reasoning, combining data-driven predictions with predefined regulatory knowledge, institutional policies, and expert-defined compliance rules. Unlike conventional black-box AI models, this layer generates explainable reasoning by associating detected anomalies with explicit logical rules and regulatory requirements, thereby improving transparency and interpretability of automated decisions (Wang et al., 2023; Psychoula et al., 2021).

The third layer introduces a compliance verification mechanism that evaluates suspicious transactions against applicable regulatory frameworks, including anti-money laundering (AML) principles, risk-based compliance procedures, and institutional governance requirements. Instead of producing autonomous legal judgments, the framework generates structured risk indicators supported by explanatory evidence that can be independently reviewed by compliance officers, auditors, or financial investigators. This design reflects the internationally accepted principle that AI should assist, rather than replace, human decision-making in high-risk regulatory environments (Financial Action Task Force [FATF], 2023; Regulation (EU) 2024/1689).

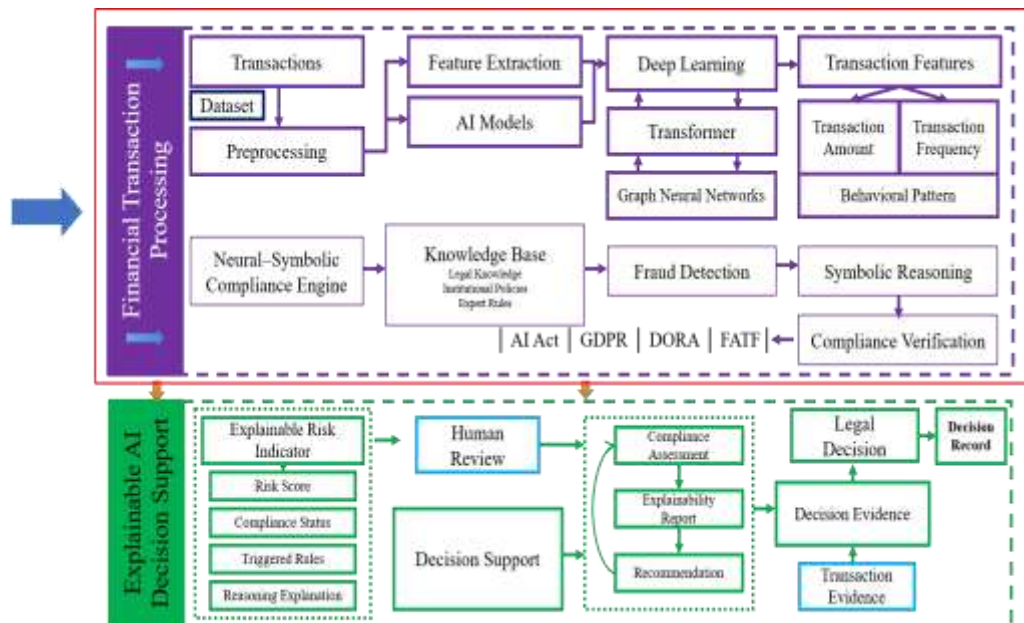


Figure 2. Proposed Neural-Symbolic Compliance Approach for Explainable and Legally Accountable Financial Fraud Detection.

Finally, the framework produces an audit-oriented decision record that documents the detected transaction, applied compliance rules, symbolic reasoning process, AI-generated explanations, and supporting evidence. Such documentation facilitates regulatory auditing, strengthens institutional accountability, and improves the traceability of AI-assisted decision-making throughout the investigation process. By maintaining human oversight over the final assessment, the proposed methodology aligns with the fundamental principles of trustworthy AI governance and responsible deployment of artificial intelligence within modern digital financial ecosystems (Regulation (EU) 2024/1689; ISO/IEC 42001:2023; Oğurlu, 2024).

3. Discussion

The proposed framework demonstrates that the future development of fraud detection systems should extend beyond maximizing prediction accuracy toward ensuring regulatory transparency and institutional accountability. Although modern artificial intelligence models have achieved remarkable success in identifying complex fraud patterns, their practical deployment within regulated financial environments depends largely on whether their decisions can be understood, justified, and verified by human experts. From this perspective, explainability should no longer be regarded as an additional feature but rather as a fundamental requirement for trustworthy AI in financial services.

One of the most significant advantages of the proposed neural–symbolic framework is its ability to combine statistical intelligence with rule-based reasoning. Instead of producing isolated probability scores, the framework associates each detected anomaly with explicit compliance rules and symbolic explanations. Such an approach allows financial institutions not only to identify suspicious transactions but also to understand the reasoning process that produced the corresponding risk assessment. Consequently, investigators, auditors, and compliance officers are provided with structured evidence that supports more informed and consistent decision-making.

Another important implication concerns the relationship between artificial intelligence and legal responsibility. In many practical applications, AI systems are often perceived as autonomous decision-makers. However, this assumption may introduce legal uncertainty, particularly in highly regulated financial sectors where decisions can directly affect customers, institutions, and regulatory obligations. The proposed framework adopts an alternative perspective in which AI functions exclusively as an intelligent decision-support system. Final legal responsibility remains with qualified human professionals who evaluate AI-generated recommendations together with institutional policies, regulatory requirements, and available evidence before taking any formal action.

The integration of compliance verification into the analytical process also strengthens the overall governance of financial institutions. Rather than evaluating regulatory compliance after suspicious transactions have been detected, compliance assessment becomes an integral component of the detection process itself. This proactive strategy improves consistency between technological innovation and legal obligations while reducing potential conflicts between automated predictions and regulatory expectations. As a result, financial institutions may improve both operational efficiency and regulatory confidence without sacrificing transparency or accountability.

Finally, the proposed framework illustrates a broader transition in artificial intelligence research. Future AI systems should not be designed solely to achieve higher predictive performance but also to produce decisions that are explainable, auditable, and legally defensible. Within this context, neural–symbolic reasoning provides a practical foundation for connecting advanced machine learning with regulatory governance and responsible AI deployment. Such an approach has the potential to support not only fraud detection but also a wider range of compliance-critical applications in digital finance, public administration, healthcare, and other domains where transparency and legal accountability are essential.

4. Conclusions

This study presented a conceptual neural–symbolic compliance-aware framework for supporting real-time fraud detection in regulated financial systems. By integrating artificial intelligence, symbolic reasoning, compliance verification, and human oversight, the proposed approach extends fraud detection beyond prediction accuracy toward explainability, transparency, auditability, and legal accountability. The framework demonstrates that effective AI deployment in financial services requires not only accurate detection models but also decision-making processes that are understandable, verifiable, and aligned with regulatory requirements.

Furthermore, this study argues that AI-generated outputs should be interpreted as structured risk indicators rather than legally binding evidence, ensuring that final legal responsibility remains with qualified human professionals. Integrating compliance into the analytical process strengthens institutional governance while supporting responsible AI adoption in highly regulated environments. Future research should focus on validating the proposed framework using real-world financial datasets and exploring its applicability to other compliance-critical domains where trustworthy and explainable AI is essential.

Acknowledgement: The authors would like to express their sincere gratitude and appreciation to Professor Yücel Oğurlu of Balıkesir University for his invaluable support, insightful comments, and constructive remarks throughout the preparation of this manuscript. Moreover, the authors would like to thank the editor and anonymous reviewers for their valuable suggestions, which significantly improved the quality and presentation of this paper.

References

Abdusalomov, A., Kutlimuratov, A., & Oğurlu, C. Ş. (2026). *A unified neural–symbolic compliance-aware framework for real-time fraud detection in regulated financial systems*. *The Review of Law, International Politics and Economics*, 2(1), 20–46. <https://doi.org/10.5281/zenodo.20947427>.

Chen, Y., Zhao, C., Xu, Y., Nie, C., & Zhang, Y. (2025). Deep learning in financial fraud detection: Innovations, challenges, and applications. *Data Science and Management*. <https://doi.org/10.1016/j.dsm.2025.100080>.

European Union. (2016). *Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data (General Data Protection Regulation)*. *Official Journal of the European Union*, L119, 1–88.

European Union. (2022). *Regulation (EU) 2022/2554 of the European Parliament and of the Council of 14 December 2022 on digital operational resilience for the financial sector (Digital Operational Resilience Act)*. *Official Journal of the European Union*, L333, 1–79.

European Union. (2024). *Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act)*. Official Journal of the European Union.

European Union Agency for Cybersecurity. (2024). *ENISA Threat Landscape 2024*. <https://www.enisa.europa.eu>.

Financial Action Task Force. (2023). *International standards on combating money laundering and the financing of terrorism & proliferation: The FATF recommendations*. FATF.

Lin, J., Guo, X., Zhu, Y., Mitchell, S., Altman, E., & Shun, J. (2024). FraudGT: A simple, effective, and efficient graph transformer for financial fraud detection. In *Proceedings of the 5th ACM International Conference on AI in Finance* (pp. 292–300). ACM.

Motie, S., & Raahemi, B. (2024). Financial fraud detection using graph neural networks: A systematic review. *Expert Systems with Applications*, 240, 122156. <https://doi.org/10.1016/j.eswa.2023.122156>.

Oğurlu, Y. (2024). Yapay zekânın hukuk tarihî usullerinden *makâsıd* ve *maslahat* ile amaç yorumu çerçevesinde yorumlanması hakkında bir deneme. *Balıkesir Üniversitesi Hukuk Dergisi*, 1(2), 144–164.

Ojo, I. P., & Tomy, A. (2025). Explainable AI for credit card fraud detection: Bridging the gap between accuracy and interpretability. *SN Computer Science*, 6, 246.

Psychoula, I., Gutmann, A., Mainali, P., Lee, S. H., Dunphy, P., & Petitcolas, F. (2021). Explainable machine learning for fraud detection. *Computer*, 54(10), 49–59. <https://doi.org/10.1109/MC.2021.3092612>.

Wang, H., Zheng, J., Carvajal-Roca, I. E., Chen, L., & Bai, M. (2023). Financial fraud detection based on deep learning: Towards large-scale pre-training transformer models. In *Knowledge Graph and Semantic Computing: China Conference, CCKS 2023* (pp. 163–177). Springer.

Yu, C., Xu, Y., Cao, J., Zhang, Y., Jin, Y., & Zhu, M. (2024). Credit card fraud detection using advanced transformer model. In *2024 IEEE International Conference on Metaverse Computing, Networking, and Applications (MetaCom)* (pp. 343–350). IEEE.

International Organization for Standardization. (2023). ISO/IEC 42001:2023 Information technology-Artificial intelligence-Management system. ISO.

Protection of Children’s Privacy and Personality Rights in Digital Environments

Esra Gültekin¹

Abstract

Digital environments provide children with substantial opportunities for education, communication, social interaction, and entertainment. At the same time, however, they create serious risks for children’s privacy, personal data, and personality rights. These risks may arise from the activities of digital platforms and third parties as well as from parents’ publication of content concerning their children. This article examines the protection of children’s privacy and personality rights under Turkish civil law, constitutional law, personal data protection law, and international children’s rights standards. Particular attention is given to parental “sharenting,” the processing of children’s data by digital gaming platforms, the legal validity of consent, and the principle of the best interests of the child. The article argues that effective protection requires not only remedies following an infringement but also preventive and child-centred digital design measures.

Keywords: children’s rights, privacy, personality rights, personal data, sharenting, digital games, best interests of the child.

1. Introduction

Digital environments offer children significant opportunities in education, communication, and entertainment; at the same time, however, they expose children’s

¹ Phd in Law, Fatih Sultan Mehmet Waqf University, Faculty of Law, egultekin@fsm.edu.tr , ORCID: 0000-0001-5690-4162.

privacy and personality rights to infringements on an unprecedented scale. A child's image, voice, name, age, location, health information, in-game behaviour, and online communications frequently enter digital circulation before the child is capable of understanding the consequences.

Moreover, infringements do not arise solely from platforms or third parties; parents' social media posts may also render the child's private life public. The legal assessment must therefore adopt a holistic approach encompassing, on the one hand, parental authority and parents' freedom of expression and, on the other, the data-processing activities of digital service providers. For this purpose, the discussion will first address infringements of children's personality rights and right to privacy by parents and will then examine such infringements by digital service providers, with particular emphasis on digital gaming platforms.

2. The Child as a Holder of Personality Rights

A child's personality right is an absolute right acquired at birth and enforceable *erga omnes* (Serozan, 2005, p. 102). Articles 8, 24, and 25 of the Turkish Civil Code (TCC) establish that children, without distinction, are holders of personality rights and may be protected against unlawful interferences.

The scope of personality rights is not subject to the *numerus clausus* principle; private life, privacy, honour and dignity, rights over one's name, voice, and image, and the right to informational self-determination all fall within the protected sphere (Akyüz, 2021, p. 129). Accordingly, the sharing on social media of a child's embarrassing moment, health condition, school information, nude or semi-nude image, or location may, depending on the circumstances of the particular case, simultaneously infringe several personality interests (Gültekin, 2018, pp. 103–143).

3. Civil, Protective, and Criminal Remedies

On behalf of a child whose personality rights have been infringed, claims may be brought under Article 25 of the TCC to prevent an imminent interference, terminate an ongoing interference, and obtain a declaratory judgment establishing the unlawfulness of an interference that has ceased.

Where the relevant conditions are satisfied, claims for pecuniary and non-pecuniary damages and for the disgorgement of unlawfully obtained gains may also be asserted. Where the infringement is attributable to the parents, the appointment of a guardian ad litem pursuant to Article 426 of the TCC may be required because of the conflict of interests.

If the infringement reaches a level that endangers the child's development and interests, the protective measures laid down in Article 346 et seq. of the TCC and the measures provided for under Child Protection Law No. 5395 may become applicable. Depending on the circumstances of the case, the unlawful recording and dissemination of images or data may also constitute offences under Articles 134–136 of the Turkish Criminal Code.

4. Constitutional and Human Rights Protection

The constitutional basis for protecting a child's privacy is formed by the right to protect and develop one's corporeal and spiritual existence, guaranteed under Article 17 of the Constitution, together with the rights to respect for private life and to the protection of personal data, enshrined in Article 20.

A child's photograph, video, voice, username, IP address, device identifier, online behaviour, and in-game preferences constitute personal data insofar as they relate to an identified or identifiable person. The Turkish Constitutional Court likewise regards the protection of personal data as an element of the right to respect for private life and recognises that the State is subject not only to a negative obligation to refrain from arbitrary interference but also to a positive obligation to provide effective protection against interferences by private persons.

Precedents concerning infringements of a child's personality rights over their image exist in both domestic and international law. In *Bogomolova v. Russia*, the European Court of Human Rights examined under Article 8 of the European Convention on Human Rights the use of a child's photograph without distinguishing between consent to the taking of the photograph and consent to its publication.

Taking into account that the context in which the photograph was published could create a false impression about the child and the child's family, the Court found a violation of the right to respect for private life. The judgment is significant because it demonstrates that consent to the taking of a photograph does not automatically amount to consent to the publication of the image in a different context (ECtHR, *Bogomolova v. Russia*, App. No. 13812/09, 20 June 2017).

5. Parental Sharing and the Phenomenon of “Sharenting”

Parents' sharing of content concerning their children constitutes the principal manifestation of the phenomenon referred to in legal scholarship as “sharenting” (Kavlak, 2025, pp. 481–519). Parental authority does not confer upon parents an unlimited power of disposition over the child.

Under Article 339 of the TCC, parents are required to take the necessary decisions concerning the child's care and education while having regard to the child's interests. Rather than constituting merely a right, parental authority is a complex of rights, powers, and duties governed by the best interests of the child.

The systematic publication of a child's image for financial gain, social visibility, or the parent's personal gratification may therefore amount to an exercise of parental authority contrary to its purpose. Nor is parents' freedom of expression unlimited when weighed against the child's privacy, personality rights, and best interests.

A fair balance must be struck between the competing rights on the basis of proportionality; the contribution of the post to a debate of public interest, the degree of intimacy of the content, the scope of its accessibility, its persistence, whether it pursues an economic purpose, and its potential consequences for the child must be assessed together (Gültekin, 2018, pp. 113–127).

6. Children's Data in Digital Gaming Environments

Digital games may incorporate a range of functions, including voice communication, image transmission, login through social media accounts, location tracking, behavioural profiling, and in-game purchases. Owing to this layered structure, the categories of data collected and the purposes for which they are processed must be determined separately for each game.

Even a child's in-game actions may, over time, enable the creation of profiles concerning the child's interests, consumption tendencies, social environment, and psychological characteristics (Akkışla, 2026, pp. 65–92). Services directed at children should therefore incorporate privacy by design, data minimisation, high-privacy settings by default, restrictions on profiling-based advertising, safe communication tools, and effective parental controls.

7. Protection Under the Turkish Personal Data Protection Law

Although Personal Data Protection Law No. 6698 (KVKK) does not establish a separate and comprehensive regime for children's data, its general principles must be applied to children within a framework of enhanced protection.

Under Article 4 of the KVKK, personal data must be processed lawfully and fairly, for specified and legitimate purposes, and in a manner that is relevant, limited, and proportionate to the purposes for which they are processed. These principles are particularly important in preventing digital games from collecting location data, contact-

list data, microphone or camera data, or biometric data that are not necessary for the service.

The data controller must discharge the information obligation under Article 10 of the KVKK in clear, plain, and age-appropriate language that the child can understand. Merely displaying a lengthy and complex privacy policy does not, in itself, establish that the child has been meaningfully informed.

8. Comparative Law: The GDPR and the Digital Services Act

In comparative law, Article 8 of the General Data Protection Regulation (GDPR) specifically regulates consent-based processing in relation to information society services offered directly to a child and, as a general rule, requires the consent or authorisation of the holder of parental responsibility for children under the age of sixteen. Member States may lower this threshold to thirteen.

The provision also requires the controller to make reasonable efforts to verify parental authorisation. Article 28 of the EU Digital Services Act, in turn, obliges online platforms accessible to minors to ensure a high level of privacy, safety, and security and prohibits the presentation to children of advertisements based on profiling.

This approach demonstrates that a protection model resting exclusively on consent is inadequate and that objective duties designed to protect children from the inception of the service are necessary (GDPR, Art. 8; European Commission, 2025 Guidelines).

9. The Best Interests and Participation of the Child

Under Article 3 of the United Nations Convention on the Rights of the Child, the best interests of the child must be a primary consideration in all actions concerning children (Akyüz, 2021, p. 53).

Article 12 of the Convention guarantees the right of a child capable of forming their own views to express those views freely in all matters affecting them, while Article 16 protects the child against arbitrary or unlawful interference with their privacy, family, home, or correspondence. Accordingly, the child's views must be given due weight in accordance with the child's age and maturity.

Nevertheless, the child's wish that content be shared or the child's acceptance of the data-processing terms of a game does not in every case constitute a valid legal ground rendering the processing lawful. The child's capacity for discernment, the nature of the processing, the risks it entails, and whether consent is genuinely informed and freely given must be assessed separately (Akyüz, 2021, p. 132; Erdoğan, 2018, pp. 2445–2467).

10. Conclusion

A child is neither an extension of the parents' digital identity nor a commercial source of data for platforms. The child's privacy is an autonomous personality interest that cannot be weakened through consent, parental authority, or platform contracts.

Effective protection should not be confined to post-infringement remedies such as content removal and compensation; it must be supported by age-appropriate information, data minimisation, child participation, safe default settings, and a preventive approach to digital design centred on the best interests of the child.

References

- Akkışla, H. Sena. "Digital Games and the Protection of Children's Personal Data," *Kişisel Verileri Koruma Dergisi* [Journal of Personal Data Protection], 2026/8(1), pp. 65–92.
- Akyüz, Emine. *Child Law*. Pegem Akademi, 2021.
- ECtHR. *Bogomolova v. Russia*, App. No. 13812/09, 20 June 2017, <https://hudoc.echr.coe.int/eng?i=001-174420>.
- Erdoğan, Canan. "Protection of Children's Personal Data," 2018, pp. 2445–2467.
- European Commission. *Guidelines on Measures to Ensure a High Level of Privacy, Safety and Security for Minors on Online Platforms*, 2025, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C_202505519.
- European Union. *General Data Protection Regulation* (GDPR), Art. 8, <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02016R0679-20160504>.
- Gültekin, Esra. "The Legal Framework of Infringements of a Child's Personality Rights by Parents through Social Media," *Çocuk ve Medeniyet* [Child and Civilisation], 2018/1, pp. 103–143.
- Kavlak, Bengül. "An Assessment of Sharenting in the Digital Age in the Light of International Regulations," *İzmir Barosu Dergisi* [İzmir Bar Association Journal], 2025, pp. 481–519.
- Legislation. Constitution of the Republic of Türkiye; Turkish Civil Code No. 4721; Turkish Criminal Code No. 5237; Child Protection Law No. 5395; Personal Data Protection Law No. 6698; United Nations Convention on the Rights of the Child.
- Serozan, Rona. *Child Law*. Vedat Kitapçılık, 2005.

Criminal Liability of Artificial Intelligence: Fundamental Principles of Criminal Law and New Approaches

Muharrem Çelik¹

Abstract

Artificial intelligence and AI-developed products continue to occupy an increasingly significant place in our daily lives. How to determine the criminal liability arising from these products has become a major subject of debate.

In this context, reflecting the EU's regulatory approach, the 2024 EU Artificial Intelligence Act holds great importance as Europe's most comprehensive framework. However, even this regulation does not contain provisions regarding criminal liability.

Discussions are currently shaped by academic literature and judicial decisions regarding individual cases. At this point, fundamental elements of classical criminal law—such as intent, culpability, and the causal relation—gain crucial significance. Furthermore, whether legal personhood is attributed to artificial intelligence will shape the answer to this question. On the other hand, whether identifiable actors such as the manufacturer, developer, operator, and user will face criminal liability arises as an important issue.

In this paper, alongside EU debates, the applicability of Turkish Criminal Law's fundamental concepts to AI and its criminal liability will be examined.

Keywords: Artificial Intelligence, Criminal Liability, intent, culpability, Personality of Artificial Intelligence.

1. General Overview

¹ Phd in Law, İstanbul 2'nolu Baro, muharrem.celik@outlook.com.tr, ORCID: 0000-0003-0582-815X.

The concept of Artificial Intelligence first appeared in history in a project proposal prepared in 1955 by John McCarthy and his colleagues, for the Dartmouth Summer Research Project on Artificial Intelligence, which took place in 1956². This project, which is accepted as the first important step in the field of artificial intelligence, was financed by the Rockefeller Foundation³.

Artificial intelligence, which has started to be used in many areas of our lives, affects fundamental rights and freedoms, and also causes serious negative effects on human life. For this reason, there is a need for legal regulations for artificial intelligence that carry the principles of transparency, explainability and accountability. In my opinion, countries will, in the near future, put forward legal reforms regulating the field of AI, one after another.

2. EU's Regulatory Initiatives

The EU's AI legislation, which entered into force on August 1, 2024, is important⁴. The EU has also shown, in the field of artificial intelligence, its tendency to be the first to make legal regulations on new technologies and to take a leading role. Anu Bradford describes this situation, in a positive sense, as the “Brussels Effect”⁵. It is a generally accepted situation that the EU is behind China and the US when it comes to AI technologies⁶. In my opinion, the EU puts forward legal instruments in order to prevent its technological backwardness from putting it at a disadvantage. In this framework, this regulation, which was drafted from a risk-based approach, ultimately pursues an economic objective. This regulation, made in order to prevent the harmful use of artificial intelligence, is important. However, this regulation does not contain a provision regarding the criminal liability of artificial intelligence.

3. Artificial Intelligence and Criminal Liability

² Michael Haenlein and Andreas Kaplan, “A Brief History of Artificial Intelligence: On the Past, Present, and Future of Artificial Intelligence,” *California Management Review* 61, no. 4 (2019): 3. For the proposal section of this project, see John McCarthy et al., “A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, August 31, 1955,” *AI Magazine* 27, no. 4 (2006): 12.

³ Haenlein and Kaplan, “Brief History,” 3.

⁴ Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 Laying Down Harmonised Rules on Artificial Intelligence (Artificial Intelligence Act), *Official Journal of the European Union*, July 12, 2024, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401689.

⁵ Anu Bradford, *The Brussels Effect: How the European Union Rules the World* (New York: Oxford University Press, 2020).

⁶ See, for example, “EU Lags US and China in AI Investments, Nvidia CEO Says,” Reuters, October 23, 2024, <https://www.reuters.com/technology/eu-lags-us-china-ai-investments-nvidia-ceo-says-2024-10-23/>.

3.1 Debates on the Personality of Artificial Intelligence

The difficulties in placing liability on human actors have brought onto the agenda the proposal of granting artificial intelligence an independent legal personality. In the recommendation prepared by the European Parliament and adopted on 16 February 2017, granting advanced and autonomous robots a limited “electronic personality” status was considered as a long-term option⁷. However, this proposal did not turn into a final and binding piece of regulation⁸.

As of now, artificial intelligence has not been granted any personality through legal regulation. While some academics state that artificial intelligence should be regarded as an object, others state that it should be attributed legal personality. In addition, some academics state that an entirely new, sui generis personality of its own should be created for it⁹.

3.2. From the Perspective of Criminal Law

3.2.1 Evaluations Regarding Will

From the perspective of criminal law, the first condition for a person to be held liable is the existence of a voluntary action in the outside world. An action is defined as conduct that is based on a person's will and that brings about a change in the outside world¹⁰. Therefore, at least for now, since artificial intelligence does not possess a will, it is not possible to regard the outputs produced by artificial intelligence as an action in the sense required by criminal law.

Since artificial intelligence does not currently have any personality of its own, liability for it may instead arise for its programmer. However, for this to happen, the other elements of criminal liability must also be present in the specific case. For example, in the event that an artificial intelligence commits an offense, in order for its programmer to be punished, the programmer must have known that the artificial intelligence would be

⁷ European Parliament, European Parliament Resolution of 16 February 2017 with Recommendations to the Commission on Civil Law Rules on Robotics (2015/2103(INL)), P8_TA(2017)0051.

⁸ Berrin Akbulut, “Yapay Zeka ve Ceza Hukuku Sorumluluğu,” *Ankara Hacı Bayram Veli Üniversitesi Hukuk Fakültesi Dergisi* 27, no. 4 (2023): 286.

⁹ For detailed information on the debates regarding the personality of artificial intelligence, see Enes Köken, “Yapay Zekânın Cezai Sorumluluğu,” *Türkiye Adalet Akademisi Dergisi* 12, no. 47 (2021): 259–63.

¹⁰ İzzet Özgenç, *Türk Ceza Hukuku Genel Hükümler*, 20th ed. (Ankara: Seçkin Yayıncılık, 2024), 183.

used as a tool in the commission of the offense — in other words, the programmer must possess culpability¹¹.

3.2.2. Causal Relation

Another element of criminal liability is the causal relation between the perpetrator and the result. As Özbek and Özbek point out, the more difficult it becomes to determine who actually holds control over the decisions made by AI systems, the more difficult it also becomes to establish the causal relation¹². In particular, the decision-making processes of deep learning systems can carry the nature of a “black box” that cannot be explained in detail even by their own developers.

3.2.3. On the Moral Element of Crime

In Turkish criminal law, the moral element of an offense is regulated under two basic categories: intent and negligence. Under Article 21/1 of the Turkish Criminal Code (TCK), for intent to exist, the elements of *knowledge and will* must be present. Along similar lines, for possible intent, what is required is that the person carries out the action *despite foreseeing the result*. Article 22 of the TCK, in turn, defines negligence as “*carrying out an act, in violation of the duty of care and attention, without foreseeing the result specified in the legal definition of the offense*”.

Both of these concepts are based on notions that are specific to human beings and to will, such as knowledge, willing, or foresight. It is not possible to accept that AI systems, at the current level of technology, possess this kind of state of consciousness, of the sort required for intent or negligence to exist.

3.3.3. Evaluations Regarding Culpability

In order for a person to be held liable for an action they have committed, they must have possessed the capacity of culpability (imputability) at the time the action was committed¹³. The capacity of culpability is expressed as the perpetrator's ability to perceive the legal meaning and consequences of the action they committed, and to direct their conduct in line with that perception¹⁴. As can be seen, it is not a realistic situation

¹¹ Köken, “Yapay Zekânın Cezai Sorumluluğu,” 267.

¹² Ceren Özbek and Veli Özer Özbek, “Yapay Zekânın Dâhil Olduğu Suçlar Bakımından Ceza Hukuku Sorumluluğunun Belirlenmesi,” *Ceza Hukuku Dergisi* 14, no. 41 (2019): 603–22.

¹³ Özgenç, *Türk Ceza Hukuku Genel Hükümler*, 459–60.

¹⁴ Selami Turabi, “Kusurluluk ve Kusurluluğu Etkileyen Haller,” *Türkiye Barolar Birliği Dergisi*, no. 101 (2012): 268.

for artificial intelligence to perceive the meaning and consequences of an action and to shape its conduct accordingly¹⁵.

4. New Approaches

In cases of harm caused by autonomous systems, consideration should be given to sharing liability between the manufacturer, the software developer, and the user/operator. In this approach, the basic question is whether the result that occurred stemmed from a design/manufacturing defect, or from the system being used without the necessary care. The liability of the manufacturer or developer will generally be capable of being based on negligence. This is assessed through breaches of the duty of care, such as the system not having been tested sufficiently before being placed on the market, foreseeable risks not having been eliminated, or the user not having been given sufficient warning and instructions. The liability of the user or operator, on the other hand, comes onto the agenda in situations such as the system being used contrary to the manufacturer's instructions, the necessary duty of supervision not being fulfilled, or the limits of the system being knowingly pushed¹⁶.

Conclusion

The use of artificial intelligence is increasing effectively with every passing day. Many legal or human problems are also arising as a result of artificial intelligence. For this reason, it is being discussed, in many countries around the world, that laws need to be made regarding artificial intelligence. Indeed, a separate and comprehensive AI regulation has also entered into force in the EU. However, here too, there is no provision regarding the criminal liability of artificial intelligence.

From the point of view of Turkish law, there is neither a regulation concerning artificial intelligence, nor a regulation on the point of criminal liability. In terms of the basic principles of criminal law, it is not possible for artificial intelligence to be punished for the actions it has carried out, on account of its lacking both will and the capacity of culpability.

Ultimately, whichever of the parts that carry human will — the manufacturer, the software developer, or the user/operator — the criminally punishable action carried out by the artificial intelligence has come about through a lack of care or intentional conduct

¹⁵ Koray Doğan, “Sürücüsüz Araçlar, Robotik Cerrahi, Endüstriyel Robotlar ve Cezai Sorumluluk,” *Dokuz Eylül Üniversitesi Hukuk Fakültesi Dergisi*, Prof. Dr. Durmuş Tezcan’a Armağan, 21, Özel Sayı (2019): 3236.

¹⁶ For a different approach to criminal liability, see also Gabriel Hallevy, “The Criminal Liability of Artificial Intelligence Entities—From Science Fiction to Legal Social Control,” *Akron Intellectual Property Journal* 4, no. 2 (2010): 171–201.

within that party's area of liability, it would be appropriate for this to be identified and for criminal liability to be determined within that scope.

References

- Akbulut, Berrin. "Yapay Zeka ve Ceza Hukuku Sorumluluğu." *Ankara Hacı Bayram Veli Üniversitesi Hukuk Fakültesi Dergisi* 27, no. 4 (2023): 267–319.
- Bradford, Anu. *The Brussels Effect: How the European Union Rules the World*. New York: Oxford University Press, 2020.
- Doğan, Koray. "Sürücüsüz Araçlar, Robotik Cerrahi, Endüstriyel Robotlar ve Cezai Sorumluluk." *Dokuz Eylül Üniversitesi Hukuk Fakültesi Dergisi*, Prof. Dr. Durmuş Tezcan'a Armağan, 21, Özel Sayı (2019): 3219–51.
- "EU Lags US and China in AI Investments, Nvidia CEO Says." Reuters, October 23, 2024. <https://www.reuters.com/technology/eu-lags-us-china-ai-investments-nvidia-ceo-says-2024-10-23/>.
- European Parliament. *European Parliament Resolution of 16 February 2017 with Recommendations to the Commission on Civil Law Rules on Robotics (2015/2103(INL))*. P8_TA(2017)0051.
- Haenlein, Michael, and Andreas Kaplan. "A Brief History of Artificial Intelligence: On the Past, Present, and Future of Artificial Intelligence." *California Management Review* 61, no. 4 (2019): 5–14.
- Hallevy, Gabriel. "The Criminal Liability of Artificial Intelligence Entities—From Science Fiction to Legal Social Control." *Akron Intellectual Property Journal* 4, no. 2 (2010): 171–201.
- Köken, Enes. "Yapay Zekânın Cezai Sorumluluğu." *Türkiye Adalet Akademisi Dergisi* 12, no. 47 (2021): 247–86.
- McCarthy, John, Marvin L. Minsky, Nathaniel Rochester, and Claude E. Shannon. "A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, August 31, 1955." *AI Magazine* 27, no. 4 (2006): 12–14.
- Özbek, Ceren, and Veli Özer Özbek. "Yapay Zekânın Dâhil Olduğu Suçlar Bakımından Ceza Hukuku Sorumluluğunun Belirlenmesi." *Ceza Hukuku Dergisi* 14, no. 41 (2019): 603–22.
- Özgenç, İzzet. *Türk Ceza Hukuku Genel Hükümler*. 20th ed. Ankara: Seçkin Yayıncılık, 2024.
- Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 Laying Down Harmonised Rules on Artificial Intelligence (Artificial Intelligence Act). *Official Journal of the European Union*, July 12, 2024. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401689.
- Turabi, Selami. "Kusurluluk ve Kusurluluğu Etkileyen Haller." *Türkiye Barolar Birliği Dergisi*, no. 101 (2012): 267–92.

AI-Assisted Inventions and The Problem of Inventorship: From The Dabus Cases To Human–AI Collaboration

Canan Küçükali¹

Abstract

The increasing involvement of artificial intelligence systems in the invention process, as in every other field, is testing patent law's assumption that "an inventor must necessarily be a natural person." This study presents a comparative analysis of the lawsuits filed worldwide by Stephen Thaler in an effort to have his AI system, DABUS, recognized as an inventor, and then turns to today's more realistic problem: how inventorship should be allocated in the common scenario where a human researcher arrives at an invention using AI tools. The discussion is framed around the shift in USPTO guidance from the "significant contribution" standard of February 2024 to the return to the traditional "conception" test in November 2025, and finally the issue is evaluated from the perspective of Turkey's Industrial Property Law No. 6769.

Keywords: artificial intelligence, patent law, inventorship, DABUS, inventive step, Industrial Property Law

Introduction

The phrase "invention in all fields of technology" in Article 27 of the TRIPS Agreement² rests on the implicit assumption that human intelligence lies behind every invention. In recent years, the growing role of generative artificial intelligence in

¹ Prof. Dr., Dean, Faculty of Law, Istanbul Sabahattin Zaim University, canan.kucukali@izu.edu.tr, ORCID:0000-0002-0403-4588

² Agreement on Trade-Related Aspects of Intellectual Property Rights TRIPS

scientific discovery and engineering design has turned this premise into an open legal problem. The issue has two dimensions: (i) what kind of status should be recognized for fully autonomous AI inventions, and (ii) in the far more common scenario, to what extent should a human's AI-assisted contribution count as "inventorship." This study first examines the first question through the DABUS cases, and then examines the second question from the perspective of Turkish law.

1. The DABUS Cases: A Comparative Overview

Applications were filed with numerous patent offices worldwide on the claim that DABUS had autonomously generated designs for a beverage container and an emergency warning light.³ Thaler named not himself but DABUS as the inventor, arguing that the right belonged to him as the owner of the machine.

The EPO Legal Board of Appeal rejected the applications in December 2021 on the grounds that an inventor must have legal capacity.⁴ The CJEU's Case C-250/25, *Like Company v. Google*, concerning the copyright dimension of generative AI, remains pending, with a decision not expected before 2027.⁵

In the United States, the USPTO's rejection was upheld by the Federal Circuit, and the Supreme Court denied certiorari in 2023.⁶ The Federal Circuit concluded that an inventor can only be a natural person, and the Supreme Court reaffirmed this human-centered approach in the copyright context in 2026.⁷ In the United Kingdom, the Supreme Court held in December 2023 in *Thaler v. Comptroller-General* that an inventor, as the "actual deviser," can only be a natural person, but that the ruling was limited to interpretation of existing legislation.⁸

In Germany, the Bundesgerichtshof reached a similar conclusion in June 2024.⁹ A human who has a determinative influence on the inventive process may be named as inventor even if their contribution is not itself creative. In Japan, the Intellectual Property High Court issued an unfavorable ruling in January 2025, but noted that the problem could be resolved not through statutory interpretation but through redesigning the system; this

³ See WIPO Standing Committee on the Law of Patents, 'Artificial Intelligence and Inventorship,' SCP/35/7, September 13, 2023, for an explanation of DABUS's technical operation and its claimed inventions (a fractal food container and an emergency signaling lamp).

⁴ EPO Legal Board of Appeal, J 8/20 ve J 9/20 (Designation of inventor/DABUS), 21 December 2021.

⁵ Case C-250/25, *Like Company v. Google*, CJEU.

⁶ *Thaler v. Vidal*, 43 F.4th 1207 (Fed. Cir. 2022), cert., 143 S. Ct. 1783 (2023).

⁷ *Thaler v. Perlmutter*, U.S. Supreme Court, No. 25-449, 2 Mart 2026

⁸ *Thaler v. Comptroller-General of Patents, Designs and Trade Marks* [2023] UKSC 49.

⁹ Bundesgerichtshof, 11 Haziran 2024, X ZB 5/22 (DABUS).

assessment was reflected in the Cabinet Office's 2025 strategic program. The JPO's March 2026 report tightened the examination of inventive step, and the process became final in March 2026 when the Supreme Court declined the appeal.¹⁰ South Africa, having registered DABUS solely because it conducts only a formal examination, carries limited precedential value as the only country to have done so.¹¹ Canada rejected the application in 2025,¹² around the same time the matter became final in Japan, while India rejected the application in April 2026 on similar grounds.¹³

Although no explicit rejection decision has been published in Singapore, IPOS's settled practice is that an inventor must be a natural person.¹⁴ The office is also conducting a consultation on the patentability threshold for inventions based on artificial neural networks.¹⁵ Thus, the DABUS proceedings have produced a body of case law that developed independently across eight separate forums, including the EPO, yet converged on the same conclusion.

2.The Legal Basis of the Common Rationale

The common rationale underlying this line of cases, spanning more than seven years, rests on two main arguments.¹⁶ First, courts and patent offices have treated the matter not as a policy question but as one of interpreting existing text, concluding that terms such as "inventor," "deviser," and "Erfinder" can, within the systematics of the legislation, refer only to a subject possessing legal personality. Second, the argument concerns the incentive-reward logic of the patent system: because a machine neither needs nor is capable of responding to an economic incentive, applying the system to a machine renders the means-end relationship meaningless. Both the British and German courts specifically emphasized that this is a limit of interpretation, and that the broader policy question of patentability remains within the authority of the legislature.

¹⁰ Japan Patent Office, Status Report 2026, 23 Marc 2026.

¹¹ Companies and Intellectual Property Commission (CIPC, Güney Afrika), Patent No. 2021/03242 (DABUS), 24 Temmuz 2021

¹² February 26, 2025, the Patent Appel Board, Canadian Patent Application No. 3,137,161 ;apan Intellectual Property High Court decision dated January 30, 2025 (DABUS); finalized by the Japan Supreme Court's March 4, 2026 dismissal of the appeal.

¹³ Indian Patent Office, Application No. 202017019068 (DABUS), 15 april 2026.

¹⁴ Patents Act 1994 (Cap. 221) (Singapur); Intellectual Property Office of Singapore (IPOS), Supplemental Guidance for the Examination of AI-related Patent Applications.

¹⁵ Emotional Perception AI Limited v. Comptroller-General of Patents, Designs and Trade Marks [2026] UKSC

¹⁶ 3, 11 Şubat 2026; IPOS, Public Consultation on the Relevance of Emotional Perception AI Limited v. Comptroller-General [2026] UKSC 3 to Singapore Patent Practice, 17 Nisan–14 Mayıs 2026.

3.Today's Real Problem: Human–AI Collaborative Inventions

The DABUS cases concern a hypothetical scenario in which AI generates an invention entirely on its own. Today's real practical problem is different: when a researcher uses a generative AI model to discover a new molecular target, identify a material combination, or optimize an engineering design, how is that person's share of inventorship to be determined?

In its February 2024 guidance,¹⁷ the USPTO adapted the Pannu factors,¹⁸ on joint inventorship to the singular human–AI relationship, which drew criticism for the resulting uncertainty over what constitutes a "significant contribution." In November 2025, the USPTO withdrew this guidance entirely, stating that the Pannu factors apply only to disputes among natural persons, and adopted instead the traditional "conception" test, applied identically whether or not AI is used.¹⁹ Under the new guidance, AI is characterized as a tool, comparable to laboratory equipment.

The fact that the same agency adopted two opposite approaches within four years is questionable from the standpoint of predictability, and has for a time destabilized patent strategy in AI-intensive sectors such as pharmaceuticals and materials science.²⁰ The new guidance also leaves open how the share of inventorship is to be determined in borderline cases where AI merely points to a target; the real uncertainty lies in applying the standard to concrete facts, and it will take time for settled case law to emerge.

4.Assessment from the Perspective of Turkish Law

Industrial Property Law No. 6769²¹ systematically presumes that the inventor is a natural person. TÜRKPATENT has not to date encountered a DABUS-type application, and its activity in this area has been limited to membership in the EPO Artificial Intelligence Working Group and an informational webinar held in June 2026.²² Without

¹⁷ USPTO, "Inventorship Guidance for AI-Assisted Inventions", Federal Register, Vol. 89, No. 30, 13 Şubat 2024.

¹⁸ Pannu v. Iolab Corp., 155 F.3d 1344 (Fed. Cir. 1998).

¹⁹ USPTO, "Revised Inventorship Guidance for AI-Assisted Inventions", Federal Register, Docket No. PTO-P-2025-0014, 28 Kasım 2025.

²⁰ Aboy, M. / Liddell, K., "Revised USPTO guidance on inventorship for AI-assisted inventions: a pro-innovation pivot away from Pannu factors", Journal of Intellectual Property Law & Practice, 2026.

²¹ Industrial Property Law No. 6769, O.G. 10/1/2017, No: 29944

²² TÜRKPATENT, "Cahit Arf'tan DABUS'a: Yapay Zekâ ve Fikrî Mülkiyetin Yolculuğu" Webinarı, 16 June 2026.

any legislative amendment, Turkish law largely aligns with both the interpretive approach of the DABUS cases and the USPTO's "tool" approach.

However, the Law contains no explicit criterion for determining the share of inventorship in human–AI collaborative inventions. The proposed approach is a synthesis of the German "determinative human influence" test and the USPTO's "conception" test.

TÜRKPATENT should develop administrative guidance that does not treat the use of AI as a separate ground for rejection, but that may require applicants to submit documentation demonstrating concrete human contribution, such as problem definition, verification of results, and technical implementation. In addition, the possibility that AI's literature-review capacity may indirectly raise the standard of the "person skilled in the art" and the threshold for inventive step deserves separate examination in the medium term.

Conclusion

The DABUS cases have shown that the principle "an inventor must be a natural person" is supported by a strong consensus reached independently, yet identically, across eight jurisdictions. This consensus, however, does not answer the real question of the AI era: where do the boundaries of inventorship begin and end in inventions where a human uses AI as a tool? The USPTO's 2024–2025 shift in guidance shows that this question cannot be reduced to a single abstract standard, and is instead a fact-specific area that will be shaped over time through case law. While the existing framework in Turkish law is capable of addressing DABUS-type claims, developing administrative guidance on human–AI collaboration would increase legal predictability for both applicants and TÜRKPATENT examiners.

References

WIPO Standing Committee on the Law of Patents, "Artificial Intelligence and Inventorship," SCP/35/7, September 13, 2023.

EPO Legal Board of Appeal, J 8/20 and J 9/20 (Designation of Inventor/DABUS), Decision, December 21, 2021.

Case C-250/25, *Like Company v. Google*, CJEU Grand Chamber.

Thaler v. Vidal, 43 F.4th 1207 (Fed. Cir. 2022), cert. denied, 143 S. Ct. 1783 (2023).

Thaler v. Perlmutter, U.S. Supreme Court, cert. denied, No. 25-449, March 2, 2026.

Thaler v. Comptroller-General of Patents, Designs and Trade Marks [2023] UKSC 49.

Bundesgerichtshof [German Federal Court of Justice], June 11, 2024, X ZB 5/22 (DABUS).

Zaisan Suishin Keikaku [Intellectual Property Strategic Program] 2025, Cabinet Office of Japan.

Japan Patent Office, Status Report 2026, March 23, 2026.

Companies and Intellectual Property Commission (CIPC, South Africa), Patent No. 2021/03242 (DABUS), July 24, 2021.

Commissioner of Patents (Canada), DABUS decision, 2025.

Indian Patent Office, Application No. 202017019068 (DABUS), Decision, April 15, 2026.

Patents Act 1994 (Cap. 221) (Singapore); Intellectual Property Office of Singapore (IPOS), Supplementary Guidelines on the Examination of AI-Related Patent Applications.

Intellectual Property Office of Singapore (IPOS), Public Consultation on the Relevance of Emotional Perception AI Limited v. Comptroller-General [2026] UKSC 3 to Singapore Patent Practice, April 17–May 14, 2026; Emotional Perception AI Limited v. Comptroller-General of Patents, Designs and Trade Marks [2026] UKSC 3, February 11, 2026.

USPTO, "Inventorship Guidance for AI-Assisted Inventions," Federal Register, Vol. 89, No. 30, February 13, 2024.

Pannu v. Iolab Corp., 155 F.3d 1344 (Fed. Cir. 1998).

Aboy, M. / Liddell, K., "Revised USPTO guidance on inventorship for AI-assisted inventions: a pro-innovation pivot away from Pannu factors," Journal of Intellectual Property Law & Practice, 2026.

USPTO, "Revised Inventorship Guidance for AI-Assisted Inventions," Federal Register, Docket No. PTO-P-2025-0014, November 28, 2025.

Türk Patent ve Marka Kurumu (TÜRKPATENT), "Cahit Arf'tan DABUS'a: Yapay Zekâ ve Fikri Mülkiyetin Yolculuğu" Webinarı, 16 Haziran 2026.

Withdrawal, Restitution, and Human Intervention in the Face of Smart Contract Immutability

Bukre Seyma Donder¹

Abstract

Smart contracts are considered significant because of their capacity for automated performance, immutability, and reduced reliance on human intermediaries. Although these features may enhance legal certainty and transactional efficiency, they also raise important questions from the perspective of private law, which recognizes mechanisms such as withdrawal, termination, invalidity, and restitution both before and after contractual performance. Blockchain technology may render a completed transaction technically irreversible. Even where the legal basis justifying the preservation of the transaction's effects has disappeared, the transaction may continue to exist technically on the blockchain.

This study examines the relationship between blockchain immutability and the legal mechanisms necessary for withdrawal, restitution, and human intervention. Its central argument is that blockchain immutability, one of the concepts most likely to create confusion, should not be understood as absolute legal irreversibility.

Although blockchain records cannot, as a rule, be altered, the legal system may restore the parties' legal positions through reverse transactions, restitutionary claims based on unjust enrichment, or judicial intervention. The principal issue, therefore, is not the deletion of the original transaction. Rather, it is the design and implementation of smart contract systems capable of accommodating subsequent legal intervention.

The article distinguishes between technical reversal and legal restitution. It also examines mechanisms such as delayed performance, withdrawal functions, reverse transactions, escrow

¹ Phd in Law, Istanbul Commerce University, bseyma.donder@istanbulticaret.edu.tr, ORCID: 0000-0003-4680-8833

arrangements, pause mechanisms, upgradeability, and human or judicial intervention. Legally sustainable smart contracts should not seek to eliminate human intervention entirely. On the contrary, while ordinary performance processes may be automated, controlled intervention mechanisms should be preserved, as in conventional contracts, for situations in which the law requires correction, withdrawal, or restitution.

Keywords: Smart contracts, blockchain, immutability, withdrawal, restitution, reverse transaction, human intervention.

1. Introduction

One of the principal innovations introduced by smart contracts is the automatic performance of contractual obligations once predetermined conditions have been satisfied. Smart contracts can automatically initiate payments, transfer digital assets, or trigger further transactions between the parties². In this context, contractual performance is carried out through blockchain technology, which makes recorded transactions resistant to subsequent alteration and misuse.

This feature, however, gives rise to certain difficulties that do not ordinarily arise in conventional private law contracts. The satisfaction of a predetermined condition does not necessarily mean that contractual performance is legally final. A contract may be invalid, voidable, terminable, or subject to a right of withdrawal. Its performance may also lack a valid legal basis. Nevertheless, the smart contract may still produce its programmed effects, leaving the parties to pursue restitution or compensation after performance.

The difficulty arises because performance occurs automatically through a blockchain transaction that ordinarily cannot be altered or deleted. Once cryptocurrency, a digital asset, or another blockchain-based value has been transferred, the situation differs from that arising under a traditional contract because the original transaction generally cannot be erased or rewritten³.

² Eliza Mik, "Smart Contracts: Terminology, Technical Limitations and Real World Complexity" (2017) 9(2) *Law, Innovation and Technology*, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3038406, p. 3, accessed 25 July 2026.

³ Bükre Şeyma Dönder, "Blokzincir Tabanlı Sözleşmelerin Fikrî Mülkiyet Hukukuna Etkisi: Dönüşüm ve Öneriler," *Akdeniz Üniversitesi Hukuk Fakültesi Dergisi* 15, no. 1 (2025), p. 652

A judicial determination that a smart contract is invalid or unenforceable does not technically reverse a transaction that has already been executed and recorded on the blockchain⁴.

In considering finality in smart contracts, a distinction must therefore be drawn between technical finality and legal finality. In traditional contracts, finality is generally assessed from a legal perspective. Smart contracts, however, also have a technical dimension. Technical finality concerns the immutability of the blockchain record, whereas legal finality concerns whether the recipient is legally entitled to retain the transferred asset or benefit.

Even where the economic consequences of a transaction are subsequently reversed through another transaction, the original smart-contract transaction ordinarily remains permanently recorded on the blockchain. There is therefore a clear distinction between technical finality and legal finality.

The central question is not whether the law can erase an “immutable” transaction. Rather, it is whether a subsequent legal remedy can restore the position required by law. More specifically, the issue is whether the performance of a smart contract can be suspended, reversed, or otherwise remedied where legal requirements so demand.

The immutability of a smart contract does not provide immunity to a party who has received a benefit without being legally entitled to retain it. Courts may intervene, and the recipient may be required to return the benefit obtained under the contract.

2. Immutability and Legal Irreversibility

The principle of blockchain immutability preserves the integrity of the transaction history from the moment a transaction is recorded. For example, if one party transfers ten digital units to another through a smart contract and the recipient is subsequently required to return them, the original transaction may remain visible on the blockchain. Restitution may then be implemented through a second transaction transferring the same amount back to the original party.

Technical reversal therefore does not ordinarily involve deleting or altering the original transaction⁵. Instead, a new transaction is created to correct or reverse its legal

⁴ Kevin Werbach and Nicolas Cornell, “Contracts Ex Machina” (2017) 67 *Duke Law Journal* 313 – 382, <https://scholarship.law.duke.edu/dlj/vol67/iss2/2>, p. 333, accessed 22 July 2026.

⁵ European Law Institute, *ELI Principles on Blockchain Technology, Smart Contracts and Consumer Protection*, p. 14-15, https://www.europeanlawinstitute.eu/fileadmin/user_upload/p_eli/Publications/ELI_Principles

and economic consequences, in a manner broadly comparable to restitution following the performance of a traditional contract.

A similar distinction exists in other areas of private law. In conventional contracts, where a contract is terminated or its legal basis disappears, the duty to perform may cease⁶. In the case of a smart contract, however, the programmed transaction may still be executed on the blockchain even after the contract has been terminated or its legal basis has ceased to exist.

The law distinguishes between the performance of an obligation and the recipient's legal entitlement to retain what has been received. Blockchain code technically determines what will occur when a predetermined condition is fulfilled. It does not, however, determine whether the resulting transfer is legally valid or whether the recipient is entitled to retain the benefit. It merely executes the programmed transaction.

Consequently, the legal consequences of the underlying transaction remain governed by the principles applicable to traditional contracts, even after automated performance has occurred.

3. Withdrawal and Automatic Performance

There is an inherent tension between blockchain-based automation and the rights and institutions recognized under traditional private law. The exercise of a right of withdrawal, particularly by a consumer, may allow a contract to be terminated through a unilateral declaration made within a prescribed period.

Automatic performance following the satisfaction of a programmed condition may undermine the practical effectiveness of this right. A smart contract may automatically release payment or transfer an asset to the other party. In other cases, it may permanently activate a digital service. Although the right of withdrawal may continue to exist legally, exercising it effectively may become more difficult after automated performance⁷.

The central issue is therefore not whether the right of withdrawal disappears, but whether the technical design of the smart contract adequately reflects and accommodates the applicable legal framework.

[on Blockchain Technology Smart Contracts and Consumer Protection.pdf](#) accessed 14 July 2026.

⁶ Christian von Bar, Eric Clive and Hans Schulte-Nölke (eds), *Principles, Definitions and Model Rules of European Private Law: Draft Common Frame of Reference*, 2776, 3668.

⁷ Mik, p 14-16; Alexander Savelyev, "Contract Law 2.0: 'Smart' Contracts as the Beginning of the End of Classic Contract Law" (2017) 26 *Information & Communications Technology Law*, p. 19.

The European Law Institute's *Blockchain Technology, Smart Contracts and Consumer Protection Principles* also recognize this problem. These principles support the establishment of technical mechanisms enabling the contracting party to initiate and exercise withdrawal procedures. Where reversal is impossible because of the nature of the performance, the right may instead give rise to restitution or compensation⁸.

Three principal models may be considered. First, the transaction may be delayed until the expiry of the withdrawal period, with the relevant asset or payment being held in escrow during that period. Second, where the original transaction has already been completed and the right of withdrawal is subsequently exercised, restitution may be implemented through a reverse transaction. Third, a hybrid model may be adopted under which some contractual effects take place immediately while others remain conditional until the withdrawal period expires.

The appropriate model will depend on the nature of the contract and the form of performance involved.

4. Restitution After Automated Performance

Restitution may require the return of benefits obtained under a contract. In the context of smart contracts, the underlying transaction may be invalid, voidable, terminated, or otherwise legally reversible even though the programmed transaction has already been executed.

Performance may also have been triggered by inaccurate data, an erroneous assessment, or circumstances that the parties did not anticipate. Nevertheless, the smart contract may execute automatically because the code is not technically capable of identifying or responding to the relevant legal defect.

Automated performance does not guarantee legally valid performance. The blockchain code merely determines whether the predefined conditions programmed into the algorithm have been satisfied. It may be unable to identify legally relevant circumstances such as incapacity, mistake, fraud, duress, illegality, unfair contract terms, the exercise of a right of withdrawal, or invalidity subsequently established by a court.

Such matters require an assessment of facts arising in the real world and cannot always be reduced to predetermined technical conditions. Under the logic of a smart contract, performance occurs automatically once the programmed condition is met. Whether that performance is legally justified is a separate question.

⁸ European Law Institute, p. 18.

Accordingly, the automated and immutable nature of a smart contract should not create a shield of immunity from the law of restitution. Where a smart contract produces a result that the recipient is not legally entitled to retain, the technical completion of the transaction does not prevent restitution.

The principal difficulties arise at the enforcement stage. If the recipient refuses to comply with an obligation to return the benefit obtained through the smart contract, the other party may need to bring proceedings before a court or arbitral tribunal. Pseudonymity, cross-border transfers, the onward transfer of digital assets, and the loss of control over private keys may complicate enforcement⁹. These practical difficulties do not, however, extinguish the underlying legal obligations.

5. Human Intervention: Ex Ante and Ex Post Mechanisms

Smart contracts are often presented as mechanisms capable of reducing dependence on intermediaries and human decision-makers while increasing transactional security and speed. From a legal perspective, however, it is neither possible nor desirable to exclude human intervention completely.

Contract law contains concepts that cannot always be reduced to binary or predetermined conditions¹⁰. Good faith, reasonableness, mistake, fraud, unfairness, and the contextual assessment of a particular case demonstrate why the human element cannot be entirely eliminated.

The availability of human intervention does not mean that a smart contract is defective, nor does it necessarily indicate that automation has failed. Properly designed intervention mechanisms may instead ensure that automation operates consistently with legal requirements.

The essential distinction is between arbitrary intervention and intervention that is structured, authorized, and legally justified. Human intervention in a smart contract may take several forms, including the exercise of contractual rights by the parties, action by an escrow agent or authorized administrator, multisignature approval, arbitral intervention through an oracle-based mechanism, emergency suspension following a technical failure, or enforcement through a judicial decision.

These mechanisms do not permit the arbitrary rewriting of blockchain history. Their purpose is to provide an appropriate response to legally recognized circumstances such

⁹ UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (2019), p. 8.

¹⁰ Mik, p. 20.

as withdrawal, fraud, invalidity, mistake, technical failure, or a judicial or arbitral decision.

Ex ante intervention mechanisms operate before or during automated performance. They may include delayed execution, escrow arrangements, multisignature approval requirements, and pre-programmed pause functions¹¹. Ex post intervention mechanisms operate after performance and may include reverse transactions, restitution, compensation, arbitral remedies, and judicial enforcement.

6. Reverse Transactions and Their Limits

Reverse transactions provide an important response to concerns arising from blockchain immutability. They make it possible to reconcile the technical immutability of the blockchain with traditional private law remedies¹².

Under this model, the original transfer produced by the automatically executed transaction is not deleted or altered. Instead, a new transaction is created to restore, as far as possible, the parties' previous economic positions.

This mechanism is particularly suitable for fungible digital assets. Nevertheless, its effectiveness may be limited where the asset has been transferred to a third party, substantially changed in value, consumed, or used within another protocol. Restitution may also become difficult or impossible where the recipient no longer controls the relevant private key or where the asset cannot be recovered.

In such circumstances, monetary restitution or compensation may provide a more appropriate remedy. The proper legal response must therefore be determined according to the circumstances of each individual case.

Relevant considerations include the nature of the asset, the position and rights of third parties, changes in value, the possibility of recovery, and the practical enforceability of the remedy.

7. Legally Responsive Smart Contracts

The objective should not be to choose between absolute smart-contract immutability and unlimited human control. A more appropriate goal is to develop a model of legally responsive immutability that preserves transactional integrity while permitting legally justified intervention when exceptional circumstances arise.

¹¹ ELI Principles, p. 34, 35.

¹² Bükre Şeyma Dönder, "Karşılaştırmalı Hukukta Akıllı Sözleşmeler", (Doktora Tezi, İstanbul Ticaret Üniversitesi, Lisansüstü Eğitim Enstitüsü, 2026), p. 234.

A legally responsive smart contract should distinguish between ordinary performance and exceptional events recognized by law. It should automate routine contractual obligations while preventing arbitrary intervention.

The code should, where possible, specify when a right of withdrawal may be exercised and when performance may be delayed, suspended, or reversed. Mechanisms addressing fraud, mistake, technical failure, disputes, and emergency suspension should also be incorporated where appropriate.

Where the code cannot technically reverse a transaction, external legal remedies should be anticipated at the design stage. These may include restitutionary obligations, compensation, arbitration, judicial enforcement, and procedures for initiating reverse transactions¹³.

This approach prevents the parties from treating code as legally infallible while preserving the principal benefits of automation. The code may govern ordinary performance, but legal institutions must remain available to address exceptional circumstances that cannot be adequately resolved through automation alone.

8. Conclusion

The immutability of smart contracts creates genuine legal difficulties when compared with traditional contracts. It does not, however, prevent judicial intervention or the exercise of contractual rights that allow the parties to terminate, withdraw from, or reverse the legal consequences of the contract.

The law does not need to delete the blockchain transaction history in order to remedy an unlawful or unfair result. Once the conditions programmed into the blockchain code have been satisfied, the system may automatically execute the transaction. Whether the resulting performance is legally valid and whether the recipient is entitled to retain the benefit remain separate questions.

It would therefore be misleading to assume that legal remedies become unavailable merely because an unfair result has arisen before or after automated performance. Three principal conclusions may be drawn.

First, the immutability of the blockchain record should not be understood as the absolute legal irreversibility of the contractual relationship. The fact that the original record cannot ordinarily be altered protects the integrity of the transaction history, but it

¹³ Werbach & Cornell, p. 345, 346.

does not prevent the legal consequences of that transaction from being reversed or corrected.

Second, rights of withdrawal, restitution, reverse transactions, monetary compensation, and other remedies can address problems arising after automated performance. The appropriate remedy will depend on the nature of the transaction, the asset concerned, the position of third parties, and the practical possibility of recovery.

Third, human and judicial intervention remains both necessary and legitimate where the law requires interpretation, correction, or enforcement. Automation should ordinarily govern routine performance, whereas exceptional circumstances should remain subject to human, arbitral, or judicial review.

The appropriate model is therefore one of controlled reversibility and legally responsive immutability. The legal system retains the power to correct unlawful or unfair outcomes while protecting the integrity of the blockchain transaction history.

Automation should not govern every stage of the contractual relationship without the possibility of intervention. It should manage ordinary performance efficiently, while human intervention remains available in exceptional cases, both through the actions of the parties and through judicial or arbitral mechanisms.

Immutability should protect the integrity of the blockchain. It should not create a shield of immunity against legal claims or remedies.

References

- Kevin Werbach and Nicolas Cornell, "Contracts Ex Machina," *Duke Law Journal* 67 (2017): 313–382.
- European Law Institute, *ELI Principles on Blockchain Technology, Smart Contracts and Consumer Protection* (2023).
- Eliza Mik, "Smart Contracts: Terminology, Technical Limitations and Real World Complexity" (2017) 9(2) *Law, Innovation and Technology*, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3038406, accessed 25 July 2026.
- UK Jurisdiction Taskforce, *Legal Statement on Cryptoassets and Smart Contracts* (2019)
- Alexander Savelyev, "Contract Law 2.0: 'Smart' Contracts as the Beginning of the End of Classic Contract Law" (2017) 26 *Information & Communications Technology Law*
- Christian von Bar, Eric Clive and Hans Schulte-Nölke (eds), *Principles, Definitions and Model Rules of European Private Law: Draft Common Frame of Reference*.
- Bükre Şeyma Dönder, "Blokzincir Tabanlı Sözleşmelerin Fikrî Mülkiyet Hukukuna Etkisi: Dönüşüm ve Öneriler," *Akdeniz Üniversitesi Hukuk Fakültesi Dergisi* 15, no. 1 (2025).

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Bükre Şeyma Dönder, “Karşılaştırmalı Hukukta Akıllı Sözleşmeler”, (Doktora Tezi, İstanbul Ticaret Üniversitesi, Lisansüstü Eğitim Enstitüsü, 2026).

Online Dispute Resolution and the Right to a Fair Trial: Balancing Efficiency and Procedural Guarantees in Digital Justice

Mükerrem Onur Basar¹

Abstract

The digital transformation of justice systems has advanced the adoption of Online Dispute Resolution (ODR) as an efficient mechanism for resolving disputes through electronic platforms. Initially developed as an extension of alternative dispute resolution, ODR has evolved into an increasingly important element of modern judicial systems, particularly following the pandemic. At the same time digital technologies have substantially improved access to justice, reduced costs, and improved procedural efficiency, they have also raised material concerns regarding the protection of fundamental procedural rights.

This presentation examines the relationship between ODR and the right to a fair trial, with particular reference to Article 6 of the European Convention on Human Rights. It explores whether the procedural guarantees that constitute the essence of a fair trial—including access to justice, equality of arms, adversarial proceedings, public hearings, judicial impartiality, and the effective participation of the parties—can be competently safeguarded within digital dispute resolution mechanisms.

This presentation delves into the emerging legal challenges of online justice, specifically examining the elements of Article 6 of the European Convention on Human Rights, and the jurisprudence of the European Court of Human Rights.

Keywords: Fair Trial; Online Dispute Resolution (ODR); Article 6 ECHR; European Court of Human Rights; Digital Justice

¹ Phd in Law, Istanbul Sabahattin Zaim University Faculty of Law, mukerrem.basar@izu.edu.tr, ORCID: 0000-0002-5002-6132

1. Introduction

The digitalization of judicial services has transformed dispute resolution mechanisms across jurisdictions, making Online Dispute Resolution (ODR) an increasingly significant element of civil justice systems. Originally established as an extension of alternative dispute resolution, ODR has emerged as a refined mechanism capable of resolving disputes through digital platforms while significantly reducing litigation costs and procedural delays. Following the COVID-19 pandemic, many jurisdictions accelerated the digital transformation of courts and dispute resolution procedures, thereby intensifying scholarly and judicial discussions regarding the compatibility of digital justice with the procedural guarantees protected under Article 6 of the European Convention on Human Rights (ECHR).²

2. Digital Justice and Article 6 of European Convention on Human Rights

This presentation examines whether ODR mechanisms can satisfy the requirements of the right to a fair trial under Article 6 ECHR. Particular attention is assigned to procedural guarantees developed by the European Court of Human Rights (ECtHR), including effective access to a court, equality of arms, adversarial proceedings, judicial independence and impartiality, reasoned decisions, publicity of proceedings, and the right to be heard.³ Rather than treating these guarantees as inflexible procedural formalities, the ECtHR has consistently interpreted Article 6 as a practical and effective instrument requiring procedural fairness accustomed to the circumstances of each case.

From this perspective, digital dispute resolution presents both significant opportunities and substantial legal challenges. Digital procedures considerably improve access to justice by reducing geographical limits, procedural costs, and delays, particularly in low-value consumer disputes where traditional litigation is often economically irrational.⁴ Nevertheless, technological innovation concurrently raises concerns regarding cybersecurity and the protection of personal data. These challenges

² Anne Kamphorst, "The Right to a Fair Trial in Online Consumer Dispute Resolution," *European Journal of Consumer and Market Law* 8, no. 5 (2019): 175–189.

³ Convention for the Protection of Human Rights and Fundamental Freedoms (European Convention on Human Rights), art. 6.

⁴ *Airey v. Ireland*, no. 6289/73 (ECtHR, 9 October 1979), §§ 24–28.

become particularly significant where digital procedures may impair the parties' ability to participate effectively in proceedings or undermine the principle of equality of arms.⁵

Employing comparative and normative legal analysis, we argue that ODR should not be regarded as an exception to the guarantees of a fair trial but rather as a procedural model that requires adapting those guarantees to the realities of digital justice. Accordingly, the legitimacy of ODR depends not solely on technological efficiency but on preserving the substantive values underlying procedural fairness through effective judicial oversight, accessible digital infrastructure, and meaningful opportunities for party participation. Ultimately, the future development of digital justice requires balancing innovation with the enduring principles of the rule of law and effective judicial protection established under European human rights jurisprudence. In light of the jurisprudence of the European Court of Human Rights, ODR should not be regarded as an alternative that diminishes the guarantees of a fair trial, but rather as a procedural model that must faithfully reflect the fundamental principles embodied in Article 6 of the European Convention on Human Rights. The Court's case law consistently emphasizes that the right of access to a court, equality of arms, effective participation, reasoned decisions, and procedural fairness must remain practical and effective rather than theoretical, illusory, and misleading. Accordingly, the legitimacy of ODR depends not solely on its capacity to enhance efficiency, reduce costs, or accelerate dispute resolution, but on its ability to preserve these essential procedural safeguards within a digital environment. As digital justice continues to evolve, the challenge for legislators, courts, and ODR providers will be to ensure that technological innovation strengthens, rather than compromises, the fundamental values of judicial protection and the rule of law established by the European Court of Human Rights.

From the perspective of the ECtHR, the integration of digital technologies into judicial proceedings is not, in itself, incompatible with the right to a fair trial guaranteed under Article 6 of the European Convention on Human Rights. Rather than focusing on the technological medium through which justice is administered, the Court adopts a functional and context-sensitive approach, assessing whether the proceedings, viewed as a whole, preserve the essential guarantees of procedural fairness. Accordingly, the decisive issue is not whether a hearing takes place online or in person, but whether the digital format enables the parties to exercise their procedural rights effectively and without disadvantage. In short, digital justice is compatible with Article 6 only if it preserves those guarantees.

4. Conclusion

⁵ *Dombo Beheer B.V. v. the Netherlands*, no. 14448/88 (ECtHR, 27 October 1993), § 33. *Ankerl v. Switzerland*, no. 17748/91 (ECtHR, 23 October 1996), §§ 37–40.

Digital justice systems must ensure effective access to the courts, equality of arms, adversarial proceedings, and the meaningful participation of all parties throughout the process. Participants must be able to communicate confidentially with their legal representatives, present evidence, examine witnesses where appropriate, challenge the opposing party's evidence, and make submissions under conditions that do not place them at a procedural disadvantage. Moreover, the technical infrastructure supporting online proceedings must be sufficiently reliable and secure to prevent interruptions, unauthorized access, or technical failures that could impair the fairness of the proceedings. Particular attention should also be given to digital accessibility, ensuring that individuals who lack adequate technological resources or digital literacy are not effectively excluded from the administration of justice. These requirements define the limits of acceptable digital justice. Ultimately, the future of ODR will depend not merely on technological advancement, but on its continued ability to uphold the fundamental procedural guarantees of a fair trial as developed in the jurisprudence of the ECtHR.

References

- Airey v. Ireland. No. 6289/73. European Court of Human Rights, 9 October 1979.
- Ankerl v. Switzerland. No. 17748/91. European Court of Human Rights, 23 October 1996.
- Convention for the Protection of Human Rights and Fundamental Freedoms (European Convention on Human Rights).
- Dombo Beheer B.V. v. the Netherlands. No. 14448/88. European Court of Human Rights, 27 October 1993.
- Kamphorst, Anne. "The Right to a Fair Trial in Online Consumer Dispute Resolution." *European Journal of Consumer and Market Law* 8, no. 5 (2019): 175–189.

Occupational Accidents and the Transformation of Social Security Law in the Digital Workplace: The Case of Kazakhstan

Kamshat Baiterekova¹, Bota Amirova²

Abstract

The article examines current issues of legal regulation of occupational accidents and the transformation of social security legislation in the context of the digitalization of labour relations in the Republic of Kazakhstan. The study focuses on analysing the impact of the digital economy, remote employment, platform work, and artificial intelligence technologies on the occupational safety and social security systems. Particular attention is paid to the problems of the legal classification of occupational accidents in the digital workplace, determining the legal status of platform workers, as well as the use of electronic evidence in the investigation of occupational accidents.

Based on the research conducted, the article proposes key areas for improving the labour and social security legislation of the Republic of Kazakhstan, taking into account current trends in the development of the digital economy.

Measures are proposed to improve the legal regulation of remote and platform employment, as well as to strengthen the social protection of workers. It is concluded that comprehensive modernization of national legislation will contribute to enhancing the effectiveness of the occupational safety system, ensuring social justice, and strengthening legal mechanisms for the protection of workers in the context of the digital transformation of the labour market.

¹ PhD Student, Faculty of Law, L.N. Gumilyov Eurasian National University, Astana, Republic of Kazakhstan, k.baiterekova@mail.ru, ORCID: 0009-0003-0753-3651

² PhD Student, Faculty of Law, L.N. Gumilyov Eurasian National University, Astana, Republic of Kazakhstan, bota8139@gmail.com ORCID: 0000-0002-2969-1947

Keywords: occupational accidents; social security; digital economy; digital workplace; platform employment; remote work; occupational safety; Republic of Kazakhstan.

1. Introduction

The Constitution of the Republic of Kazakhstan, adopted at the republican referendum on 15 March 2026 and entering into force on 1 July 2026, established the constitutional foundations for ensuring human rights, the rule of law, and the development of a social state.

The Preamble to the Constitution proclaims the building of a Just Kazakhstan, ensuring the rule of law and supremacy of legislation, as well as strict observance of human rights and freedoms as fundamental values of the state [1].

The rapid development of digital technologies has significantly transformed the content and forms of labour relations. The spread of remote employment, platform work, artificial intelligence, and digital platforms, while increasing labour productivity, also creates new requirements for occupational safety and social security systems [2, p. 4].

In Kazakhstan, digitalization is one of the priority areas of state policy. The introduction of electronic employment contracts, the digitalization of employment records, and the transition of public services to electronic formats have contributed to the modernization of the labour sphere. At the same time, new forms of labour relations have raised important issues concerning the identification of occupational accidents, ensuring occupational safety, and improving the social insurance system [3, p. 105].

Although the existing labour legislation is primarily based on the traditional model of labour relations, it does not fully cover the specific features of legal relationships arising in the digital work environment. In particular, additional legal regulation is required with regard to the classification of occupational injuries occurring during remote work, the determination of the legal status of platform workers, and the procedures for their participation in the social insurance system.

The purpose of this study is to provide a comprehensive analysis of the legal regulation of occupational accidents and the transformation of social security legislation in the context of the digitalization of labour relations in the Republic of Kazakhstan, as well as to develop scientifically grounded proposals for its improvement.

The objectives of the study are:

to identify the legal characteristics of the digital workplace;

to analyse the problems of legal regulation of occupational accidents;

- to assess the current state of the social security system;
- to examine international experience;
- to develop proposals for improving the legislation of the Republic of Kazakhstan.

1. Digital Workplace: Concept and Legal Features

In the context of the digital economy, work activities are increasingly carried out through the use of information and communication technologies, digital platforms, and the Internet. In this regard, the concept of the “digital workplace” has become widely used in legal scholarship [4, p. 91].

A digital workplace is a work environment in which the performance of job functions, the organization of work processes, and the monitoring of work results are carried out through the use of digital technologies. This model increases employment flexibility; however, at the same time, it complicates the provision of occupational safety and the implementation of workers’ social guarantees [5].

In the Republic of Kazakhstan, the digitalization of labour relations is being implemented through the introduction of electronic employment contracts, the digitalization of employment records, and the development of state information systems. At the same time, the legal status of platform workers has not yet been fully established in legislation, which creates challenges in the areas of occupational safety and social security.

An important feature of the digital work environment is the use of algorithmic management and artificial intelligence technologies. Automated task allocation and digital monitoring increase the efficiency of work organization; however, they also create risks of violations of labour rights, personal data protection, and workers’ privacy.

The international standards of the International Labour Organization (ILO) and the European Union provide for equal social protection of workers regardless of their form of employment, as well as the improvement of the legal regulation of platform work and algorithmic management [6].

Thus, the development of the digital workplace requires the adaptation of the labour legislation of the Republic of Kazakhstan to the current conditions of the digital economy, the legislative definition of the legal status of platform workers, and the improvement of mechanisms for ensuring occupational safety.

2. Legal Issues of Occupational Accidents in the Digital Work Environment

The digitalization of labour relations necessitates the improvement of the legal regulation of occupational accidents. While, under traditional forms of work organization, establishing the fact that an occupational injury occurred in the performance of work

duties generally does not present significant difficulties, this task becomes considerably more complex in the context of remote and platform-based employment. The absence of clearly defined workplace boundaries and flexible working hours creates conditions for new types of legal disputes.

Under the Labour Code of the Republic of Kazakhstan, an occupational accident is recognized as harm caused to the health of an employee in the performance of their work duties. However, in the context of remote work, it is not always possible to reliably establish the work-related nature of an incident. For example, when an employee is injured while performing work duties at home, the question arises as to whether such an incident should be considered an occupational risk or a domestic injury. The current legislation does not provide clear criteria for resolving such situations.

The expansion of platform-based employment also creates a number of legal challenges. Taxi drivers, couriers, and other individuals providing services through digital platforms often operate not under employment contracts but within the framework of civil-law relationships. As a result, questions arise regarding their entitlement to social insurance benefits in the event of an occupational injury, as well as the determination of the liability of the employer or the digital platform operator.

Furthermore, the nature of occupational risks itself is changing in the digital economy. While physical factors represented the primary hazards in traditional production sectors, information overload, the need to remain constantly online, psycho-emotional stress, and the blurring of boundaries between working and personal time are becoming increasingly significant. These circumstances create new types of occupational risks that require appropriate legal regulation.

At the same time, the importance of electronic evidence in the investigation of occupational accidents is increasing. Working-time records, geolocation data, electronic logs of digital platforms, records from information systems, and other digital documents may serve as important evidence in establishing the circumstances of an incident. In this regard, it is necessary to establish the legal status of electronic evidence in the legislation of the Republic of Kazakhstan and to improve the procedures for its use in the investigation of occupational accidents.

The International Labour Organization recommends adhering to the principle of universal occupational safety and social protection regardless of the form of employment. In turn, the European Union Directive on platform work provides for strengthening the protection of platform workers' rights, ensuring transparency in algorithmic management, and increasing the level of social protection for persons engaged through digital platforms. This experience may be taken into account in the further improvement of the legislation of the Republic of Kazakhstan.

3. Transformation of the Social Security System in the Republic of Kazakhstan

The development of digital technologies has had a significant impact on the social security system of the Republic of Kazakhstan, contributing to improved access to public services and greater efficiency in the implementation of citizens' social rights.

The legal framework for the social protection of workers is provided by the Social Code of the Republic of Kazakhstan, which regulates the system of mandatory social insurance and the provision of social benefits, and the Labour Code of the Republic of Kazakhstan, which establishes the procedures for investigating occupational accidents and determines the liability of employers.

The digitalization of public services, including the introduction of e-government (eGov), electronic employment contracts, and the integration of state information systems, has enabled the automation of processes for assigning social benefits and has improved access to social services.

At the same time, the development of the digital labour market requires further improvement of the mandatory social insurance system. The legal status of platform workers remains insufficiently regulated, which limits the realization of their social guarantees in the event of occupational accidents.

International practices and recommendations of the International Labour Organization (ILO) and the Organisation for Economic Co-operation and Development (OECD) confirm the need to ensure equal access of all workers to social insurance systems, regardless of their form of employment.

In this regard, it is necessary to include platform workers in the mandatory social insurance system, develop digital mechanisms for registering occupational accidents, and establish in legislation the use of electronic data when determining eligibility for and assigning social benefits.

Thus, the further digital transformation of the social security system should be accompanied by the improvement of legal regulation of modern forms of employment and the strengthening of guarantees for the social protection of workers.

4. International Experience and Proposals for Improving the Legislation of the Republic of Kazakhstan

The development of the digital economy has led to the modernization of labour and social security legislation in many countries. The spread of remote and platform-based employment has necessitated the development of new legal mechanisms for protecting workers, making the study of international experience particularly relevant for the Republic of Kazakhstan.

The International Labour Organization (ILO) emphasizes the need to ensure equal access to social protection for all workers, regardless of their form of employment. A similar approach is reflected in the 2024 European Union Directive on platform work, which provides for greater transparency in algorithmic management, the determination of the legal status of platform workers, and the strengthening of their social guarantees.

The experience of Germany and the member states of the Organisation for Economic Co-operation and Development (OECD) demonstrates the need to develop a risk-based approach to occupational safety, use electronic evidence in the investigation of occupational accidents, and improve mandatory social insurance mechanisms in the context of the digital labour market [7].

Taking into account international experience, it is considered appropriate to:

establish in the Labour Code of the Republic of Kazakhstan specific rules for the classification of occupational accidents in the context of remote and platform-based employment;

legally define the status of platform workers and ensure their participation in the mandatory social insurance system;

improve the use of electronic evidence in the investigation of occupational accidents and strengthen the protection of workers' personal data.

The implementation of these measures will contribute to increasing the effectiveness of the occupational safety system, ensuring adequate social protection for workers, and adapting the legislation of the Republic of Kazakhstan to the current conditions of the digital economy.

Conclusion

The study conducted has shown that digitalization is significantly transforming labour relations and the social security system, creating new challenges for the legal regulation of occupational accidents. The development of remote and platform-based employment requires the improvement of labour legislation, the legal definition of the status of platform workers, and the expansion of their participation in the mandatory social insurance system.

International experience confirms the need to modernize national legislation in accordance with current digital technologies and international standards. Improving the legal regulation of occupational accidents and the social security system will contribute to enhancing the effectiveness of occupational safety, strengthening the social protection of workers, and further developing the digital economy of the Republic of Kazakhstan.

References

Constitution of the Republic of Kazakhstan. Adopted by referendum on 15 March 2026. Entered into force on 1 July 2026.

Labour Code of the Republic of Kazakhstan No. 414-V ZRK of 23 November 2015 (as amended and supplemented).

Social Code of the Republic of Kazakhstan No. 224-VII ZRK of 20 April 2023 (as amended and supplemented).

International Labour Organization. World Employment and Social Outlook 2021: The Role of Digital Labour Platforms in Transforming the World of Work. Geneva: ILO, 2021.

International Labour Organization. World Employment and Social Outlook: Trends 2024. Geneva: ILO, 2024.

European Union. Directive (EU) 2024/2831 of the European Parliament and of the Council of 23 October 2024 on Improving Working Conditions in Platform Work. Official Journal of the European Union, 2024.

OECD. OECD Employment Outlook 2024. Paris: OECD Publishing, 2024.

Digitalisation of Civil Justice In EU

Dijana Gjorgieva¹

Abstract

Digital technologies have increasingly transformed the way justice systems operate, and the EU has recognized digitalization as an important step toward creating more efficient, accessible, and modern judicial procedures. In the field of civil justice, digital solutions play a particularly important role in facilitating cross-border cooperation and improving access to justice for citizens and businesses.

This paper examines the main aspects of the digitalization of civil justice in the EU, with particular focus on the role of digital tools in cross-border proceedings, including the electronic service of documents, the taking of evidence, and the exchange of judicial information.

Key words: EU civil procedure, civil justice, digitalization

Introduction

Digital technologies have transformed the functioning of justice systems, and the EU has recognized digitalization as a key element in improving access to justice and judicial efficiency. In civil proceedings, digital solutions facilitate cross-border cooperation and simplify procedures through tools such as electronic communication, videoconferencing, e-evidence exchange, and e-CODEX. This paper analyzes the role of these instruments in the modernization of EU civil justice and their contribution to more effective judicial cooperation.

¹ Phd in Law, International University Vision in Gostivar, Republic of North Macedonia, dijana.gjorgieva@vision.edu.mk, ORCID: 0009-0006-6077-0463

1. The Treaty of Lisbon and the Digitalization of Civil Justice

The digitalization of civil justice in the EU is rooted in the legal framework established by the Treaty of Lisbon. Through the development of the Area of Freedom, Security and Justice, the Treaty strengthened the Union's role in judicial cooperation in civil matters with cross-border implications. In context of these Articles 67 and 81 of the Treaty on the Functioning of the EU provide the legal basis for the adoption of measures designed to improve access to justice, facilitate cooperation between national courts and reinforce the principle of mutual recognition of judicial decisions. Against this background, the introduction of digital solutions, including electronic filing, videoconferencing, and the e-CODEX system, has become an important means of modernizing civil justice. These tools contribute to more efficient judicial procedures, improve access to justice for citizens and businesses, and support greater interoperability among the judicial systems of the Member States.

2. Digitalization of Civil Justice

The digitalization of civil justice constitutes a practical expression of the European Union's broader commitment to ensuring effective access to justice. Achieving this objective represents a complex and long-term process that requires the gradual digital transformation of judicial systems throughout the EU, particularly regarding the resolution of civil disputes involving cross-border elements, while simultaneously encouraging the modernization of national justice systems.

The establishment of an open, accessible, and digitally adapted justice system within the EU is also consistent with the objectives of the European Strategy for Justice for the period 2025–2030. This strategic framework reflects the EU's commitment to modernizing traditional justice systems, including both civil law and common law traditions, through the integration of innovative methods, technological solutions, and updated procedural approaches. Digitalization represents a central element of this transformation and starts with e-justice portal, encompassing electronic communication between judicial actors, online judicial procedures, digital case management systems, and the wider use of technological tools in court proceedings. These developments aim to enhance the efficiency, accessibility, and effectiveness of justice systems while ensuring that fundamental procedural guarantees remain protected because the The system is designed to be citizen centered.

The principles and objectives derived from the founding Treaties of the EU and the Strategy are already manifested in the functioning and evolution of EU civil procedural law. A clear manifestation of this development can be observed in the adoption of new

rules on the service of judicial and extrajudicial documents in civil proceedings, the modernised framework for the taking of evidence, the possibility of conducting civil hearings through videoconferencing, and the establishment of e-CODEX — a decentralised digital system designed to interconnect the national judicial systems of the EU Member States. In this way, with these three starting instruments the impact of the digitalisation of justice is becoming increasingly evident within the legal framework of civil procedural law.

2.1. Electronic documents and digital communication in the cross-border service of judicial and extrajudicial documents

Regulation (EU) 2020/1784 replaced Regulation (EC) No 1393/2007 and introduced a more digitally oriented framework for the cross-border service of documents in civil matters. According to Regulation (EU) 2020/1784 electronic documents are one of the key elements of the modernization of cross-border service procedures. Main innovation of this Regulation is also the promotion of electronic communication between transmitting and receiving agencies through a decentralized IT system.

Regulation (EU) 2020/1784 increased use of electronic documents and digital communication in the cross-border service of judicial and extrajudicial documents. The Regulation establishes a more efficient system for transmitting documents between competent authorities through a decentralized IT system, allowing courts and other judicial bodies in different Member States to exchange procedural documents electronically in a secure manner. Under this framework, documents related to civil and commercial proceedings, such as statements of claim, court decisions, summonses, and other procedural acts, may be transmitted electronically between transmitting and receiving agencies. The use of electronic communication reduces the delays associated with traditional postal methods, lowers administrative burdens, and improves the reliability of cross-border service procedures. The Regulation also introduces safeguards to ensure that electronic transmission maintains the necessary standards of security, authenticity, and confidentiality. Electronic documents must be exchanged through secure and interoperable systems, ensuring that judicial authorities can verify the origin and integrity of the transmitted documents. This approach contributes to mutual trust between Member States and supports the effective functioning of the European judicial area.

Key advantages of Regulation (EU) 2020/1784 are the following: creation of mandatory decentralized IT system for electronic transmission of requests, forms and communications (applicable from 1 May 2025), electronic communication between authorities, new types of modern electronic methods, including service by electronic

means where conditions are fulfilled and creates a more structured digital network between transmitting and receiving agencies.

2.2. Digital solutions for obtaining evidence in cross-border civil cases

Regulation (EU) 2020/1783 replaced Regulation (EC) No 1206/2001 and introduced a more modern framework for obtaining evidence in cross-border civil and commercial cases. A significant improvement brought by the Regulation is the promotion of digital solutions in judicial cooperation, especially using videoconferencing and other forms of remote communication. These tools enable courts in one Member State to obtain testimony from witnesses, experts, or parties located in another Member State without the need for them to travel and appear physically before the court. This contributes to faster procedures, greater efficiency, and easier access to justice in cross-border proceedings. This regulation for the first time addresses the issue of minimum technical standards for the development of software used for videoconferencing in civil proceedings.

The development of digital civil justice is also evident in the expanded application of videoconferencing within judicial procedures. Remote hearings allow courts to conduct proceedings effectively while preserving essential procedural guarantees and facilitating the involvement of participants situated in different Member States. Particularly in disputes with a cross-border element, videoconferencing reduces practical barriers caused by distance and supports the uninterrupted functioning of judicial proceedings. Consequently, digital technologies have become an important instrument for improving cooperation between courts and enhancing the effectiveness of justice within the European Union.

A significant emerging trend is the development and implementation of e-evidence digital exchange systems, which aim to establish secure, standardized, and efficient mechanisms for the submission, authentication, and exchange of electronic evidence within judicial proceedings. These systems represent an important step toward the digital transformation of courts and the modernization of procedural frameworks. In the context of civil proceedings, e-evidence systems facilitate a range of digital procedures, including the electronic filing and management of documentary evidence, the integration of remote hearings and videoconferencing, streamlined digital disclosure and discovery processes, the secure exchange of expert evidence, and more efficient communication between courts and participating parties.

2.3. Creation of e-CODEX

The most important step in the digital transformation of European judicial cooperation in civil matters is the introduction of e-CODEX (e-Justice Communication

via Online Data Exchange). E- CODEX is a decentralized digital infrastructure aimed at facilitating the interconnection of national judicial systems within the EU.

Established within a legal framework by Regulation (EU) 2022/850, e-CODEX provides a secure platform for the electronic exchange of data, documents, and communications between courts and judicial authorities of different Member States. The system enhances the efficiency of cross-border judicial procedures, including mechanisms such as the European Payment Order procedure and the European Small Claims Procedure, by enabling faster and more reliable electronic transmission of judicial documents.

E-CODEX reduces administrative burdens associated with traditional paper-based procedures, improves access to cross-border justice, and supports the effective implementation of mechanisms such as the European Payment Order and European Small Claims Procedures. By ensuring interoperability between national judicial systems, e-CODEX contributes to the development of a more integrated and digitally advanced European judicial area.

Conclusion

The digital transformation of civil justice constitutes one of the most significant developments in the modernization of judicial cooperation within the EU. Building upon the legal foundations established by the Treaty of Lisbon, particularly the creation of the Area of Freedom, Security and Justice, the EU has gradually developed a comprehensive legal and technological framework aimed at facilitating access to justice, enhancing cooperation between national courts, and improving the effectiveness of cross-border judicial procedures.

The introduction of digital solutions, including electronic communication systems, videoconferencing, e-evidence exchange platforms, and the e-CODEX infrastructure, reflects the Union's efforts to adapt judicial processes to the requirements of a modern and interconnected society.

The digitalization of civil justice should be viewed as a broader legal and institutional transformation rather than simply a technological innovation. Its future development will depend on maintaining a balance between the opportunities offered by new technologies and the preservation of essential procedural safeguards.

References

- Gascón Inchausti, F. (2024). Digitalization of justice in the European Union and in Spain. Ritsumeikan University.
- Gorgieva, D. (2024). EU civil procedure after the Lisbon Treaty. *Justicia*, 305–310.
- Hess, B. (2025). Digitalization of civil procedure and AI: The European perspective. *Pázmány Law Review*, 213–220. <https://doi.org/10.55019/plr.2025.1.213-220>
- Vidaki, A. N. (2025). Digitalization of justice in the EU: Challenges and future prospects. In *Internet law and digital society: An international overview*. Milano University Press.
- Regulation (EU) 2020/1784 of the European Parliament and of the Council of 25 November 2020 on the service in the Member States of judicial and extrajudicial documents in civil or commercial matters (service of documents) (recast). (2020). *Official Journal of the European Union*, L 405, 2 December 2020.
- Regulation (EU) 2020/1783 of the European Parliament and of the Council of 25 November 2020 on cooperation between the courts of the Member States in the taking of evidence in civil or commercial matters (taking of evidence) (recast). (2020). *Official Journal of the European Union*, L 405, 2 December 2020.
- Regulation (EU) 2022/850 of the European Parliament and of the Council of 30 May 2022 on a computerized system for the cross-border electronic exchange of data in the area of judicial cooperation in civil and criminal matters (e-CODEX system), and amending Regulation (EU) 2018/1726. (2022). *Official Journal of the European Union*, L 150, 1 June 2022.

Artificial Intelligence and the Displacement of Procedural Justice in Criminal Proceedings

Cüneyt Şamil Oğurlu¹

Abstract

The penetration of artificial intelligence (AI) tools and complex digital evidence into criminal proceedings subjects the right of defence — the core of a fair trial — to a structural test. This paper treats that right as a process running from the moment a person becomes a “suspect” to the end of appellate review, and analyses the risks of AI and digital evidence phase by phase. Its central thesis is that decisive epistemic determinations of guilt and risk are shifting from the courtroom to the design and model-training stage, where procedural safeguards find no application — eroding the equality of arms, the adversarial (dialectical) principle and the presumption of innocence in practice, if not in norm. Explainable AI (XAI) is pertinent but insufficient alone, for the law requires not mere explanation but contestability. The paper therefore proposes a layered regime of safeguards — access to evidence and decision logic, independent audit, protected access, and XAI — and locates one of its long-term preconditions in engineering itself: procedural safeguards by design will be the guarantee of fair trial in the digital age.

Keywords: Right of defence, artificial intelligence, digital evidence, equality of arms, adversarial proceedings, engineering.

1. Introduction

¹ Phd in Law, Criminal Law Specialist, Department of Law, Istanbul Chamber of Commerce, Istanbul, Türkiye, cuneyt.ogurlu@ito.org.tr, ORCID id: 0009-0003-3708-755X

In criminal procedure, evidence has undergone a radical displacement from physical object to data point; location data, biometric surveillance, mobile-device examinations and algorithmic assessments are today the ordinary material of adjudication². While this transformation offers powerful means of reaching the material truth, it confronts the traditional guarantees of the defence with a new test³. The paper's thesis is two-layered: since the right of defence is a process spread across phases, the impact of AI must be analysed phase by phase; more fundamentally, decisive determinations are migrating to a pre-trial domain — the design stage — which lies outside the reach of procedural safeguards.

2. The Inception of the Right of Defence

The right of defence is not a single power but a bundle of rights — information, access to the file, adequate time and facilities, assistance of counsel, examination of witnesses and adversarial proceedings — all resting on the equality of arms⁴. Article 6/3 ECHR guarantees the minimum defence rights of everyone charged with a criminal offence⁵. Contrary to widespread assumption, the right arises not at trial but at the moment the person becomes a “suspect”; the ECtHR has held that the guarantees apply from the earliest stage of the investigation, from the first moment a charge is directed at the individual⁶. Early recognition of that status makes the individual a subject endowed with rights and obligations rather than a mere addressee of an accusation. On this basis the right may be examined in four phases: preventive, investigation, trial and appellate review. Criminal procedure reaches the material truth through a dialectical synthesis born of the confrontation of accusation and defence⁷; AI affects that dialectical structure differently in each phase.

2.1. The Pre-Proceedings Phase

The most insidious problem arises where the right of defence has not yet come into being. Predictive policing, mass surveillance and facial-recognition systems produce the determinations that render a person a “suspect” before that person has any means of

² Tezcan, D. et al. (2022). *Dijital Ceza Muhakemesi Hukuku*, Ankara: Seçkin, p. 400.

³ Balcı, M. and Çakır, K. (2023). *Dijital Ceza Hukuku-I*, Ankara: Adalet, p. 17.

⁴ Tezcan et al. (2022), p. 110; Yavuz Kılıç, Ö. C. (2024). “Adil Ceza Yargılamasında Çelişmeli Yargılama ve Silahların Eşitliği İlkeleri Bakımından Müdafinin Önemi”, *ASBÜHFD*, Vol. 6, No. 2, p. 2481.

⁵ Constitution of the Republic of Türkiye, Art. 36; ECHR Art. 6/3; Zafer, H. (2023). “Savunma Hakkı ve Sınırları”, *TİHEK İnsan Hakları Makaleleri Seçkisi II*, p. 9.

⁶ *Imbrioscia v. Switzerland* (1993); *Deweert v. Belgium* (1980); Birtok, F. (2013). “Cumhuriyet Savcısı'nın Delilleri ve Fiili Takdir Yetkisi”, *Marmara ÜHFHAD*, Vol. 19, No. 2, p. 959.

⁷ Erem, F. (1977). “Diyalektik Açısından Ceza Yargılaması”, *AÜHFD*, Vol. 34, No. 1, p. 6.

defence⁸. Digital criminal justice detaches the individual from context and reduces them to a two-dimensional “data-vidual” built from pre-defined “risk factors”⁹. Since no procedural status yet exists, the salient guarantee here is not individual access to a file but systemic oversight of the tool itself.

Although proportionality is decisive at this stage, the person's ignorance of the process impedes review; pressures on freedom of expression push individuals towards anonymity while law enforcement traces perpetrators through IP records and provider data, rendering fragile the balance between individual rights and public security¹⁰. Not knowing which data shaped the accusation, the person is deprived of the first element of the defence — information — from the outset; the right, even at its birth, stands in the shadow of a past, unreviewable determination. Because the individual is not yet a procedural subject, the parties' positions are asymmetrical, and the obligation to secure the lawfulness of the process concentrates correspondingly upon public authority.

2.2. The Investigation Phase

In the investigation phase, digital evidence is the product not of a single act but of an integrated process of identification, acquisition, preservation, examination and interpretation¹¹. Being by nature dispersed and “volatile”, digital data can easily be altered, duplicated or deleted; preserving authenticity and integrity therefore requires specific technical safeguards¹². Chain of custody, hash verification and time-stamping are critical to the soundness of the evidence, and international digital-forensics standards regulate these processes¹³.

In practice, presenting digital evidence solely as paper printout is irreconcilable with the integrity and forensic-soundness requirements of those standards: it severs complex data structures from their original context, and the defence's inability to supervise the process casts serious doubt on the evidence's reliability¹⁴. Finally, the algorithmic selection of which data count as “relevant” performs a filtering invisible to

⁸ Council of Europe (2017). *Algorithms and Human Rights*, p. 38.

⁹ Završnik, A. (2007). “The Absence of Body in Cyberspace – Criminal Justice Impact”, *Masaryk University Journal of Law and Technology*, Vol. 1, No. 1, p. 49 (the term “data-vidual”, coined by Franko Aas, as conveyed by Završnik).

¹⁰ On anonymity and proportionality, *Delfi v. Estonia*; see further Balci and Çakır (2023), p. 37.

¹¹ Özen, M. and Özocak, G. (2015). “Adli Bilişim... (CMK m. 134)”, *Ankara Barosu Dergisi*, No. 1, p. 59; Sarsıkoğlu, Ş. (2025), *İstanbul Medipol ÜHFD*, Vol. 12, No. 1, p. 307.

¹² Casey, E. (2011). *Digital Evidence and Computer Crime*, Academic Press, p. 25.

¹³ ISO/IEC 27037 and ISO/IEC 27042; for technical methods, Eren, M. A. (2023). *Dijital Deliller ve Delil Yasakları*, Ankara: Seçkin, pp. 102-120.

¹⁴ Turkish Code of Criminal Procedure (CMK), Art. 134/5; on the inadequacy of paper printouts and access to metadata, Council of Europe (2019). *Electronic Evidence in Civil and Administrative Proceedings*, p. 16.

the defence; since contestation is possible only over accessible evidence, the equality of arms is impaired at the very birth of the evidence¹⁵.

The engineering counterpart of the access layer is an immutable decision log for every determination¹⁶, recording the input feature vector, the cryptographic hash of the model version, the time stamp and the output probability score, with training data and model weights traceable through version control. This should be complemented by model cards reporting performance, intended use and known limitations in standard form¹⁷, and by datasheet-type documentation of the training data's composition and collection¹⁸. Its legal counterpart is the right to inspect the file and the principle of adequate time and facilities; the decision log and provenance record perform, for digital evidence, the function of the chain-of-custody record for physical evidence.

2.3. The Trial Phase

Four fractures crystallise at trial. The first is the black box and trade secrecy. Most algorithms used in the justice system are developed by private firms treating source code and training data as trade secrets; where the defendant's liberty turns on an output, the defence's lack of access to the mechanism renders adversarial proceedings inoperative¹⁹. The reasoning the law demands goes beyond stating the decision's legal bases: the chain of reasoning by which the judge reached conscientious conviction — with the technical information, documents, findings and evidence relied upon — must be set out in intelligible, reviewable form.

The second is automation bias. Although the judge evaluates evidence freely, the unwarranted aura of technical infallibility attached to algorithmic output steers that evaluation from the outset, and a probabilistic result is read as established fact²⁰. Under the adversarial and immediacy principles (Arts. 209 and 217 of the Turkish Code of

¹⁵ Galič, M. (2020). "Defence Rights in the Context of Huge Data Sets and Big Data Forensic Tools in Criminal Proceedings", p. 2.

¹⁶ Buscemi, A., Deckenbrunnen, T., Kabir, F., Mishchenko, K., Mowla, N. (2026). "Assessing High-Risk AI Systems under the EU AI Act: From Legal Requirements to Technical Verification", arXiv:2512.13907, p. 6.

¹⁷ Mitchell, M., Wu, S., Zaldivar, A., Barnes, P., Vasserman, L., Hutchinson, B., Spitzer, E., Raji, I. D., Gebru, T. (2019). "Model Cards for Model Reporting." Proceedings of the Conference on Fairness, Accountability, and Transparency (FAT* '19), 220-229. <https://doi.org/10.1145/3287560.3287596>.

¹⁸ Gebru, T., Morgenstern, J., Vecchione, B., Vaughan, J. W., Wallach, H., Daumé III, H., Crawford, K. (2021). "Datasheets for Datasets." Communications of the ACM, 64(12), 86-92. <https://doi.org/10.1145/3458723>.

¹⁹ Wexler, R. (2018). "Life, Liberty, and Trade Secrets", Stanford Law Review, 70(5), p. 1343 et seq.; Pasquale, F. (2015). The Black Box Society, Harvard University Press.

²⁰ On automation bias, Casey (2011), p. 20; Završnik (2007), p. 48.

Criminal Procedure), the judge may rely only on evidence produced and debated at the hearing; the defence must therefore have access not merely to the evidence's "result" but to its "source and processing"²¹. At the design stage, the engineering counterpart of the XAI layer is a preference for inherently interpretable architectures (decision trees, rule-based systems, monotonicity-constrained models) over post-hoc explanation layers; the engineering literature itself has shown that curing opacity through post-hoc explanations in high-stakes decisions yields weak fidelity to the model's true decision logic and a spurious appearance of transparency²².

The third is authenticity and proof. Generative AI and deepfakes render the probative value of audio and images doubtful. Under the presumption of innocence, the legal burden of proof does not shift to the accused (Art. 6/2 ECHR); what shifts is the de facto burden of demonstrating the falsity of the evidence — eroding the presumption not normatively but in practice²³.

The fourth is the technical–financial asymmetry. The prosecution commands state-funded forensic laboratories, whereas the average defendant's ability to commission an independent expert most often depends on financial means; this asymmetry, together with the impossibility of testing a decisive expert opinion at the hearing, has been found by the ECtHR to violate adversarial proceedings and the equality of arms²⁴.

2.4. The Phase of Judicial Review

Although appellate review is meant to control the lawfulness and merits of the first-instance judgment, it is derivative in character, conducted on the file and confined to the record created below. Not only the inexplicability of the algorithmic decision, but the entire technical–legal asymmetry in the collection and evaluation of evidence, the deficiency of reasoning and the defence's lack of access carry over intact to the higher court. The higher courts' lack of technical capacity to re-examine digital evidence independently entrenches this continuity; where no reviewable chain of reasoning — as the right to a reasoned judgment requires — was established at first instance, appellate review degenerates into formal ratification. The erosion suffered in earlier phases is thus not remedied on appeal but becomes cumulative and, in most cases, irreversible.

²¹ Gökpınar, M. (2024). "Delillerin Doğrudan Doğrualığı", *Akdeniz ÜHFD*, Vol. 14, No. 2, p. 938.

²² Rudin, C. (2019). "Stop Explaining Black Box Machine Learning Models for High Stakes Decisions and Use Interpretable Models Instead." *Nature Machine Intelligence*, 1(5), 206-215.

²³ On the distinction between the legal burden of proof and the de facto burden, and "technical information asymmetry", Galič (2020), p. 2; Zafer (2023), p. 28.

²⁴ *Avagyan v. Armenia*, App. No. 1837/10, 22 November 2018; CMK Arts. 67-68 (expert opinion and examination of the court expert at the hearing).

The independent, accredited audit layer can be concretised through a certifiable AI management-system framework at the institutional level²⁵ and a voluntary risk-management framework built on the Govern-Map-Measure-Manage functions²⁶; their measurement function encompasses statistical bias testing comparing false-positive and false-negative rates across subgroups — precisely the analysis on which independent journalistic scrutiny of risk-scoring tools has rested²⁷. The legal anchor of this layer is the institution of court experts; the proposed difference is that the audit operates per tool rather than per case, through a pre-accredited pool of experts and institutions, structurally reducing the technical–financial asymmetry between prosecution and defence.

3. Critical Assessment

The prevailing proposal is Explainable AI (XAI). It is valuable but insufficient alone, for the law requires not mere explanation but contestability. Post-hoc explanations may be unfaithful to the model, and an explanation's plausibility does not mean it reflects the model's actual decision logic: post-hoc methods typically produce not the computation the model in fact performs but a separate, humanly intelligible approximation fitted to it from outside — so a plausible yet unfaithful explanation can itself mislead²⁸. The Council of Europe's Ethical Charter on AI in judicial systems likewise treats transparency, impartiality and auditability as fundamental principles²⁹. What is needed is therefore not a single instrument but a layered regime of safeguards: (i) access to evidence and decision logic; (ii) independent, accredited audit; (iii) closed access to code under a protective reservation; and (iv) XAI at the design stage. Each layer must be built together with its engineering counterpart and legal justification: immutable decision logs and provenance records are the digital equivalent of the right of access to the file; ISO/IEC 42001 and NIST AI RMF-type accreditation regimes, a pre-verified version of the expert-witness institution; air-gapped examination environments, the proportionality balance between trade secrecy and the defence; and inherently interpretable architectures, the engineering counterpart of Article 11 of the Turkish Personal Data Protection Law (KVKK). Concretely, the defence should receive access to a hash-verified raw copy of the evidence and the opportunity for counter-examination by its own expert within a reasonable time;

²⁵ ISO/IEC 42001:2023, Information Technology — Artificial Intelligence — Management System, International Organization for Standardization; Buscemi et al., op. cit., p. 10.

²⁶ National Institute of Standards and Technology, Artificial Intelligence Risk Management Framework (AI RMF 1.0), NIST AI 100-1, January 2023.

²⁷ Angwin, J., Larson, J., Mattu, S., Kirchner, L. (2016). “Machine Bias.” ProPublica, 23 May 2016 (for the subgroup-based error-rate analysis of the COMPAS risk-scoring tool).

²⁸ Wachter, S., Mittelstadt, B. and Floridi, L. (2017). Science Robotics, 2(6); Kheiri, M. A. et al. (2025). “Authenticity of Using AI Systems in Proving Electronic Evidence”, p. 48.

²⁹ Council of Europe (2018). European Ethical Charter on the Use of Artificial Intelligence in Judicial Systems and Their Environment.

even where evidence is tendered only as output, access to metadata must not be barred, so that reproducibility is secured³⁰.

4. A Step Towards a Solution

Law usually trails technology; since decisive determinations have shifted to the design stage, safeguards must be extended back to cover it. This makes the engineering dimension not an accessory but a structural precondition of fair trial — yet it cannot stop there: the institutional practice in which systems are produced must itself be restructured. System designers and IT specialists should be organised within an interdisciplinary core team alongside experts in anthropology, sociology, psychology, statistics and legal philosophy³¹. Within such a team the engineer is not a mere technical executor but a design partner who interrogates, with interdisciplinary colleagues, which social, psychological and legal assumptions the system encodes. Curricula should parallel this model: teaching that algorithms are not neutral mathematical objects but value-laden socio-technical systems, treating “value-sensitive design” and “procedural safeguards by design” as core competences, and bringing law and engineering together in joint workshops where code is subjected to legal contestation³². This requires lawyer and engineer to meet in a shared language of responsibility; otherwise, ethical and legal concerns remain confined to electives at the curriculum's margins. Whether justice will still remain just under digitalisation depends on technology being designed in conformity with fair-trial principles³³.

When explainability and auditability become design criteria as fundamental as accuracy and efficiency, technology turns into an infrastructure that strengthens rather than weakens the right of defence — a right anyone may need at any moment. Historical experience shows that this right has been most systematically abolished in authoritarian and totalitarian regimes, where law becomes an arbitrary instrument of political power. An architecture building explainability and auditability upon transparency, good governance and the standards of the democratic rule of law can therefore become a structural guarantee of the defence's resilience — not only in individual trials, but even where the rule of law itself is suspended.

³⁰ On access to metadata, Council of Europe (2019), p. 16.

³¹ Oğurlu, C. Ş. (2026). *Dijitalleşmenin Ceza Muhakemesinin Temel İlkelerine Etkisi ve Savunma Hakkı*, Ankara: Seçkin Yayıncılık, p. 417.

³² IEEE (2019). *Ethically Aligned Design*.

³³ van den Hoogen, R. (2008). “Will E-Justice Still be Justice? Principles of a Fair Electronic Trial”, *International Journal for Court Administration*, 1(1), p. 65.

5. Conclusion

As the phase-by-phase analysis has shown, a decision without an addressee in the preventive phase, unreviewable data in the investigation, an inexplicable algorithm at trial and a derivative, formalised review on appeal display one and the same structural pattern recurring across four phases. The right of defence is tested not in a single act but across the whole process from its inception to appellate review. The general conclusion is that the real threat is the migration of decisive determinations to a design stage beyond the reach of legal procedural safeguards. Since explainability alone has been shown insufficient, the remedy must be sought not in a single intervention but in a comprehensive approach uniting explanation, audit, access and education³⁴ within interdisciplinary integrity. In the digital age, the guarantee of a fair trial ultimately begins where the code is written.

References

- Angwin, J., Larson, J., Mattu, S., Kirchner, L. (2016). "Machine Bias." ProPublica, 23 May 2016 (subgroup-based error-rate analysis of the COMPAS risk-scoring tool).
- Balcı, M. and Çakır, K. (2023). *Dijital Ceza Hukuku-I: Sosyal Medyada İşlenen Suçlar*, Ankara: Adalet Yayınevi.
- Birtek, F. (2013). "Cumhuriyet Savcısı'nın Delilleri ve Fiili Takdir Yetkisi", *Marmara Üniversitesi Hukuk Fakültesi Hukuk Araştırmaları Dergisi*, Vol. 19, No. 2, pp. 953-990.
- Buscemi, A., Deckenbrunnen, T., Kabir, F., Mishchenko, K., Mowla, N. (2026). "Assessing High-Risk AI Systems under the EU AI Act: From Legal Requirements to Technical Verification." arXiv:2512.13907.
- Casey, E. (2011). *Digital Evidence and Computer Crime: Forensic Science, Computers and the Internet*, USA: Academic Press.
- Council of Europe (2017). *Algorithms and Human Rights: Study on the Human Rights Dimensions of Automated Data Processing Techniques*, Strasbourg.
- Council of Europe (2018). *European Ethical Charter on the Use of Artificial Intelligence in Judicial Systems and Their Environment (CEPEJ)*, Strasbourg.
- Council of Europe (2019). *Electronic Evidence in Civil and Administrative Proceedings*, Strasbourg.
- Erem, F. (1977). "Diyalektik Açından Ceza Yargılaması", *Ankara Üniversitesi Hukuk Fakültesi Dergisi*, Vol. 34, No. 1, pp. 1-7.
- Eren, M. A. (2023). *Dijital Deliller ve Delil Yasakları*, Ankara: Seçkin Yayıncılık.

³⁴ "Starting from the 11 high-level requirements used as the normative basis, the mapping decomposes these obligations into 48 operational sub-requirements and associates them with 66 verification activities." Buscemi et al., op. cit., p. 15.

Galič, M. (2020). Defence Rights in the Context of Huge Data Sets and Big Data Forensic Tools in Criminal Proceedings, <https://ssrn.com/abstract=3838680>.

Gebru, T., Morgenstern, J., Vecchione, B., Vaughan, J. W., Wallach, H., Daumé III, H., Crawford, K. (2021). "Datasheets for Datasets." *Communications of the ACM*, 64(12), 86-92. <https://doi.org/10.1145/3458723>.

Gökpınar, M. (2024). "Ceza Muhakemesinin Temel Bir İlkesi Olarak Delillerin Doğrudan Doğrualığı", *Akdeniz Üniversitesi Hukuk Fakültesi Dergisi*, Vol. 14, No. 2, pp. 937-986.

IEEE (2019). *Ethically Aligned Design: A Vision for Prioritizing Human Well-being with Autonomous and Intelligent Systems*, IEEE.

ISO/IEC 27037:2012, *Guidelines for Identification, Collection, Acquisition and Preservation of Digital Evidence*; ISO/IEC 27042:2015, *Guidelines for the Analysis and Interpretation of Digital Evidence*, ISO.

ISO/IEC 42001:2023, *Information Technology — Artificial Intelligence — Management System*, International Organization for Standardization.

Case law: *Imbrioscia v. Switzerland* (1993); *Deweert v. Belgium* (1980); *Delfi v. Estonia* (2015); *Avagyan v. Armenia* (2018).

Kheiri, M. A., Qashta, N. and Aljaradat, D. I. (2025). "Authenticity of Using Artificial Intelligence Systems in Proving Electronic Evidence", *Pakistan Journal of Life and Social Sciences*, Vol. 23, No. 1.

Mitchell, M., Wu, S., Zaldivar, A., Barnes, P., Vasserman, L., Hutchinson, B., Spitzer, E., Raji, I. D., Gebru, T. (2019). "Model Cards for Model Reporting." *Proceedings of the Conference on Fairness, Accountability, and Transparency (FAT* '19)*, 220-229. <https://doi.org/10.1145/3287560.3287596>.

National Institute of Standards and Technology (2023). *Artificial Intelligence Risk Management Framework (AI RMF 1.0)*, NIST AI 100-1, January 2023.

Oğurlu, C. Ş. (2026). *Dijitalleşmenin Ceza Muhakemesinin Temel İlkelerine Etkisi ve Savunma Hakkı*, Ankara: Seçkin Yayıncılık.

Özen, M. and Özocak, G. (2015). "Adli Bilişim, Elektronik Deliller ve Bilgisayarlarda Arama ve El Koyma Tedbirinin Hukuki Rejimi (CMK m. 134)", *Ankara Barosu Dergisi*, No. 1, pp. 43-77.

Pasquale, F. (2015). *The Black Box Society: The Secret Algorithms That Control Money and Information*, Harvard University Press.

Rudin, C. (2019). "Stop Explaining Black Box Machine Learning Models for High Stakes Decisions and Use Interpretable Models Instead." *Nature Machine Intelligence*, 1(5), 206-215.

Sarsıkoğlu, Ş. (2025). "Bilişim Sistemlerinden Delil Elde Edilmesine Yönelik İşlemler (CMK m. 134) Hakkında Bir Değerlendirme", *İstanbul Medipol Üniversitesi Hukuk Fakültesi Dergisi*, Vol. 12, No. 1.

Tezcan, D. et al. (2022). *Dijital Ceza Muhakemesi Hukuku*, Ankara: Seçkin Yayıncılık.

van den Hoogen, R. (2008). "Will E-Justice Still be Justice? Principles of a Fair Electronic Trial", *International Journal for Court Administration*, 1(1), p. 65.

Wachter, S., Mittelstadt, B. and Floridi, L. (2017). “Transparent, Explainable, and Accountable AI for Robotics”, *Science Robotics*, 2(6), eaan6080.

Wexler, R. (2018). “Life, Liberty, and Trade Secrets: Intellectual Property in the Criminal Justice System”, *Stanford Law Review*, 70(5), pp. 1343-1429.

Yavuz Kılıç, Ö. C. (2024). “Adil Ceza Yargılamasında Çelişmeli Yargılama ve Silahların Eşitliği İlkeleri Bakımından Müdafinin Önemi”, *Ankara Sosyal Bilimler Üniversitesi Hukuk Fakültesi Dergisi*, Vol. 6, No. 2, pp. 2456-2507.

Zafer, H. (2023). “Savunma Hakkı ve Sınırları”, *Türkiye İnsan Hakları ve Eşitlik Kurumu İnsan Hakları Makaleleri Seçkisi II*, pp. 8-47.

Završnik, A. (2007). “The Absence of Body in Cyberspace – Criminal Justice Impact”, *Masaryk University Journal of Law and Technology*, Vol. 1, No. 1, pp. 43-52.

Current Trends in the Internationalization of Engineering Education and International Scientific Cooperation

Zokir Mamirovich Zikriyayev¹

Abstract

The internationalization of higher education has become one of the defining characteristics of contemporary university development. Rapid technological advancement, globalization of knowledge, digital transformation and the growing demand for highly qualified engineering professionals have significantly expanded the role of international academic cooperation. Engineering universities are increasingly expected to integrate global educational standards, international research collaboration and cross-border innovation networks into their institutional development strategies. Consequently, internationalization has evolved beyond traditional student exchange programmes into a comprehensive process involving joint educational initiatives, collaborative scientific research, academic mobility, technology transfer and institutional partnerships.

This paper examines current trends in the internationalization of engineering education with particular emphasis on international scientific cooperation as a catalyst for innovation and sustainable development. The study analyzes emerging models of academic collaboration, digital internationalization, interdisciplinary research networks and strategic university partnerships that contribute to improving educational quality and research excellence. Furthermore, the paper discusses the role of international cooperation in strengthening engineering education through joint research projects, academic mobility and innovation ecosystems. It concludes that successful internationalization requires systematic institutional policies, digital transformation and long-term strategic partnerships capable of responding to rapidly changing technological and societal challenges.

¹ Almalyk State Technical Institute, Almalyk, Uzbekistan, E-mail: zikriyayev.zm@odti.uz;
ORCID: 0009-0005-6938-3980

Keywords: Internationalization, Engineering Education, International Scientific Cooperation, Academic Mobility, Innovation, Higher Education, Global Partnerships, Technology Transfer.

Introduction

The twenty-first century has fundamentally transformed the landscape of higher education. Globalization, digital technologies and the rapid expansion of scientific knowledge have created unprecedented opportunities for universities to collaborate across national boundaries. Engineering education, in particular, has experienced profound changes due to increasing technological complexity, industrial digitalization and the globalization of innovation ecosystems. Under these conditions, universities are no longer expected to educate professionals solely for national labour markets; rather, they are responsible for preparing globally competent engineers capable of working within multicultural, interdisciplinary and technologically advanced environments.

Internationalization has consequently become one of the principal strategic priorities for higher education institutions worldwide. Universities actively establish international partnerships, participate in global research networks, implement joint educational programmes and promote academic mobility in order to enhance educational quality, scientific productivity and institutional competitiveness. Engineering universities have been particularly active in this process because technological innovation increasingly depends upon international collaboration involving universities, research institutions, industrial enterprises and governmental organizations.

The concept of internationalization extends considerably beyond the traditional understanding of international student exchange. Contemporary internationalization encompasses curriculum development, collaborative scientific research, double-degree programmes, international accreditation, digital learning environments, joint innovation projects and global technology transfer mechanisms. Such comprehensive cooperation contributes not only to institutional development but also to addressing global challenges related to sustainable development, energy transition, artificial intelligence, digital manufacturing and environmental protection.

International organizations including UNESCO, OECD, the European Commission and the World Bank consistently emphasize that international cooperation significantly improves research quality, innovation capacity and graduate employability. Universities participating in international scientific networks generally demonstrate higher research productivity, greater citation impact and stronger connections with industrial innovation

ecosystems. Consequently, internationalization should be regarded as an essential component of institutional development rather than an optional academic activity.

For engineering universities in developing economies, international cooperation provides access to advanced scientific infrastructure, innovative teaching methodologies, international research funding and globally recognized quality assurance mechanisms. Through strategic partnerships, universities strengthen institutional capacity while contributing to national technological modernization and sustainable economic development.

This paper explores the contemporary trends shaping the internationalization of engineering education and examines the strategic importance of international scientific cooperation in strengthening research excellence, educational innovation and global academic partnerships. The study further identifies institutional priorities that can support the development of internationally competitive engineering universities capable of responding effectively to future technological challenges.

Contemporary Trends in the Internationalization of Engineering Education

The internationalization of engineering education has undergone profound transformation during the last two decades. Traditional forms of international cooperation, primarily based on student exchange programmes and bilateral agreements, have gradually evolved into comprehensive institutional strategies encompassing education, scientific research, innovation, technology transfer and global academic networking. Universities are increasingly positioning themselves as international knowledge hubs where education, research and industrial collaboration transcend geographical boundaries.

One of the most significant trends is the growing emphasis on international curriculum integration. Engineering programmes are increasingly designed according to internationally recognized educational frameworks that ensure compatibility of qualifications and facilitate graduate mobility across countries. Competency-based curricula, outcome-oriented education and internationally benchmarked quality assurance systems have become essential elements of engineering education. This harmonization enables graduates to compete successfully within the global labour market while supporting international recognition of academic qualifications.

A second important trend is the rapid expansion of English-medium instruction (EMI) in engineering education. As English has become the dominant language of science, technology and international communication, universities

worldwide increasingly offer engineering programmes in English to attract international students, facilitate academic mobility and strengthen participation in global research networks. English-medium education also enables students to access international scientific literature, collaborate with researchers from different countries and participate more effectively in multinational engineering projects.

Another defining characteristic of contemporary internationalization is the development of joint and double-degree programmes. Universities increasingly establish collaborative educational initiatives that allow students to complete portions of their studies at partner institutions and receive degrees recognized by multiple universities. Such programmes strengthen academic cooperation, encourage intercultural competence and expose students to different educational systems and engineering practices. They also contribute to institutional reputation by demonstrating universities' ability to meet international academic standards.

Digital transformation has introduced entirely new models of internationalization. The emergence of virtual mobility, collaborative online international learning (COIL), digital classrooms and cloud-based educational platforms has significantly expanded opportunities for international academic cooperation. Students and faculty members can now participate in joint courses, research seminars and engineering design projects without geographical limitations. These digital approaches complement traditional physical mobility while increasing accessibility and reducing financial barriers to international participation.

International accreditation has become another strategic priority for engineering universities. Accreditation by internationally recognized organizations not only enhances institutional credibility but also improves graduate employability and facilitates international academic cooperation. Accreditation processes encourage universities to continuously improve curricula, learning outcomes, laboratory infrastructure and quality assurance mechanisms according to globally accepted standards. Consequently, accreditation serves as both a quality improvement instrument and a catalyst for institutional internationalization.

The internationalization of engineering education is also increasingly influenced by sustainability and the Sustainable Development Goals (SDGs). Universities integrate sustainability principles into engineering curricula, research agendas and international cooperation projects. Global challenges such as climate change, renewable energy, water management, environmental protection and smart cities require collaborative engineering solutions that cannot be developed within the boundaries of a single country. International engineering education therefore plays a crucial role in preparing professionals capable of addressing these shared global challenges.

Moreover, the concept of Internationalization at Home (IaH) has gained considerable attention. Recognizing that not all students can participate in physical mobility programmes, universities increasingly incorporate international and intercultural dimensions into domestic educational environments. International guest lecturers, multicultural project teams, globally oriented curricula and collaborative virtual learning activities provide students with international competencies regardless of whether they study abroad. This inclusive approach broadens the impact of internationalization across the entire student population.

These developments clearly demonstrate that internationalization is no longer an auxiliary activity undertaken by university international offices. Rather, it has become a comprehensive institutional philosophy influencing governance, curriculum design, research strategy, quality assurance and stakeholder engagement. Engineering universities capable of integrating these contemporary trends into their long-term development strategies will be significantly better positioned to enhance educational quality, strengthen research excellence and contribute to global technological progress.

International Scientific Cooperation as a Driver of Innovation

Scientific cooperation has become one of the most influential factors shaping the development of engineering education and technological innovation. In an era characterized by increasingly complex scientific challenges, no university can independently generate all the knowledge, expertise and technological resources required for breakthrough discoveries. International scientific cooperation therefore serves as a strategic mechanism for combining intellectual capacity, research infrastructure and financial resources across institutional and national boundaries.

Engineering research has become particularly dependent upon international collaboration because contemporary technological challenges—including artificial intelligence, advanced materials, renewable energy, digital manufacturing, cybersecurity and smart infrastructure—require multidisciplinary expertise and sophisticated research facilities. Collaborative international projects enable researchers to share scientific knowledge, utilize advanced laboratories and jointly develop innovative engineering solutions that would be difficult to achieve independently.

One of the most visible indicators of successful international scientific cooperation is the continuous growth of international co-authored publications. Research demonstrates that publications produced through international collaboration generally receive higher citation rates, greater scientific visibility and stronger international recognition than nationally authored studies. Collaborative

research also encourages methodological diversity, interdisciplinary thinking and broader dissemination of scientific findings, thereby enhancing both research quality and institutional reputation.

International cooperation further facilitates participation in competitive research funding programmes. Initiatives such as Horizon Europe, Erasmus+, COST Actions, TÜBİTAK international research programmes and other multinational funding schemes provide universities with opportunities to conduct large-scale collaborative research while strengthening institutional research capacity. Participation in these programmes not only supports scientific innovation but also contributes to the internationalization of engineering education through researcher mobility, joint supervision of doctoral candidates and shared research infrastructure.

Engineering universities increasingly establish international research centres and joint laboratories dedicated to strategic technological fields. These collaborative platforms enable researchers from different countries to address industrial challenges through interdisciplinary scientific approaches while promoting technology transfer and innovation commercialization. Such institutional arrangements strengthen relationships between universities, industry and government, thereby contributing to sustainable economic development and global technological competitiveness.

Beyond collaborative research projects, international scientific cooperation has become an important instrument of scientific diplomacy. Science diplomacy refers to the use of scientific collaboration as a means of strengthening international relations, addressing common global challenges and promoting peaceful cooperation among nations. In engineering education, science diplomacy facilitates the exchange of knowledge, research infrastructure and technological expertise while creating long-term partnerships between universities, governments and industrial organizations.

Engineering universities increasingly participate in international scientific networks that transcend political and geographical boundaries. Global research initiatives addressing climate change, renewable energy, digital transformation, smart manufacturing and sustainable infrastructure require multidisciplinary teams composed of researchers from different countries. These international collaborations accelerate scientific discovery by combining diverse perspectives, complementary expertise and advanced research facilities.

The growing importance of global research networks has significantly influenced the way engineering universities organize scientific activities. Universities are no longer isolated institutions conducting independent research; rather, they function as interconnected partners within international knowledge ecosystems. Participation in these networks enables researchers to share experimental data, jointly supervise postgraduate

students, organize international conferences and develop innovative engineering solutions that address complex global challenges.

The quality of scientific cooperation is increasingly evaluated through internationally recognized research indicators. Collaborative publications indexed in Scopus and Web of Science, international citation impact, joint patents and multinational research grants have become important measures of institutional research performance. Universities actively encourage international co-authorship because collaborative publications generally achieve greater scientific visibility, wider dissemination and stronger academic impact than nationally authored research.

Another emerging trend is the establishment of interdisciplinary research consortia involving universities, research institutes, industrial enterprises and governmental agencies. Such collaborative structures facilitate the integration of engineering sciences with information technologies, environmental studies, economics and social sciences. This interdisciplinary approach is particularly important because contemporary engineering problems require comprehensive solutions that combine technological innovation with economic feasibility, environmental sustainability and social responsibility.

Artificial intelligence is also transforming international scientific cooperation. AI-supported research platforms assist researchers in analyzing scientific literature, identifying potential collaborators, managing research data and predicting emerging technological trends. Digital collaboration tools powered by artificial intelligence facilitate multilingual communication, automate administrative procedures and improve coordination of multinational research projects. Consequently, AI has become an important enabler of efficient international research cooperation.

Open Science initiatives further strengthen international collaboration by promoting transparency, accessibility and knowledge sharing. Open-access publications, open research data and collaborative digital repositories enable researchers worldwide to access scientific findings without institutional or geographical limitations. These initiatives accelerate scientific progress while reducing duplication of research efforts and encouraging interdisciplinary innovation.

Universities should therefore establish institutional policies that actively encourage participation in global research communities. Incentive mechanisms supporting international publications, joint grant applications, researcher mobility and collaborative doctoral supervision contribute significantly to strengthening institutional research capacity. Sustainable international scientific cooperation

should be integrated into university development strategies as a long-term investment in academic excellence and technological innovation rather than being treated as isolated international activities.

Strategic Priorities for Strengthening the Internationalization of Engineering Education

The successful internationalization of engineering education requires more than the expansion of international partnerships; it demands a comprehensive institutional strategy that integrates global perspectives into education, research, innovation and university governance. Internationalization should therefore become an integral component of institutional development rather than the responsibility of a single administrative unit.

The first strategic priority involves strengthening the international dimension of engineering curricula. Educational programmes should incorporate internationally recognized engineering standards, global case studies, interdisciplinary project-based learning and cross-cultural competencies. Such curricula prepare graduates for professional careers within multinational companies and international research environments while enhancing the global recognition of academic qualifications.

A second priority concerns the expansion of academic mobility. Student and faculty mobility programmes facilitate the exchange of knowledge, teaching methodologies and research experience. However, mobility should evolve beyond short-term exchanges toward long-term institutional cooperation involving joint supervision of doctoral candidates, collaborative curriculum development and shared research infrastructure. Hybrid models combining physical and virtual mobility can further increase accessibility and participation.

The third priority is the establishment of international research and innovation centres. Engineering universities should create joint laboratories with foreign partner institutions focusing on strategically important technological fields such as artificial intelligence, renewable energy, advanced materials, digital engineering, mining technologies and environmental sustainability. Such centres strengthen scientific cooperation while promoting technology transfer and innovation commercialization.

Digital transformation represents another strategic priority. Universities should utilize advanced digital technologies to support international education and research through virtual laboratories, collaborative online learning, cloud-based engineering platforms and artificial intelligence-supported academic management. Digital internationalization significantly expands opportunities for global cooperation while reducing geographical and financial barriers.

Finally, universities should adopt comprehensive internationalization policies supported by measurable performance indicators. Institutional success should be

evaluated not only by the number of signed cooperation agreements but also by joint scientific publications, internationally funded research projects, academic mobility, international accreditation, graduate employability and the practical outcomes of collaborative innovation activities. Such an evidence-based approach ensures that internationalization contributes meaningfully to institutional quality and long-term strategic development.

Experience of Almalyk State Technical Institute in Advancing Internationalization

The internationalization of engineering education has become one of the strategic priorities guiding the long-term development of Almalyk State Technical Institute. Recognizing that engineering education is increasingly shaped by global technological progress and international scientific cooperation, the Institute has adopted a development strategy focused on strengthening academic partnerships, expanding research collaboration and enhancing the international competitiveness of its educational programmes.

Particular attention has been devoted to establishing sustainable cooperation with foreign universities, research institutions and industrial partners. International agreements have created opportunities for academic mobility, collaborative scientific research, joint educational initiatives and the exchange of academic experience. These partnerships enable faculty members and students to participate in international conferences, scientific workshops, research internships and professional development programmes while promoting intercultural communication and academic excellence.

The Institute has also prioritized the internationalization of scientific research. Academic staff are encouraged to participate in collaborative research projects, publish in internationally indexed scientific journals and engage in multidisciplinary research addressing contemporary engineering challenges. Increasing the visibility of scientific research through international publications and collaborative projects contributes to strengthening institutional research capacity and improving the global recognition of the Institute's academic achievements.

Special emphasis has been placed on cooperation between higher education institutions and industrial enterprises within an international context. Engineering education is increasingly supported by collaborative initiatives involving universities, research centres and industrial organizations from different countries. Such cooperation facilitates technology transfer, joint innovation projects and the practical implementation of scientific research while ensuring that educational programmes remain responsive to international technological developments.

Digital transformation has further expanded opportunities for international cooperation. Online scientific seminars, virtual academic exchanges, collaborative research platforms and digital learning technologies have enabled the Institute to participate more actively in global academic communities regardless of geographical distance. These digital instruments complement traditional forms of academic mobility while creating more inclusive opportunities for international engagement.

Looking ahead, the Institute aims to strengthen its participation in international research networks, expand collaborative engineering laboratories, increase involvement in multinational research programmes and further develop strategic partnerships with internationally recognized universities. These initiatives are expected to contribute not only to institutional development but also to the broader modernization of engineering education and technological innovation in Uzbekistan.

The experience of Almalyk State Technical Institute demonstrates that sustainable internationalization is achieved through systematic institutional policies, continuous investment in academic quality and the establishment of long-term partnerships based on mutual trust, shared scientific interests and common educational objectives.

Conclusion

Internationalization has become one of the most influential forces shaping the future of engineering education. The growing complexity of scientific research, technological innovation and industrial transformation requires universities to strengthen international academic cooperation as an essential component of institutional development. Engineering education can no longer be viewed exclusively within national boundaries; instead, it must be integrated into global educational, scientific and innovation ecosystems capable of responding to common technological and societal challenges.

This study demonstrates that contemporary internationalization extends far beyond traditional academic mobility. Modern engineering universities increasingly engage in collaborative curriculum development, joint research projects, international accreditation, digital education, interdisciplinary innovation and global technology transfer. These dimensions collectively contribute to improving educational quality, strengthening scientific productivity and enhancing institutional competitiveness.

International scientific cooperation has emerged as one of the principal drivers of engineering innovation. Collaborative research networks enable universities to combine intellectual resources, advanced research infrastructure and multidisciplinary expertise while addressing global challenges related to artificial intelligence, sustainable energy, digital manufacturing, environmental protection and industrial modernization. Universities actively participating in international scientific communities generally

demonstrate higher research impact, greater innovation capacity and stronger international visibility.

Digital technologies are simultaneously transforming the nature of international cooperation. Virtual mobility, collaborative online learning, artificial intelligence-supported research management and cloud-based scientific platforms have significantly expanded opportunities for global academic interaction. These innovations complement traditional mobility programmes and make international cooperation more accessible, flexible and sustainable.

The experience of Almalyk State Technical Institute illustrates that systematic internationalization contributes significantly to institutional development by strengthening academic partnerships, promoting collaborative research and supporting educational modernization. The continued expansion of international cooperation will further enhance the Institute's capacity to prepare globally competitive engineering professionals capable of contributing to technological innovation and sustainable industrial development.

In conclusion, the future of engineering education depends upon universities' ability to integrate internationalization into every dimension of institutional activity. Strategic partnerships, scientific diplomacy, collaborative research, digital transformation and global knowledge exchange should be regarded not as separate initiatives but as interconnected elements of a comprehensive development strategy. Universities that successfully implement these principles will strengthen their international competitiveness while making meaningful contributions to scientific progress, technological innovation and sustainable global development.

References

Altbach, P. G., & de Wit, H. (2021). *International Higher Education: Reflections on Policy and Practice*. Boston College Center for International Higher Education.

European Commission. (2022). *A European Strategy for Universities*. Brussels: European Commission.

European University Association. (2021). *Universities without Walls: A Vision for 2030*. Brussels: EUA.

Knight, J. (2015). Updated definition of internationalization. *International Higher Education*, 33, 2–3.

OECD. (2023). *Education at a Glance 2023: OECD Indicators*. Paris: OECD Publishing.

QS Quacquarelli Symonds. (2025). *QS World University Rankings 2025*. London: QS.

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education

Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Times Higher Education. (2024). *World University Rankings 2024: International Outlook Methodology*. London: THE.

UNESCO. (2021). *UNESCO Recommendation on Open Science*. Paris: UNESCO.

UNESCO. (2024). *Global Education Monitoring Report 2024*. Paris: UNESCO Publishing.

World Bank. (2024). *Higher Education and Skills for Economic Transformation*. Washington, DC: World Bank.

World Economic Forum. (2025). *The Future of Jobs Report*. Geneva: World Economic Forum.

Priority Areas for the Integration of Higher Education and Industry in the Innovative Development of Engineering and Technical Fields

Utkir Mirzakamolovich Xalikulov¹

Abstract

The rapid advancement of digital technologies, industrial modernization and global economic transformation has substantially redefined the role of engineering education in sustainable development. Universities are increasingly expected to function not only as educational institutions but also as strategic partners of industry, innovation centers and contributors to national competitiveness. The integration of higher education and industry has therefore become one of the principal priorities for engineering universities seeking to respond effectively to technological progress and labor market demands.

This paper examines the strategic priorities for strengthening university–industry integration within engineering and technical education. Particular attention is given to collaborative research, technology transfer, innovation ecosystems, competence-oriented education and international academic cooperation. The study argues that effective integration requires comprehensive institutional mechanisms that connect scientific research, industrial production and educational modernization. The experience of engineering universities demonstrates that sustainable partnerships with industry significantly improve graduate employability, research commercialization and technological innovation.

Furthermore, the paper emphasizes that engineering education should be aligned with Industry 4.0 and Industry 5.0 principles while maintaining flexibility to address emerging technological and societal challenges. The findings highlight that universities capable of

¹ Almalyk State Technical Institute, Almalyk, Uzbekistan E-mail: u.xalikulov@odti.uz; ORCID: 0009-0004-1844-319X

integrating education, research and industrial cooperation will play a decisive role in promoting sustainable economic development and technological competitiveness.

Keywords: Engineering Education, University–Industry Integration, Innovation, Technology Transfer, Industry 4.0, Sustainable Development, Higher Education.

Introduction

The twenty-first century has witnessed an unprecedented acceleration of technological innovation, digital transformation and industrial modernization. Artificial intelligence, advanced manufacturing, automation, digital engineering and smart production systems are rapidly reshaping global economies while simultaneously transforming the competencies required of engineering graduates. These developments have fundamentally altered the traditional mission of universities. Engineering institutions are no longer evaluated solely by the quality of education they provide or the quantity of scientific publications they produce. Increasingly, they are assessed by their contribution to technological innovation, industrial competitiveness and regional socio-economic development.

The World Economic Forum, UNESCO and the OECD consistently emphasize that universities must become active participants in national innovation ecosystems rather than isolated educational organizations. Consequently, closer cooperation between higher education institutions and industrial enterprises has become an international priority. Engineering universities occupy a particularly important position because they prepare specialists capable of generating technological solutions for rapidly changing industrial environments.

The integration of higher education and industry extends far beyond organizing student internships or signing cooperation agreements. It represents a comprehensive institutional strategy that combines education, scientific research, technological innovation, entrepreneurship and knowledge commercialization into a unified development model. Such integration enables universities to adapt educational programmes to labor market requirements, strengthen applied research, accelerate technology transfer and improve graduate employability.

For countries undergoing rapid industrial modernization, including Uzbekistan, university–industry cooperation has acquired strategic significance. National development priorities emphasize innovation, technological independence and the preparation of highly qualified engineering specialists capable of supporting sustainable economic growth. Under these conditions, engineering universities serve as important catalysts for regional industrial transformation by generating new knowledge, developing

innovative technologies and strengthening cooperation with industrial enterprises. This paper examines the strategic priorities that should guide the integration of higher education and industry in engineering and technical fields. It argues that sustainable cooperation requires institutional modernization, interdisciplinary education, innovation-oriented research and strong international partnerships capable of supporting long-term technological development.

Engineering education has become one of the principal drivers of technological advancement and industrial competitiveness in the knowledge-based economy. The accelerating pace of digital transformation, accompanied by the emergence of Industry 4.0 and the gradual transition toward Industry 5.0, has fundamentally altered the relationship between universities and industrial enterprises. Engineering universities are increasingly expected to educate specialists who are not only technically competent but also capable of generating innovation, adapting to rapidly evolving technologies and contributing to sustainable industrial development.

The traditional model of engineering education, which primarily emphasized theoretical knowledge and discipline-specific specialization, is no longer sufficient to satisfy the demands of contemporary industries. Modern manufacturing systems require engineers who possess interdisciplinary competencies, digital literacy, analytical thinking, project management skills and entrepreneurial capabilities. Consequently, engineering education must evolve into a dynamic ecosystem where education, scientific research and industrial practice continuously reinforce one another.

International experience demonstrates that the world's leading engineering universities have successfully transformed themselves into innovation-oriented institutions. Universities such as the Massachusetts Institute of Technology, Stanford University, Tsinghua University and the Technical University of Munich have established comprehensive cooperation mechanisms with industrial enterprises through joint laboratories, technology transfer centers, industrial research consortia and innovation parks. These institutional models significantly accelerate the commercialization of scientific discoveries while simultaneously improving the practical relevance of engineering education.

One of the defining characteristics of successful university–industry integration is the mutual exchange of knowledge. Universities contribute scientific expertise, advanced research methodologies and highly qualified human resources, whereas industrial enterprises provide practical challenges, technological infrastructure and opportunities for real-world application of scientific knowledge. Such reciprocal cooperation enables engineering curricula to remain responsive to technological developments while ensuring that graduates possess competencies directly aligned with labor market requirements.

Furthermore, industrial collaboration substantially strengthens applied research. Academic research increasingly addresses practical engineering problems involving automation, energy efficiency, digital manufacturing, materials science, artificial intelligence and environmental sustainability. Research outcomes generated through industrial partnerships generally exhibit greater commercialization potential because they emerge directly from technological needs identified by industrial stakeholders. Consequently, universities enhance both their scientific impact and their contribution to national economic development.

Engineering education also plays a decisive role in developing innovation culture among students. Participation in industrial projects, interdisciplinary design competitions, entrepreneurial initiatives and technology commercialization activities enables future engineers to acquire competencies extending beyond traditional technical knowledge. Innovation-oriented educational environments encourage creativity, critical thinking and collaborative problem-solving, which are increasingly recognized as essential professional qualities within modern engineering practice.

The transition toward Industry 5.0 further expands the strategic mission of engineering education. Unlike Industry 4.0, which primarily emphasizes automation and digitalization, Industry 5.0 promotes human-centered innovation, sustainability and resilience. Engineers are therefore expected to design technological systems that simultaneously improve industrial productivity, environmental protection and societal well-being. Universities must consequently integrate ethical responsibility, sustainable development principles and social innovation into engineering curricula alongside advanced technological education.

Another important strategic priority concerns the development of flexible educational models capable of responding rapidly to technological change. Traditional academic programmes frequently require several years to implement curricular modifications, whereas industrial technologies evolve continuously. Engineering universities should therefore establish permanent advisory councils involving industrial experts, employers and professional associations to ensure that educational programmes remain consistent with emerging technological trends and workforce demands.

The digitalization of higher education also contributes significantly to industrial innovation. Virtual laboratories, digital twins, simulation platforms, cloud-based engineering software and artificial intelligence-supported learning systems provide students with opportunities to develop practical competencies that closely resemble real industrial environments. These technologies increase educational quality while reducing barriers between academic learning and professional engineering practice.

Ultimately, engineering education should be regarded as a strategic investment in national innovation capacity. Universities capable of integrating education, scientific research and industrial cooperation establish the intellectual foundation necessary for sustainable technological development. Such institutions become not merely providers of higher education but active participants in industrial modernization, technological competitiveness and long-term economic growth.

The successful integration of higher education and industry requires a comprehensive institutional strategy rather than isolated collaborative initiatives. Sustainable partnerships emerge when universities and industrial enterprises establish long-term mechanisms for knowledge exchange, joint research and technological innovation. Based on contemporary international experience, several strategic priority areas can be identified as fundamental for strengthening this integration.

Modernization of Engineering Curricula

One of the primary priorities is the continuous modernization of engineering curricula in accordance with technological progress and industrial requirements. Educational programmes should be developed through active participation of employers, industrial associations and professional organizations to ensure that graduates possess competencies demanded by rapidly changing labor markets. Modern curricula should integrate digital engineering, artificial intelligence, robotics, industrial automation, cybersecurity, sustainable manufacturing and innovation management into traditional engineering disciplines.

In addition, competence-based education should replace knowledge-centered instructional models. Students should develop practical engineering abilities through project-based learning, interdisciplinary teamwork and industry-sponsored design projects. Such educational approaches significantly improve graduate readiness for professional practice while strengthening university–industry cooperation throughout the educational process.

Scientific research represents one of the strongest mechanisms connecting universities with industry. However, research activities should increasingly focus on solving practical technological problems encountered by industrial enterprises. Universities should therefore establish interdisciplinary research centers, innovation laboratories and technology transfer offices capable of coordinating collaborative research projects involving academic researchers, graduate students and industrial experts.

Innovation ecosystems further enhance research commercialization by supporting patent applications, prototype development, start-up creation and technology licensing. International evidence demonstrates that universities possessing well-developed

innovation infrastructure generate substantially greater economic and societal impact through successful commercialization of scientific discoveries.

Technology transfer represents one of the most effective mechanisms for connecting academic research with industrial production. In the contemporary innovation economy, universities are expected not only to generate scientific knowledge but also to facilitate its practical application through commercialization, industrial implementation and entrepreneurial activities. Consequently, strengthening technology transfer has become a strategic priority for engineering universities worldwide.

Technology transfer should be understood as a comprehensive process involving intellectual property management, patent protection, licensing agreements, collaborative research, prototype development and the creation of university spin-off companies. Successful commercialization enables scientific discoveries to evolve into competitive technologies that contribute directly to industrial productivity and national economic development.

To achieve this objective, engineering universities should establish well-structured Technology Transfer Offices (TTOs) equipped with multidisciplinary expertise in engineering, intellectual property law, innovation management and business development. Such institutional structures perform multiple strategic functions, including the identification of commercially promising research, protection of intellectual property rights, negotiation of industrial partnerships and attraction of investment for technological innovation.

Furthermore, universities should actively encourage academic staff and graduate students to participate in commercialization activities through institutional incentive systems. Scientific excellence should be evaluated not only by academic publications but also by patents, industrial contracts, technology licensing and successful innovation projects. This balanced approach promotes research that simultaneously advances scientific knowledge and addresses practical industrial needs.

Digital technologies further enhance technology transfer by facilitating virtual collaboration among researchers, industrial enterprises and investors across different countries. Digital innovation platforms, online research repositories and collaborative engineering environments significantly accelerate the dissemination and practical implementation of scientific knowledge.

Ultimately, effective technology transfer transforms universities into active contributors to regional innovation ecosystems, strengthens industrial competitiveness and supports sustainable economic development through knowledge-based technological advancement.

International cooperation has become an indispensable component of engineering education and scientific research. The complexity of contemporary technological challenges requires universities to participate actively in global academic networks where scientific knowledge, research infrastructure and innovation experience are shared across institutional and national boundaries.

Strategic international partnerships provide universities with access to advanced laboratories, collaborative research funding, academic mobility programmes and joint educational initiatives. Such cooperation significantly enhances research quality while enabling engineering students and academic staff to engage with international best practices in technology development and industrial innovation.

Joint degree programmes, international research consortia and collaborative innovation projects contribute substantially to strengthening institutional capacity. Participation in multinational engineering projects exposes researchers to diverse technological approaches while promoting interdisciplinary collaboration capable of generating globally competitive scientific outcomes.

Equally important is cooperation with internationally recognized industrial corporations. Global technology companies increasingly collaborate with universities through sponsored research, industrial internships, professional certification programmes and innovation laboratories. These partnerships facilitate the transfer of advanced technologies into educational environments while improving graduate employability within international labour markets.

International collaboration also strengthens institutional reputation. Universities actively participating in global scientific networks generally demonstrate higher research productivity, greater innovation capacity and improved international visibility. Consequently, expanding international partnerships should be regarded as a strategic investment in long-term institutional development rather than merely an academic activity.

Human capital remains the most valuable resource within every innovation ecosystem. Regardless of technological advancement, sustainable industrial development ultimately depends upon highly qualified engineers capable of generating creative solutions, adapting to technological change and leading organizational transformation.

Future engineers require competencies extending well beyond traditional technical expertise. Digital literacy, systems thinking, interdisciplinary collaboration, project management, entrepreneurial leadership and effective communication have become essential professional attributes. Universities should therefore implement educational strategies that promote holistic competence development through experiential learning, research participation and industrial engagement.

Continuous professional development of academic staff is equally important. Engineering educators should maintain close interaction with industrial enterprises in order to remain informed about emerging technologies, manufacturing processes and professional standards. Faculty internships, industrial sabbaticals and participation in collaborative research projects significantly strengthen the practical relevance of university teaching.

The cultivation of innovation culture among students also deserves strategic attention. Innovation cannot be developed solely through classroom instruction; it requires educational environments encouraging experimentation, creativity, critical inquiry and responsible risk-taking. Student innovation competitions, engineering design challenges, entrepreneurship incubators and interdisciplinary research projects provide valuable opportunities for developing these competencies.

Moreover, engineering education should increasingly emphasize lifelong learning. Rapid technological evolution requires engineers to continuously update their professional knowledge throughout their careers. Universities should therefore establish flexible educational pathways, including micro-credentials, professional certification programmes and continuing engineering education designed to support lifelong competence development.

As one of Uzbekistan's leading engineering higher education institutions located within a major industrial region, Almalyk State Technical Institute possesses unique opportunities to strengthen cooperation between higher education and industry. The close proximity of large mining, metallurgical, chemical and energy enterprises creates favourable conditions for integrating education, scientific research and industrial innovation within a unified regional development framework.

Recognizing these advantages, the Institute has identified university–industry integration as one of its strategic development priorities. Educational programmes are continuously improved through consultation with industrial stakeholders to ensure that graduates acquire competencies aligned with technological modernization and labour market requirements. Practical training, industrial internships and employer participation in curriculum development have become important mechanisms for enhancing educational quality.

Scientific research at the Institute increasingly addresses technological challenges encountered by industrial enterprises operating within the region. Collaborative research projects enable academic staff and graduate students to develop innovative engineering solutions capable of improving production efficiency, environmental sustainability and technological competitiveness. Such cooperation simultaneously strengthens applied research and contributes to regional economic development.

International cooperation further reinforces the Institute's strategic development objectives. Partnerships with foreign universities, participation in international scientific conferences, academic mobility programmes and collaborative research initiatives facilitate the exchange of knowledge and best practices in engineering education and innovation management. These activities contribute to improving institutional capacity while supporting the internationalization of higher education.

Looking toward the future, Almalyk State Technical Institute aims to further expand technology transfer mechanisms, strengthen interdisciplinary research, establish new innovation platforms and deepen strategic partnerships with industrial enterprises and international academic institutions. Through these initiatives, the Institute seeks to contribute meaningfully to Uzbekistan's technological modernization and sustainable industrial development while preparing highly qualified engineering professionals capable of addressing the challenges of the digital economy.

Conclusion

The accelerating pace of technological innovation has fundamentally transformed the mission of engineering universities. Higher education institutions are no longer expected to function solely as providers of academic knowledge; they have become strategic actors within national innovation ecosystems, responsible for generating scientific knowledge, supporting technological advancement and contributing to sustainable socio-economic development. Under these conditions, the integration of higher education and industry has evolved from an institutional objective into a strategic necessity.

This study demonstrates that effective university–industry integration requires a holistic and long-term approach encompassing educational modernization, applied research, technology transfer, innovation management and international cooperation. Sustainable partnerships between universities and industrial enterprises create mutual value by improving the relevance of engineering education, accelerating the commercialization of scientific research and strengthening regional innovation capacity. Universities that successfully integrate these dimensions become powerful catalysts of technological transformation and economic competitiveness.

Engineering education must continue evolving in response to Industry 4.0, Industry 5.0 and the rapidly expanding digital economy. Future engineers should possess not only advanced technical expertise but also interdisciplinary competencies, entrepreneurial thinking, digital literacy, ethical awareness and leadership capabilities. Such comprehensive professional preparation enables graduates to respond effectively to increasingly complex technological and societal challenges.

Technology transfer represents one of the most important institutional mechanisms supporting innovation-driven development. Universities should therefore strengthen technology transfer offices, expand intellectual property management systems and establish innovation infrastructures that facilitate collaboration among researchers, industrial enterprises, investors and governmental organizations. These institutional reforms will significantly increase the practical impact of academic research while supporting sustainable industrial modernization.

International cooperation will remain an essential driver of engineering education. Collaborative research projects, academic mobility, joint educational programmes and strategic partnerships with internationally recognized universities and industrial corporations create opportunities for knowledge exchange, institutional learning and technological innovation. Strengthening such cooperation contributes not only to academic excellence but also to the international competitiveness of national higher education systems.

The experience of Almalyk State Technical Institute confirms that engineering universities located within industrial regions possess unique opportunities to become regional innovation hubs. Through systematic collaboration with industrial enterprises, modernization of engineering curricula, expansion of applied research and active international engagement, universities can effectively bridge the gap between education, science and production. Such integration contributes directly to technological modernization, workforce development and sustainable economic growth.

In conclusion, the future success of engineering education depends upon the establishment of dynamic innovation ecosystems in which universities, industry, government and international partners cooperate within a shared strategic vision. Universities capable of integrating education, research and industrial innovation will not only prepare highly qualified engineers but will also shape the technological future of their nations. The strengthening of higher education–industry integration should therefore remain among the highest strategic priorities for engineering universities seeking to contribute to sustainable development in the twenty-first century.

References

- Clark, B. R. (1998). *Creating Entrepreneurial Universities: Organizational Pathways of Transformation*. Pergamon.
- Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: From National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. *Research Policy*, 29(2), 109–123.
- European Commission. (2022). *A New European Innovation Agenda*. Brussels: European Commission.

OECD. (2019). *University-Industry Collaboration: New Evidence and Policy Options*. Paris: OECD Publishing.

OECD. (2023). *Education at a Glance 2023: OECD Indicators*. Paris: OECD Publishing.

Porter, M. E. (1998). *Clusters and the New Economics of Competition*. *Harvard Business Review*, 76(6), 77–90.

Schwab, K. (2017). *The Fourth Industrial Revolution*. Geneva: World Economic Forum.

UNESCO. (2021). *Engineering for Sustainable Development: Delivering on the Sustainable Development Goals*. Paris: UNESCO.

World Economic Forum. (2023). *The Future of Jobs Report 2023*. Geneva: World Economic Forum.

World Intellectual Property Organization. (2022). *World Intellectual Property Indicators 2022*. Geneva: WIPO.

World Intellectual Property Organization. (2023). *Global Innovation Index 2023: Innovation in the Face of Uncertainty*. Geneva: WIPO.

Zhou, C., & Li, J. (2021). University–Industry Collaboration and Innovation Performance in Engineering Education. *Journal of Engineering Education*, 110(3), 612–635.

Technology Transfer, Legal Regulation and Future Perspectives of Engineering Education in the Digital Era

Sarvar Toshpo‘latovich Parmonov¹

Abstract

The rapid advancement of digital technologies, artificial intelligence, automation and data-driven industrial systems has fundamentally transformed the role of engineering education in modern society. Universities are no longer expected to produce graduates with technical knowledge alone; they are increasingly required to generate innovative technologies, facilitate knowledge transfer and contribute directly to economic development through effective collaboration with industry. Under these conditions, technology transfer has become one of the most important mechanisms for transforming scientific knowledge into practical solutions and commercial innovations. At the same time, the expansion of digital technologies has introduced new legal challenges concerning intellectual property rights, data governance, cybersecurity, licensing and the regulation of artificial intelligence. Consequently, engineering education must prepare graduates who possess not only technical competencies but also an understanding of legal, ethical and entrepreneurial aspects of technological innovation. This paper examines the relationship between technology transfer, legal regulation and engineering education in the digital era. Using comparative and analytical approaches, the study evaluates international experience and discusses current challenges affecting university–industry collaboration. Particular attention is given to the experience of Almalyk State Technical Institute in strengthening industrial cooperation, promoting innovation and developing technology transfer mechanisms that support regional economic development. The findings indicate that effective integration of engineering, law and innovation management significantly improves the commercialization of research outcomes and enhances the quality of engineering education.

¹ Almalyk State Technical Institute, Almalyk, Uzbekistan, E-mail: s.toshpulatovich@odti.uz; ORCID: 0000-0001-6634-8606

Keywords: Technology Transfer, Engineering Education, Artificial Intelligence, Digital Transformation, University–Industry Cooperation, Intellectual Property, Innovation Management, Engineering Law.

Introduction

The Fourth Industrial Revolution has fundamentally reshaped the relationship between higher education, technological innovation and industrial development. Rapid advances in artificial intelligence, automation, robotics, cloud computing, digital manufacturing and cyber-physical systems have accelerated technological progress at an unprecedented pace. These developments are transforming not only industrial production but also the objectives, structure and content of engineering education. Universities are increasingly expected to educate engineers capable of responding to technological change while simultaneously generating innovative solutions that contribute directly to sustainable economic development.

In this context, engineering education has moved beyond its traditional mission of providing theoretical knowledge and technical skills. Modern engineering universities are expected to become innovation hubs that integrate education, scientific research and industrial collaboration into a unified ecosystem. Consequently, technology transfer has emerged as a strategic instrument for connecting scientific discoveries with industrial applications and transforming academic knowledge into commercially valuable technologies.

Despite significant scientific achievements in engineering disciplines, many universities continue to face difficulties in transferring research results into practical industrial applications. Numerous innovative ideas remain confined to academic publications, dissertations or laboratory experiments without reaching manufacturing enterprises or contributing to technological modernization. This gap between academic research and industrial implementation represents one of the major challenges confronting engineering education worldwide.

Digital transformation has further complicated this challenge. Artificial intelligence, autonomous systems, big data analytics and smart manufacturing technologies have created new opportunities for innovation while simultaneously raising complex legal and ethical questions. Issues concerning intellectual property protection, data ownership, cybersecurity, digital evidence, algorithmic accountability and legal responsibility for autonomous systems have become increasingly important for both engineers and legal scholars. Therefore, engineering education can no longer be separated from legal awareness and innovation management.

International organizations such as UNESCO, OECD and the World Intellectual Property Organization emphasize that future engineers should possess interdisciplinary competencies that combine technical expertise with legal knowledge, entrepreneurial thinking and digital literacy. Universities capable of integrating these competencies into their educational systems are more likely to achieve successful commercialization of research results and strengthen their contribution to national innovation systems.

Against this background, this paper explores the role of technology transfer as a bridge between engineering education, technological innovation and legal regulation in the digital era. It also discusses the institutional mechanisms required to strengthen university–industry cooperation and examines the experience of Almalyk State Technical Institute in promoting innovation-oriented engineering education.

Materials and Methods

This study employs a qualitative research design based on comparative, analytical and descriptive methods. The research primarily relies on the systematic review of recent international literature concerning engineering education, technology transfer, innovation management and legal regulation of emerging technologies. Publications of international organizations, including UNESCO, OECD, the World Intellectual Property Organization (WIPO), and the European Commission, together with peer-reviewed journal articles indexed in Scopus and Web of Science, were analyzed to identify current trends affecting engineering education in the digital era.

A comparative approach was applied to evaluate different models of university–industry collaboration implemented in technologically advanced countries. Particular attention was given to technology transfer offices (TTOs), innovation ecosystems, entrepreneurial universities and institutional mechanisms supporting research commercialization. In addition, document analysis was used to examine international legal frameworks regulating intellectual property, digital technologies and artificial intelligence.

Institutional analysis was employed to assess the practical experience of Almalyk State Technical Institute in strengthening industrial cooperation, supporting innovation activities and improving technology transfer mechanisms. The combination of these research methods provides a comprehensive understanding of the relationship between engineering education, technological innovation and legal regulation in the context of digital transformation.

Results and Discussion

Technology transfer has become one of the most important indicators of university performance in the twenty-first century. While universities have traditionally been evaluated according to their educational quality and scientific publications, modern

higher education institutions are increasingly assessed by their capacity to transform research findings into innovative products, industrial technologies and commercially viable solutions. Consequently, technology transfer is no longer considered an additional activity but rather a core mission of engineering universities.

The concept of technology transfer refers to the systematic movement of scientific knowledge, technical expertise and research outcomes from universities and research institutions to industry and society. It encompasses a broad range of activities including patenting, licensing, commercialization of research, establishment of start-up companies, industrial consultancy, collaborative research and the creation of innovation ecosystems. Effective technology transfer enables scientific discoveries to generate tangible economic and social benefits while simultaneously increasing the competitiveness of universities and national economies.

Recent international experience demonstrates that successful engineering universities are distinguished not only by academic excellence but also by their ability to establish sustainable partnerships with industry. Institutions such as the Massachusetts Institute of Technology (MIT), Stanford University, Tsinghua University, the National University of Singapore and KAIST have developed comprehensive innovation ecosystems where scientific research is closely integrated with industrial development. Their technology transfer offices actively support patent applications, negotiate licensing agreements, assist researchers in establishing spin-off companies and facilitate collaboration with industrial partners. As a result, research outcomes rapidly evolve into commercially successful technologies.

The transformation of universities into entrepreneurial institutions has significantly changed the role of engineering education. Students are no longer passive recipients of knowledge; instead, they actively participate in innovation projects, interdisciplinary research teams and industrial problem-solving activities. Engineering curricula increasingly incorporate project-based learning, innovation management, entrepreneurship and commercialization strategies alongside traditional technical subjects. This educational model prepares graduates capable of creating technological solutions rather than merely applying existing technologies.

One of the principal challenges affecting technology transfer is the persistent gap between academic research and industrial implementation. Universities often prioritize scientific publications and theoretical achievements, whereas industries primarily seek practical, market-oriented solutions capable of increasing productivity and reducing production costs. This difference in institutional priorities frequently limits effective cooperation. Consequently, many valuable engineering innovations remain confined to laboratories despite possessing considerable commercial potential.

The Triple Helix model, developed by Etzkowitz and Leydesdorff, provides a useful theoretical framework for overcoming this challenge. According to this model, innovation emerges through continuous interaction among universities, industry and government. Universities generate scientific knowledge, industries transform knowledge into commercial products, while governments establish regulatory frameworks and financial incentives supporting innovation. Sustainable technological development therefore depends upon balanced cooperation among these three institutional actors.

The emergence of Industry 4.0 and Industry 5.0 has further strengthened the strategic importance of technology transfer. Smart manufacturing systems, industrial robotics, digital twins, additive manufacturing, artificial intelligence and cyber-physical production systems require universities to maintain continuous interaction with industrial enterprises. Engineering education must therefore become increasingly adaptive, interdisciplinary and innovation-oriented. Technology transfer offices consequently perform not only administrative functions but also strategic roles in coordinating research commercialization, intellectual property management and industrial partnerships.

For engineering universities located within major industrial regions, technology transfer acquires even greater significance. Scientific research conducted in such institutions should directly address industrial challenges related to productivity, energy efficiency, environmental sustainability, automation and digital transformation. Universities thereby become active contributors to regional economic development rather than remaining isolated academic institutions.

In this regard, technology transfer should be recognized not merely as the final stage of scientific research but as an integrated process beginning with research planning and continuing through commercialization, industrial implementation and long-term technological development. Engineering education capable of incorporating this comprehensive perspective will be substantially better positioned to respond to future technological and economic challenges.

The rapid expansion of digital technologies has significantly altered the legal environment surrounding engineering innovation. Artificial intelligence, machine learning, blockchain technologies, autonomous systems, cloud computing and industrial Internet of Things (IIoT) have generated entirely new categories of legal relationships that did not exist only a decade ago. As engineering solutions become increasingly intelligent and autonomous, traditional legal frameworks are often unable to provide adequate regulation for emerging technologies. Consequently, legal regulation has become an essential component of engineering innovation rather than an external administrative requirement.

One of the most significant legal issues concerns intellectual property rights. Engineering innovations usually involve substantial investments in scientific research, laboratory experimentation and industrial testing. Without effective legal protection, innovators face considerable risks of unauthorized reproduction, technology theft and unfair commercial competition. Patent protection therefore remains one of the primary instruments ensuring that scientific achievements can be successfully commercialized while protecting the interests of researchers, universities and industrial partners.

However, the digital economy has introduced new challenges that extend beyond conventional patent systems. Artificial intelligence is now capable of generating software code, engineering designs, optimization models and even technical inventions with minimal human intervention. These developments raise complex legal questions regarding authorship and ownership. If an artificial intelligence system independently develops an engineering solution, determining the legal owner of that invention becomes increasingly complicated. Existing intellectual property legislation in many jurisdictions has not yet fully addressed these emerging situations, creating uncertainty for universities and technology companies.

Data governance has also become a critical legal issue within engineering education and industrial innovation. Modern manufacturing systems continuously collect enormous volumes of operational data through sensors, digital platforms and connected industrial equipment. These data constitute valuable strategic assets that can improve production efficiency, predictive maintenance and decision-making processes. Nevertheless, questions concerning data ownership, access rights, cybersecurity and confidentiality require comprehensive legal regulation. Universities engaged in collaborative research with industrial enterprises must therefore establish transparent agreements governing data sharing, intellectual property ownership and confidentiality obligations.

Artificial intelligence additionally introduces new dimensions of legal responsibility. Autonomous engineering systems increasingly perform tasks that were previously controlled exclusively by human operators. Self-regulating industrial robots, automated quality control systems and AI-assisted production management significantly improve productivity but simultaneously create legal uncertainty. If an autonomous industrial system causes financial loss, environmental damage or workplace accidents, determining legal liability becomes highly complex. Responsibility may potentially involve software developers, equipment manufacturers, system operators, university researchers or industrial enterprises depending upon the circumstances. Consequently, engineering education should incorporate fundamental legal knowledge enabling future engineers to understand the legal implications of technological decision-making.

Another increasingly important area concerns ethical governance of technological innovation. Engineering solutions directly influence public safety, environmental

sustainability and social welfare. The development of artificial intelligence applications, autonomous vehicles, facial recognition systems and digital surveillance technologies requires engineers to consider ethical principles alongside technical performance. International organizations, including UNESCO and the European Commission, have emphasized that trustworthy artificial intelligence must respect transparency, accountability, fairness and human rights. Engineering education should therefore integrate ethical reasoning into technical curricula, ensuring that graduates understand both technological capabilities and societal responsibilities.

Licensing agreements represent another essential legal instrument supporting technology transfer. Universities frequently collaborate with industrial enterprises to commercialize patented inventions or software solutions. Well-structured licensing agreements clearly define ownership rights, financial arrangements, responsibilities and conditions for technology utilization. Effective legal support during licensing negotiations significantly increases investor confidence and facilitates successful commercialization of academic research. Consequently, technology transfer offices increasingly employ legal experts specializing in intellectual property management and contract negotiation.

International collaboration further emphasizes the importance of harmonized legal standards. Engineering research increasingly involves multinational partnerships where universities, industries and research organizations operate under different legal systems. Differences in patent legislation, copyright protection, data privacy regulations and technology export controls may complicate collaborative innovation projects. Therefore, engineering universities should provide researchers with appropriate legal guidance to ensure compliance with international regulatory requirements while protecting institutional interests.

For engineering education institutions, these developments indicate that legal literacy has become an essential professional competence rather than a supplementary qualification. Future engineers should understand the legal environment governing innovation, intellectual property protection, technology commercialization and digital governance. Likewise, legal professionals increasingly require fundamental knowledge of engineering technologies to develop effective regulatory frameworks capable of supporting technological progress without restricting innovation.

In this context, technology transfer offices perform a strategic bridging function between engineering research and legal regulation. Their responsibilities extend beyond patent administration to include legal consultation, intellectual property management, licensing negotiations, contract preparation, risk assessment and regulatory compliance. Strengthening these institutional capacities significantly enhances the commercialization

potential of engineering research while reducing legal uncertainty for universities and industrial partners.

Ultimately, successful technological innovation in the digital era depends not only on scientific excellence but also on the establishment of reliable legal frameworks capable of balancing innovation, commercial interests, public safety and ethical responsibility. Engineering education must therefore prepare graduates who are capable of navigating both technological complexity and the evolving legal environment that governs digital innovation.

The future of engineering education will be shaped by the convergence of digital technologies, interdisciplinary knowledge and innovation-driven economic development. Traditional engineering curricula, which primarily focused on technical theory and discipline-specific competencies, are gradually evolving into flexible educational models that emphasize creativity, entrepreneurship, digital literacy and lifelong learning. Universities are increasingly expected to educate engineers who can successfully operate in rapidly changing technological environments while contributing to sustainable industrial development.

One of the defining characteristics of future engineering education is interdisciplinarity. Modern engineering problems rarely belong to a single scientific discipline. Instead, they require integrated knowledge of mechanical engineering, information technology, artificial intelligence, environmental science, economics, management and law. Consequently, engineering programmes should encourage interdisciplinary collaboration through project-based learning, multidisciplinary research teams and joint educational initiatives involving different academic departments.

Digitalization will continue transforming teaching methodologies. Virtual laboratories, digital twins, cloud-based simulation platforms, augmented reality and artificial intelligence-assisted learning environments provide students with opportunities to develop practical competencies beyond traditional classroom instruction. These technologies enable universities to deliver highly personalized learning experiences while strengthening students' analytical and problem-solving abilities.

Another important trend concerns entrepreneurial engineering education. Universities increasingly recognize that engineering graduates should possess competencies extending beyond technical problem solving. Knowledge of innovation management, start-up creation, venture financing, intellectual property commercialization and business development has become equally important. Entrepreneurial engineers are capable not only of designing technological solutions but also of transforming those solutions into commercially sustainable enterprises that contribute to economic growth.

In addition to entrepreneurial competencies, future engineering education must prioritize sustainability and social responsibility. Contemporary engineering solutions are expected to address global challenges such as climate change, renewable energy, resource efficiency and environmental protection. Consequently, concepts such as Green Engineering, Circular Economy and Sustainable Manufacturing are becoming integral components of engineering curricula worldwide. Engineering graduates should therefore be capable of evaluating not only the technical feasibility of innovations but also their environmental, economic and social impacts.

Artificial intelligence will undoubtedly become one of the defining technologies influencing engineering education over the next decade. AI-powered design optimization, predictive maintenance, intelligent manufacturing systems and autonomous industrial processes are already changing the professional responsibilities of engineers. Rather than replacing engineers, artificial intelligence is expected to augment human decision-making by improving analytical capabilities and reducing routine tasks. Engineering education should therefore focus on preparing graduates who are capable of working collaboratively with intelligent systems while maintaining critical thinking and professional judgment.

The CDIO (Conceive–Design–Implement–Operate) educational framework represents one of the most successful international models for modern engineering education. This approach encourages students to participate in the complete innovation cycle—from identifying societal needs and designing engineering solutions to implementing prototypes and evaluating operational performance. Universities adopting CDIO have reported significant improvements in students' practical competencies, teamwork, communication skills and innovation capacity. Integrating similar educational approaches into engineering programmes can substantially enhance graduate employability and industrial relevance.

Another important trend is the increasing internationalization of engineering education. Academic mobility, joint degree programmes, collaborative research projects and international innovation networks enable universities to exchange knowledge, share research infrastructure and develop globally competitive graduates. Participation in international research consortia also facilitates technology transfer by providing access to advanced scientific equipment, funding opportunities and multinational industrial partnerships. Consequently, engineering universities should actively strengthen international cooperation as part of their long-term development strategies.

Digital transformation additionally requires universities to modernize their institutional governance systems. Decision-making processes should increasingly rely on digital information systems, learning analytics and evidence-based management. Smart university concepts integrating digital administration, virtual learning environments, research information systems and innovation management platforms are becoming

essential components of institutional competitiveness. Universities capable of effectively utilizing digital technologies in both academic and administrative activities will be better positioned to respond to future educational challenges.

Ultimately, the future of engineering education depends upon universities' ability to integrate technological innovation, interdisciplinary learning, entrepreneurship and legal awareness into coherent educational ecosystems. Institutions that successfully combine these dimensions will produce graduates capable of leading technological transformation while contributing responsibly to sustainable social and economic development.

Experience of Almalyk State Technical Institute

Almalyk State Technical Institute occupies a strategically important position within one of Uzbekistan's largest industrial regions. This geographical advantage creates favourable conditions for strengthening university–industry cooperation and aligning engineering education with the technological needs of major mining, metallurgical, chemical and energy enterprises operating in the region. The Institute therefore considers technology transfer and industrial collaboration as strategic priorities for institutional development.

In recent years, the Institute has expanded collaborative relationships with industrial enterprises through joint scientific projects, applied research initiatives and student internship programmes. Particular emphasis has been placed on directing graduation projects, master's theses and doctoral research toward solving practical technological challenges encountered by regional industries. This approach enables students to acquire practical experience while simultaneously contributing to industrial innovation.

The Institute has also intensified efforts to modernize research infrastructure by establishing specialized laboratories and promoting interdisciplinary research activities. Cooperation with international universities has further strengthened institutional capacity in engineering education, scientific research and technology transfer. Academic exchange programmes, joint conferences and collaborative research initiatives have facilitated the sharing of international best practices concerning innovation management and commercialization of research outcomes.

Recognizing the growing importance of legal regulation within technological innovation, the Institute actively encourages interdisciplinary dialogue among engineering, management and legal scholars. Such collaboration contributes to a more comprehensive understanding of intellectual property management, technology commercialization and regulatory challenges associated with digital transformation. This integrated approach reflects the Institute's commitment to preparing engineers capable of addressing both technological and societal challenges.

Looking forward, Almalyk State Technical Institute aims to further strengthen its technology transfer mechanisms by expanding international partnerships, improving innovation support services, promoting start-up activities and enhancing collaboration with industrial stakeholders. These initiatives are expected to contribute not only to institutional development but also to the broader technological modernization and sustainable economic growth of Uzbekistan.

Conclusion

Digital transformation has fundamentally changed the relationship between engineering education, technological innovation and legal regulation. Universities are increasingly expected to function as innovation ecosystems capable of generating scientific knowledge, commercializing research outcomes and supporting sustainable industrial development. Under these conditions, technology transfer represents a strategic mechanism that connects academic research with practical implementation while strengthening the competitiveness of higher education institutions.

The study demonstrates that successful technology transfer depends upon several interconnected factors, including effective university–industry collaboration, well-developed innovation infrastructure, comprehensive intellectual property management and appropriate legal regulation. Modern engineering education must therefore extend beyond technical specialization by integrating legal literacy, entrepreneurial thinking and interdisciplinary competencies into academic programmes.

Emerging technologies such as artificial intelligence, smart manufacturing and digital platforms create unprecedented opportunities for technological progress while simultaneously introducing complex legal and ethical challenges. Preparing engineers capable of addressing these challenges requires educational models that combine scientific excellence with innovation management and regulatory awareness. Universities should therefore strengthen cooperation with legal scholars, industrial enterprises and governmental institutions in order to establish comprehensive innovation ecosystems.

The experience of Almalyk State Technical Institute illustrates that close interaction with regional industries, investment in research infrastructure and active international cooperation significantly enhance technology transfer and innovation capacity. Continued development of these institutional mechanisms will contribute to improving engineering education, accelerating research commercialization and supporting national economic development.

In conclusion, the future of engineering education depends not only on technological advancement but also on the successful integration of innovation, legal regulation and university–industry collaboration. Universities capable of achieving this

integration will play a decisive role in shaping sustainable technological development in the digital era.

References

- Chesbrough, H. W. *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston: Harvard Business School Press, 2003.
- Etzkowitz, H., & Leydesdorff, L. *The Triple Helix: University–Industry–Government Innovation in Action*. New York: Routledge, 2008.
- Tidd, J., & Bessant, J. *Managing Innovation: Integrating Technological, Market and Organizational Change*. 7th ed. Hoboken, NJ: John Wiley & Sons, 2021.
- World Intellectual Property Organization (WIPO). *World Intellectual Property Indicators 2024*. Geneva: WIPO, 2024.
- Organisation for Economic Co-operation and Development (OECD). *OECD Science, Technology and Innovation Outlook 2023*. Paris: OECD Publishing, 2023.
- United Nations Educational, Scientific and Cultural Organization (UNESCO). *Recommendation on the Ethics of Artificial Intelligence*. Paris: UNESCO, 2021.
- Fatkhutdinov, R. A. *Innovation Management*. 6th ed. Moscow: INFRA-M Publishers, 2021. *(Translated from Russian.)*
- Castells, M. *The Information Age: Economy, Society and Culture*. Moscow: Higher School of Economics Publishing House, 2000. *(Russian edition.)*
- Glazyev, S. Yu. *Theory of Long-Term Techno-Economic Development*. Moscow: VlaDar Publishers, 2013.
- Bovin, A. A., Cherednikova, L. E., & Yakimovich, V. A. *Innovation Management in Organizations*. Moscow: Omega-L Publishers, 2018.
- Mirziyoyev, Sh. M. *The Strategy of New Uzbekistan*. Tashkent: Uzbekistan Publishing House, 2021.
- Law of the Republic of Uzbekistan "On Innovation Activity", No. ORQ-630, July 24, 2020.
- Decree of the President of the Republic of Uzbekistan "On the Uzbekistan–2030 Strategy", No. PF-158, September 11, 2023.

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education
Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Law of the Republic of Uzbekistan "On Education", No. ORQ-637, September 23, 2020.

Cabinet of Ministers of the Republic of Uzbekistan. *Collection of normative Legal Documents on the Development of Science and Innovation Activities*. Tashkent, 2023.

Modern Approaches to Infrastructure Development and Efficient Resource Utilization in Technical Higher Education Institutions

Nusratilla Rajabovich Barakayev¹

Abstract

The modernization of technical higher education institutions has become one of the strategic priorities for improving educational quality, strengthening research capacity and supporting sustainable industrial development. Contemporary engineering universities require not only highly qualified academic staff but also advanced educational infrastructure, intelligent resource management systems and digital technologies capable of supporting innovation-oriented learning environments. Consequently, infrastructure development and efficient resource utilization have emerged as fundamental components of institutional competitiveness.

This paper examines modern approaches to infrastructure development in technical universities with particular emphasis on digital transformation, Smart Campus technologies, intelligent resource management and university–industry integration. The study discusses the role of digital platforms, advanced laboratories, energy-efficient infrastructure and artificial intelligence in improving institutional performance. International experience demonstrates that universities successfully integrating digital management systems with sustainable infrastructure achieve higher educational quality, improved operational efficiency and stronger research outcomes.

The paper concludes that investment in intelligent infrastructure and effective resource management should be regarded as a strategic priority for technical higher education institutions seeking to strengthen innovation capacity and international competitiveness.

Keywords: Technical Higher Education, Smart Campus, Digital Transformation, Infrastructure Development, Resource Management, Engineering Education, Innovation.

¹ Almalyk State Technical Institute, Almalyk, Uzbekistan E-mail: bnr-1967@mail.ru; ORCID: 0000-0002-3798-3851

Introduction

The rapid development of science, engineering and digital technologies has fundamentally transformed the operational environment of higher education institutions. Universities are increasingly expected to provide modern educational infrastructure capable of supporting advanced teaching methodologies, scientific research and technological innovation. Within technical universities, infrastructure represents far more than physical buildings and laboratories; it encompasses integrated digital platforms, intelligent management systems, research facilities and innovation environments that collectively determine institutional effectiveness.

Global competition among universities has further increased the importance of infrastructure modernization. International university rankings increasingly evaluate institutions according to research capacity, digital readiness, sustainability, innovation performance and industry collaboration. Consequently, technical universities must continuously modernize their infrastructure while ensuring the efficient utilization of financial, material and intellectual resources.

In Uzbekistan, comprehensive reforms implemented within the higher education sector have created favourable conditions for strengthening engineering education through infrastructure modernization and digital transformation. New laboratories, digital learning environments, research centers and international partnerships are gradually improving institutional capacity. Nevertheless, sustainable development requires systematic approaches capable of integrating educational infrastructure, digital governance and efficient resource management into a unified institutional strategy.

This paper analyzes contemporary approaches to infrastructure development and effective resource utilization in technical higher education institutions while examining international best practices that may contribute to improving institutional competitiveness and educational quality.

Infrastructure development in technical higher education institutions has evolved into a multidimensional strategic process that extends far beyond the construction of academic buildings and laboratories. Modern engineering universities require integrated educational ecosystems where physical infrastructure, digital technologies, research facilities and intelligent management systems operate in harmony to support education, scientific research and innovation. Consequently, infrastructure modernization should be regarded as a long-term institutional investment rather than a series of isolated construction projects.

One of the most important priorities is the establishment of Smart Campus environments. A Smart Campus integrates digital technologies into every aspect of

university management, including academic administration, research activities, campus security, facility management and student services. Through centralized digital platforms, universities can improve operational efficiency, enhance transparency and provide high-quality educational services while reducing administrative costs.

Another strategic priority involves the modernization of engineering laboratories. Technical universities should continuously invest in advanced laboratory equipment capable of supporting education in automation, robotics, materials science, artificial intelligence, mining technologies, chemical engineering and digital manufacturing. Laboratories should not function solely as teaching facilities but also as multidisciplinary research centers where academic staff, graduate students and industrial experts collaborate on solving practical engineering problems. Such laboratories create favorable conditions for innovation while strengthening cooperation between universities and industrial enterprises.

Digital transformation has also introduced new opportunities for improving institutional governance. Enterprise Resource Planning (ERP) systems enable universities to integrate financial management, procurement, human resources, research administration and academic services within a single information platform. Similarly, Learning Management Systems (LMS) and Higher Education Management Information Systems (HEMIS) facilitate effective monitoring of educational processes, curriculum implementation, student performance and institutional quality assurance. The integration of these digital platforms significantly improves decision-making through real-time data analysis and evidence-based management.

Efficient infrastructure management increasingly depends upon intelligent technologies capable of optimizing resource utilization. Internet of Things (IoT) applications allow universities to monitor energy consumption, laboratory occupancy, environmental conditions and equipment performance through interconnected digital sensors. Such systems contribute to reducing operational expenditures while improving the reliability and sustainability of campus infrastructure.

Building Information Modeling (BIM) has emerged as another valuable technology supporting infrastructure planning and management. Digital building models provide comprehensive information concerning construction, maintenance and renovation processes throughout the entire life cycle of university facilities. Engineering students also benefit from practical exposure to BIM technologies, which have become standard tools within modern construction and infrastructure industries.

Environmental sustainability should constitute an essential component of infrastructure development strategies. Universities are increasingly expected to reduce carbon emissions, improve energy efficiency and utilize renewable energy resources. The

installation of solar energy systems, intelligent lighting technologies, automated climate control systems and energy monitoring platforms contributes not only to environmental protection but also to significant reductions in operational costs. Sustainable infrastructure therefore represents both an ecological responsibility and an economically efficient institutional strategy.

Finally, infrastructure modernization should support stronger integration between education, research and industrial production. Innovation centers, engineering incubators, technology transfer offices and joint university–industry laboratories provide effective institutional mechanisms for transforming scientific research into practical technological solutions. Such integrated infrastructure strengthens graduate employability, promotes applied research and enhances the competitiveness of technical universities within both national and international higher education systems.

The effectiveness of a technical university depends not only on the availability of modern infrastructure but also on its ability to manage institutional resources efficiently. Financial investments, laboratory equipment, digital technologies, academic facilities and human capital constitute strategic resources that directly influence educational quality, scientific productivity and institutional sustainability. Therefore, effective resource management has become one of the fundamental principles of contemporary university governance.

Resource utilization in technical higher education institutions should be based on the principles of transparency, accountability, digital management and continuous performance evaluation. Traditional administrative approaches, often characterized by fragmented planning and decentralized decision-making, are gradually being replaced by integrated digital management systems capable of supporting evidence-based governance. Such systems enable university administrators to allocate resources more efficiently while improving institutional responsiveness to emerging educational and technological challenges.

Financial sustainability represents the first dimension of efficient resource management. Universities should diversify funding sources by combining government support with competitive research grants, industrial contracts, international projects and private-sector partnerships. This diversified financial model increases institutional resilience while creating additional opportunities for infrastructure modernization, laboratory development and academic innovation.

The efficient utilization of physical infrastructure is equally important. Laboratories, research facilities, classrooms and specialized engineering equipment require systematic planning to maximize their educational and scientific value. Shared laboratory models, interdisciplinary research facilities and centralized equipment

management systems allow multiple academic departments to utilize expensive technological resources more effectively. Such approaches reduce unnecessary duplication of equipment while significantly improving return on institutional investment.

Digital resource management has become another essential component of university administration. The integration of Enterprise Resource Planning (ERP) systems enables centralized management of finance, procurement, maintenance, inventories and human resources. Combined with Learning Management Systems (LMS) and Higher Education Management Information Systems (HEMIS), these technologies create a comprehensive digital environment supporting academic planning, quality assurance and institutional decision-making. The availability of real-time data enables university leaders to identify operational inefficiencies and implement timely corrective measures.

Information resources also require strategic management. Digital libraries, scientific databases, cloud computing services and institutional research repositories provide students and academic staff with immediate access to global scientific knowledge. Universities should continuously invest in digital information infrastructure to ensure equal access to high-quality educational resources while strengthening research productivity and international collaboration.

Human capital remains the most valuable institutional resource. Universities should therefore establish continuous professional development programmes that enhance the pedagogical, scientific and digital competencies of academic staff. Participation in international training programmes, industrial internships and collaborative research initiatives enables faculty members to maintain professional relevance while introducing contemporary technological knowledge into engineering education.

Furthermore, universities should implement performance evaluation systems based on measurable indicators rather than solely administrative procedures. The assessment of infrastructure utilization, laboratory productivity, research output, energy efficiency and educational performance provides valuable information for strategic planning and continuous institutional improvement. Data-driven management contributes to greater transparency while supporting more effective allocation of institutional resources.

Ultimately, efficient resource utilization is not simply an economic objective; it is a strategic management philosophy that enables technical universities to maximize educational quality, scientific excellence and institutional competitiveness while ensuring sustainable long-term development.

International experience demonstrates that the world's leading technical universities have achieved significant success by integrating digital technologies, sustainable infrastructure and innovation-oriented governance into comprehensive institutional

development strategies. Although each country has developed its own educational model, several common principles can be identified that are directly applicable to the modernization of technical higher education institutions.

Germany provides one of the most successful examples of university–industry cooperation. Technical universities maintain long-term partnerships with manufacturing companies through joint research laboratories, applied engineering centres and collaborative innovation projects. This close interaction ensures that university infrastructure continuously evolves in accordance with industrial technological requirements while providing students with practical experience using advanced engineering equipment.

South Korea has become internationally recognized for implementing Smart Campus technologies throughout higher education institutions. Universities employ integrated digital platforms for academic administration, intelligent classroom management, electronic identification systems, automated library services and campus-wide information management. These technologies significantly improve institutional efficiency while creating highly digitalized learning environments that support innovation and interdisciplinary collaboration.

Finland has placed particular emphasis on sustainable campus development. Energy-efficient buildings, environmentally responsible construction standards and renewable energy systems have become integral components of university infrastructure planning. Sustainability is viewed not only as an environmental responsibility but also as a practical educational model that familiarizes engineering students with modern green technologies and sustainable engineering practices.

Singapore represents another outstanding example of digital transformation within higher education. Universities actively utilize artificial intelligence, Digital Twin technologies and Internet of Things (IoT) systems to monitor infrastructure performance, optimize energy consumption and improve operational management. Intelligent campus management systems provide real-time information regarding laboratory utilization, facility maintenance and resource allocation, thereby increasing institutional efficiency while reducing operational costs.

These international experiences demonstrate that infrastructure modernization should not focus exclusively on physical expansion. Rather, sustainable institutional development depends upon the successful integration of digital governance, intelligent resource management, research infrastructure and strong collaboration with industry. Universities capable of combining these strategic elements are significantly better positioned to respond to technological change, improve educational quality and strengthen their international competitiveness.

Conclusion

The modernization of infrastructure and the efficient utilization of institutional resources have become fundamental prerequisites for the sustainable development of technical higher education institutions. In the context of rapid technological advancement and digital transformation, universities must adopt comprehensive development strategies that integrate educational infrastructure, intelligent management systems, scientific research and industrial collaboration into a unified institutional framework.

This study demonstrates that infrastructure should no longer be viewed merely as a collection of academic buildings and laboratories. Instead, it should be understood as a dynamic educational ecosystem comprising Smart Campus technologies, digital governance platforms, modern research facilities, innovation centers and sustainable engineering solutions. Such integrated infrastructure significantly enhances the quality of education, improves research productivity and strengthens universities' capacity to respond to the technological needs of industry.

Efficient resource utilization is equally important for ensuring institutional sustainability. The implementation of Enterprise Resource Planning (ERP) systems, Learning Management Systems (LMS), Higher Education Management Information Systems (HEMIS), Internet of Things (IoT) technologies and Building Information Modeling (BIM) enables universities to optimize financial, material and human resources while improving transparency, accountability and strategic decision-making. These digital management tools contribute to higher operational efficiency and more effective allocation of institutional resources.

International experience confirms that universities achieving the highest levels of competitiveness consistently combine infrastructure modernization with innovation-oriented governance, strong university–industry partnerships and sustainable resource management. The experiences of Germany, South Korea, Finland and Singapore clearly demonstrate that investment in digital infrastructure and intelligent management systems generates long-term educational, scientific and economic benefits.

For technical higher education institutions in Uzbekistan, these international practices provide valuable guidance for future development. The continued modernization of laboratories, expansion of Smart Campus technologies, strengthening of digital governance, establishment of joint research centers with industrial enterprises and promotion of environmentally sustainable infrastructure should remain among the highest institutional priorities. These initiatives will contribute to improving engineering education, strengthening scientific capacity and preparing graduates capable of supporting the country's technological modernization.

In conclusion, infrastructure development and efficient resource utilization should be regarded not merely as operational management tasks but as strategic instruments for achieving academic excellence, fostering innovation and enhancing the international competitiveness of technical higher education institutions. Universities that successfully integrate digital transformation, sustainable infrastructure and effective governance will be better positioned to meet the challenges of the Fourth Industrial Revolution and contribute meaningfully to national and global technological development.

References

- Altbach, P. G., Reisberg, L., & de Wit, H. (2017). *Responding to Massification: Differentiation in Postsecondary Education Worldwide*. Sense Publishers.
- Drucker, P. F. (2008). *Management: Tasks, Responsibilities, Practices*. Harper Business.
- European Commission. (2021). *Digital Education Action Plan (2021–2027)*. Brussels.
- ISO. (2018). *ISO 50001:2018 Energy Management Systems — Requirements with Guidance for Use*. International Organization for Standardization.
- OECD. (2023). *Digital Education Outlook 2023*. OECD Publishing.
- OECD. (2024). *Education at a Glance 2024: OECD Indicators*. OECD Publishing.
- QS Quacquarelli Symonds. (2025). *QS World University Rankings 2025*. QS.
- Salmi, J. (2009). *The Challenge of Establishing World-Class Universities*. World Bank.
- UNESCO. (2023). *Higher Education in a Digital World*. UNESCO Publishing.
- UNESCO. (2024). *Global Education Monitoring Report 2024*. UNESCO Publishing.
- World Bank. (2023). *Improving Higher Education for Economic Growth*. World Bank.

Electronic Monitoring In Penal Enforcement Law: Between Technological Surveillance and Fundamental Rights

Cafer Erdem Umudum¹

Abstract

Electronic monitoring has emerged as an increasingly important means of supervising suspects, accused persons, and convicted offenders within the community while preserving their family, employment, and educational ties. This study examines the legal nature, practical benefits, and fundamental-rights implications of electronic monitoring in criminal enforcement law, with particular reference to Turkish law and comparative standards. It argues that electronic monitoring is not an autonomous punishment but a technological method for enforcing a judicial measure and therefore must not extend the scope of the underlying legal decision. Although radio-frequency, GPS, biometric, and remote alcohol-monitoring technologies may reduce reliance on imprisonment, enhance victim safety, and support social reintegration, they also create significant risks concerning privacy, data protection, freedom of movement, stigmatisation, and the expansion of penal control. The study maintains that a rights-based electronic-monitoring system requires substantive and procedural legality, judicial review, individualised proportionality assessments, the use of the least intrusive technology, data minimisation, limited retention periods, human verification of automated alerts, and independent evaluation. Electronic monitoring should complement rather than replace probation services, psychosocial assistance, treatment, education, and employment support. Ultimately, its success should be measured not by the number of persons monitored or the technical completion of monitoring periods, but by its capacity genuinely to reduce imprisonment, protect victims, facilitate rehabilitation, and achieve these objectives with the least possible interference with fundamental rights.

¹ Research Assistant, Tekirdağ Namık Kemal University, Criminal and Criminal Procedure Law, e-mail: ceumudum@nku.edu.tr, ORCID: 0000-0001-7613-8637

Keywords: Electronic monitoring, criminal enforcement law, fundamental rights, right to privacy; data protection; proportionality; social reintegration.

Introduction

Electronic monitoring represents one of the most visible points of intersection between criminal justice and technology. Radio frequency (RF), global positioning systems (GPS), biometric verification, and remote alcohol monitoring make it possible to supervise suspects, accused persons, or convicted offenders within the community. By allowing individuals to maintain their family, employment, and educational ties, these technologies may mitigate the adverse consequences of custodial measures. Nevertheless, while removing the physical walls of imprisonment, electronic monitoring also introduces surveillance into the body, the home, and everyday life, thereby creating new risks of human rights violations². The central issue, therefore, is not so much whether technology should be used, but rather for what purpose, with what degree of intensity, and subject to which safeguards it should be employed.

1. Legal Nature, Technology, and Purpose

Electronic monitoring is not an autonomous punishment in itself, but a technological method used to enforce a judicial measure or obligation imposed on an individual. This characterisation is important: technology cannot create an independent power of surveillance that extends the scope of the legal decision on which it is based. In Turkish law, its principal legal basis is Article 15/A of Law No. 5402 on Probation Services. The 2021 Regulation on Probation Services defines electronic monitoring as a method used to enforce decisions intended to support the protection of victims and society. It also regulates its use in connection with home confinement, exclusion from or confinement within designated areas, alcohol monitoring, and victim protection measures³.

The general category of “electronic monitoring” encompasses technologies involving different degrees of interference. RF systems are generally used to verify whether an individual is present at home during specified hours. GPS systems, by contrast, generate real-time location data and movement histories and can be used to monitor exclusion or inclusion zones. Remote alcohol monitoring collects bodily samples

² Denetimli Serbestlik Bağlamında Elektronik İzleme, İstanbul Üniversitesi Sosyal Bilimler Enstitüsü, Yüksek Lisans Tezi, İstanbul 2019, s. 97-103; Mike Nellis, “Understanding the Electronic Monitoring of Offenders in Europe: Expansion, Regulation and Prospects”, *Crime, Law and Social Change*, C. 62, S. 4, 2014, s. 489-510.

³ 5402 sayılı Denetimli Serbestlik Hizmetleri Kanunu m. 15/A; Denetimli Serbestlik Hizmetleri Yönetmeliği, RG 10.11.2021, S. 31655, m. 97-103; T.C. Adalet Bakanlığı Ceza ve Tevkifevleri Genel Müdürlüğü, “Elektronik İzleme”.

or measurement data, while victim protection systems may jointly assess the locations of the offender and the victim and issue an alert in the event of a breach of a restraining or non-contact order⁴. The choice of technology is therefore more than a merely technical procurement decision: using continuous GPS monitoring simply to verify whether a person remains at home during specified hours would generate data disproportionate to the intended purpose.

The anticipated benefits of electronic monitoring include reducing the prison population, limiting the adverse effects of institutional culture, enhancing victim safety, and facilitating social reintegration. The United Kingdom Ministry of Justice's 2022 strategy similarly states that electronic monitoring may help preserve employment, accommodation, treatment, education, and family ties. At the same time, it emphasises that electronic monitoring should not become an end in itself but should remain an instrument of offender management⁵. This approach is equally appropriate for Turkish penal enforcement law: fitting an electronic monitoring device should not replace social support and rehabilitation programmes.

2. Principal Risks to Fundamental Rights

The first risk concerns the right to respect for private and family life. GPS records do not merely reveal a person's location. When accumulated over time, they can facilitate inferences concerning the individual's working patterns, use of healthcare services, religious beliefs, social relationships, and everyday habits. As Dinler observes in relation to technological surveillance instruments, records concerning where, when, and with whom an individual is present may transcend their original security purpose and render personal preferences visible⁶. Devices installed in the home also affect the lives of spouses, children, and other persons living in the same household. The mere existence of a statutory basis is therefore insufficient; under Articles 13 and 20 of the Turkish Constitution and Article 8 of the European Convention on Human Rights, the interference must also be necessary and proportionate.

The second risk is data concentration. Although the integration of biometric verification, images, GPS, RF, and alcohol-monitoring data within a common database

⁴ Ferhat Elçi, "Elektronik İzleme Sistemlerinin Türkiye'de Kullanımı", sunum, 23.05.2018, s. 3-10; Soner Demirtaş, "Elektronik Cihazların Kullanılması Suretiyle İzleme", EÜHFD, C. XIX, S. 3-4, 2015, s. 24-29; Nilay Yıldırım / Asaf Varol, "Türkiye ve Dünya'da Elektronik İzleme Yöntemleri", Türkiye'de Denetimli Serbestlik 10. Yıl Uluslararası Sempozyumu, 2015, s. 195-202.

⁵ UK Ministry of Justice, Electronic Monitoring in the Criminal Justice System, Haziran 2022, s. 7 ve 11.

⁶ Türkiye Cumhuriyeti Anayasası m. 13 ve 20; Avrupa İnsan Hakları Sözleşmesi m. 8; Veysel Dinler, "Özgürlük-Güvenlik İkileminde Teknolojik İzleme ve Kayıt Araçlarının Özel Hayatın Gizliliğine Etkisi", s. 1, 4-7; Umudum, s. 103-104.

provides operational convenience, it may also transform individual movement records into detailed personal profiles⁷. The purposes for which particular data are collected, who may access them, how long they may be retained, whether they may be transferred for use in other investigations, and how inaccurate records may be corrected must all be clearly defined. An automated alert should not, in itself, be treated as proof of a violation. Signal interruptions, battery problems, device malfunctions, and location inaccuracies must be verified by a human decision-maker.

The third risk is the blurring of the boundary between restrictions on freedom of movement and deprivation of liberty. Requirements to remain at home throughout the day, extensive exclusion zones, and prolonged, uninterrupted monitoring increase the severity of the interference, even where the same device is used. Proportionality must be assessed by considering together the duration of the measure, its geographical scope, the permitted area of movement, and the individual's employment, healthcare needs, and caregiving responsibilities. The Council of Europe likewise provides that the type, duration, and manner of implementation of electronic monitoring must be proportionate to the seriousness of the offence, that individual circumstances must be taken into account, and that the decision must be reviewed regularly⁸.

The impact of electronic monitoring on everyday life extends beyond the wording of legal rules. Özkan's qualitative study, conducted with a limited number of participants, indicates that an electronic tag may blur the boundary between "punishment" and "liberty" by making surveillance visible on the body and may impose burdens on family life, financial circumstances, and social relationships⁹. The visible and stigmatising appearance of the device, the need to keep it charged, and the possibility that a technical malfunction may give rise to suspicion of a breach can affect the individual's employment and social interactions. Any individual assessment conducted before the measure is imposed should therefore take these practical burdens into account.

The fourth risk is that electronic monitoring may expand the reach of criminal justice rather than operate as a genuine alternative to imprisonment. Imposing electronic monitoring merely because the technology is available on a person who would not otherwise have been detained or who could have been released subject to a less restrictive obligation results in "net-widening." Comparative assessments suggest that this risk may be reduced by restricting electronic monitoring to persons who would otherwise be

⁷ Yıldırım / Varol, s. 201-202.

⁸ Avrupa Konseyi Bakanlar Komitesi, Elektronik İzlemeye İlişkin CM/Rec(2014)4 sayılı Tavsiye Kararı, Temel İlkeler, kural 1-6.

⁹ Bahar Özkan, Post-Panoptik Gözetim ve Elektronik İzleme: Elektronik Kelepçe Anlatıları, Akdeniz Üniversitesi Sosyal Bilimler Enstitüsü, Yüksek Lisans Tezi, Antalya 2022; Bahar Özkan / Gönül Demez, "Hükümlülerin Ceza ve 'Serbestlik' Sınırında Elektronik İzleme Yöntemine Dair Anlatıları", Bozok Sosyal Bilimler Dergisi, C. 1, S. 1, 2023, s. 12-26.

imprisoned¹⁰. Nor is the individual's consent to the use of their own device sufficient in itself, given the unequal power relationship involved. Consent must be informed and revocable, and a refusal to consent should not automatically lead to a more severe outcome¹¹.

3. Safeguards for a Rights-Based System

The first requirement of a rights-based system is compliance with both substantive and procedural legality. The relevant decision must clearly specify the purpose of the measure, the type of technology to be used, its scope and duration, permitted and prohibited areas, and the consequences of a breach. The initial imposition, extension, and intensification of the measure should be subject either to a judicial decision or to prompt and effective judicial review. Under the current Regulation, the fact that a technical assessment is conducted by the Department upon a recommendation from the relevant commission does not eliminate the need for judicial safeguards where a change expands the scope of the interference with fundamental rights¹².

The second requirement is the combined application of the principles of the "least intrusive technology" and "data protection by design." Continuous GPS monitoring should not be used where compliance with an obligation can be verified by RF technology. Data must be adequate, relevant, and limited to what is necessary for the specified purpose, and they must be retained only for a short period. Access to data must be logged, authorisations must be narrowly defined, audits must be independent and periodic, and records must be securely erased once the retention period expires¹³. As the Council of Europe's expert study indicates, the differing ethical implications of RF, GPS, alcohol-monitoring, and biometric systems must be assessed before the relevant technology is deployed¹⁴.

The third requirement is the adoption of appropriate criteria for measuring success. The fact that a device operates without technical problems or that the monitoring period is completed successfully does not, in itself, demonstrate long-term desistance from crime. The findings reviewed by Graham and McIvor indicate that the effects of electronic monitoring on reoffending are complex and that electronic monitoring alone should not be expected to produce lasting behavioural change. The high rates of technical

¹⁰ Hannah Graham / Gill McIvor, *Electronic Monitoring in the Criminal Justice System*, IRISS Insights 40, 2017, s. 5-8; CM/Rec(2014)4, kural 3.

¹¹ 5402 sayılı Kanun m. 15/A; Denetimli Serbestlik Hizmetleri Yönetmeliği m. 103.

¹² Denetimli Serbestlik Hizmetleri Yönetmeliği m. 100; Umudum, s. 109-110; CM/Rec(2014)4, kural 2.

¹³ Dinler, s. 6-7; CM/Rec(2014)4, kural 29-32.

¹⁴ Mike Nellis / Dominik Lehner, *Scope and Definitions: Electronic Monitoring*, European Committee on Crime Problems, PC-CP (2012) 7 rev2, 16.10.2012, s. 1, 3-4.

completion reported in relation to the practice in Hesse provide only limited information concerning the achievement of long-term objectives and therefore support the same distinction¹⁵. Evaluations should accordingly consider a combination of indicators, including actual reductions in imprisonment and pre-trial detention, breaches and reoffending, victim safety, employment, accommodation, family ties, and the monitored individual's experience of their rights¹⁶.

Finally, technology should complement rather than replace human contact. Without guidance from probation officers, psychosocial support, addiction treatment, education, and employment services, a device merely controls the spatial limits of an individual's conduct. Electronic monitoring serves the rehabilitative purpose of penal enforcement only to the extent that it does not weaken constructive professional relationships and supports individualised social interventions¹⁷.

Conclusion

While electronic monitoring offers a less restrictive and more individualised alternative to imprisonment, disproportionate use may transform the home into a digital prison and everyday life into a sphere of surveillance that continuously generates data. Success should not be measured by the number of people monitored, but by the system's capacity genuinely to reduce imprisonment, enhance victim safety, support social reintegration, and achieve these objectives with the least possible interference with fundamental rights. Where legality, judicial review, individualisation, technology-specific impact assessments, data minimisation, limited retention periods, human verification, and independent effectiveness reviews are ensured together, electronic monitoring can remain not an end of penal enforcement law, but a legally constrained instrument that respects human dignity.

References

Avrupa Konseyi Bakanlar Komitesi, *Recommendation CM/Rec(2014)4 on Electronic Monitoring*, 19.02.2014.

Demirtaş, Soner, "Elektronik Cihazların Kullanılması Suretiyle Şüpheli, Sanık veya Hükümlülerin Toplum İçinde İzlenmesi", *Erzincan Üniversitesi Hukuk Fakültesi Dergisi*, C. XIX, S. 3-4, 2015, s. 23-55.

Dinler, Veysel, "Özgürlük-Güvenlik İkileminde Teknolojik İzleme ve Kayıt Araçlarının Özel Hayatın Gizliliğine Etkisi".

Elçi, Ferhat, "Elektronik İzleme Sistemlerinin Türkiye'de Kullanımı", sunum, 23.05.2018.

¹⁵ Graham / McIvor, s. 7-10; Demirtaş, s. 29-30.

¹⁶ UK Ministry of Justice, s. 11; Graham / McIvor, s. 8-10.

¹⁷ Nellis / Lehner, s. 1-3; CM/Rec(2014)4, kural 8, 39 ve 40.

Graham, Hannah / McIvor, Gill, *Electronic Monitoring in the Criminal Justice System*, IRISS Insights 40, 2017.

Nellis, Mike, “Understanding the Electronic Monitoring of Offenders in Europe: Expansion, Regulation and Prospects”, *Crime, Law and Social Change*, C. 62, S. 4, 2014, s. 489-510.

Nellis, Mike / Lehner, Dominik, *Scope and Definitions: Electronic Monitoring*, European Committee on Crime Problems, PC-CP (2012) 7 rev2, 16.10.2012.

Özkan, Bahar, *Post-Panoptik Gözetim ve Elektronik İzleme: Elektronik Kelepçe Anlatıları*, Akdeniz Üniversitesi Sosyal Bilimler Enstitüsü, Yüksek Lisans Tezi, Antalya 2022.

Özkan, Bahar / Demez, Gönül, “Hükümlülerin Ceza ve ‘Serbestlik’ Sınırlarında Elektronik İzleme Yöntemine Dair Anlatıları”, *Bozok Sosyal Bilimler Dergisi*, C. 1, S. 1, 2023, s. 12-26.

T.C. Adalet Bakanlığı Ceza ve Tevkifevleri Genel Müdürlüğü, “Elektronik İzleme”.

UK Ministry of Justice, *Electronic Monitoring in the Criminal Justice System*, Haziran 2022.

Umudum, Cafer Erdem, *Denetimli Serbestlik Bağlamında Elektronik İzleme*, İstanbul Üniversitesi Sosyal Bilimler Enstitüsü, Yüksek Lisans Tezi, İstanbul 2019.

Yıldırım, Nilay / Varol, Asaf, “Türkiye ve Dünya’da Elektronik İzleme Yöntemleri ve Elektronik İzlemede Kullanılan Cihazlar Üzerine Bir Araştırma”, *Türkiye’de Denetimli Serbestlik 10. Yıl Uluslararası Sempozyumu*, 2015, s. 195-205.

Transparency, Accountability, and Administrative Liability in Algorithmic Administrative Decisions

Zeynep Celik Gulseven¹

Abstract

The increasing use of artificial intelligence technologies in public administration has led to the widespread adoption of algorithmic systems in administrative decision-making processes, giving rise to new debates in administrative law. In particular, algorithmic administrative decisions that may significantly affect individuals' fundamental rights and freedoms necessitate the establishment of new safeguards concerning the transparency of decision-making processes, accountability, and legal liability. To address this need, the European Union's Artificial Intelligence Act has adopted a risk-based regulatory model and laid down detailed obligations for high-risk artificial intelligence systems. This study examines the concept of algorithmic administrative decisions within the framework of the Artificial Intelligence Act and evaluates the transparency and accountability obligations imposed on public authorities in relation to these systems. It also considers the Act's approach to liability not only in terms of the consequences arising from algorithmic decisions but also within the broader framework of obligations that must be fulfilled throughout the development and deployment of such systems.

Keywords: European Union Artificial Intelligence Act, algorithmic administrative decision, high-risk artificial intelligence system, transparency, accountability.

Introduction

The increasing use of artificial intelligence technologies in public administration has also led public authorities to employ algorithmic systems in their decision-making processes. While big data analytics, machine learning, and automated decision-making

¹ PhD in Law, Research Assistant, Faculty of Law, İstanbul Ticaret University, zcgulseven@ticaret.edu.tr, ORCID: 0000-0002-9546-4857.

mechanisms enable administrative activities to be carried out more rapidly and efficiently, this transformation has also raised new questions concerning the transparency of decision-making processes, accountability, and legal liability. In response to these developments, the European Union has established a comprehensive legal framework, particularly for high-risk artificial intelligence systems, through the adoption of the Artificial Intelligence Act. The Act seeks to ensure that algorithmic decision-making processes operate in a manner that respects fundamental rights and is subject to effective oversight and scrutiny, as well as being reliable. Against this background, this study examines the concept of algorithmic administrative decisions within the framework of the Artificial Intelligence Act and aims to assess the obligations imposed in relation to high-risk artificial intelligence systems in light of the principles of transparency and accountability.

6. “Algorithmic Administrative Decisions” under the Artificial Intelligence Act

An algorithmic administrative decision refers to the adoption of legally binding administrative acts by public authorities through the use of algorithms, machine-learning systems, or other artificial intelligence applications in the decision-making process. Such decisions may be made entirely automatically or generated semi-automatically under the limited supervision of an administrative authority. Unlike traditional administrative decision-making processes, algorithmic decisions rely on big data analytics, statistical modelling, and artificial intelligence techniques. They therefore give rise to new legal issues, including the explainability of the grounds on which a decision is based, the accuracy of the data used, and the risk of discrimination. Algorithmic decision-making mechanisms are becoming increasingly prevalent, particularly in areas such as the allocation of social benefits, tax inspections, immigration and asylum procedures, and the assessment of public-sector personnel.²

The European Union has sought to regulate algorithmic decision-making processes within the framework of trustworthy artificial intelligence. In this context, the Artificial Intelligence Act largely classifies AI systems used by public authorities that may affect individuals’ fundamental rights as high-risk AI systems. The Act defines an “AI system” (Article 3) and a “high-risk AI system” (Article 6 and Annex III). Under the Act, an AI system is considered high-risk if it is used as a safety component of a product regulated by the relevant legislation or is deployed in one of the areas listed in Annex III that are

² Karen Yeung, “Algorithmic Regulation: A Critical Interrogation”, *Regulation & Governance*, C. 12, S. 4, 2018, s. 505-523; Cary Coglianese ve David Lehr, “Regulating by Robot: Administrative Decision Making in the Machine-Learning Era”, *Georgetown Law Journal*, C. 105, S. 5, 2017, s. 1147-1223.

regarded as sensitive in terms of fundamental rights. These areas include education, employment, access to essential public services, law enforcement, migration and border management, the administration of justice, and democratic processes (Article 6). A substantive assessment within this framework indicates that algorithmic administrative decisions fall within the category of high-risk AI systems. Furthermore, where public authorities act as providers or deployers within the meaning of Article 3, the AI systems they use may be classified as high-risk due to their potential to significantly affect fundamental rights, health, safety, or individuals' legal status.

7. Transparent and Accountable Administrative Decisions

Under the Act, providers and organisations deploying such systems—including public authorities—are required to establish a risk-management system, use high-quality datasets, prepare technical documentation, maintain records, ensure human oversight, meet accuracy and cybersecurity standards, and operate the system in a transparent and traceable manner. In the context of public administration, these obligations are intended to ensure that administrative decision-making processes are subject to effective scrutiny and that individuals' fundamental rights are protected. Accordingly, the concept of “high risk” under the Artificial Intelligence Act constitutes not merely a technical risk assessment but also a normative mechanism that safeguards constitutional values relating to the rule of law, accountability, and the protection of fundamental rights.³

The EU Artificial Intelligence Act sets out the minimum safeguards within which algorithmic decision-making processes involving high-risk AI systems must operate. Article 13 of the Act requires such systems to be designed not merely as technical tools that generate outputs but as transparent systems that enable an understanding of the processes underlying a decision. Accordingly, users must be provided with information concerning the system's intended purpose, performance characteristics, level of accuracy, the nature of the datasets used, and the manner in which its outputs should be interpreted. The objective is thus to ensure that the technical and legal basis of an AI-generated output can be explained. From the perspective of administrative law, this approach demonstrates that algorithmic decisions cannot be regarded merely as automatically generated outputs; rather, they must form part of a reasoned decision-making process that is amenable to legal review (Article 13).

The Act does not permit algorithmic decisions to be left entirely to artificial intelligence; instead, it treats human oversight and technical reliability as integral

³ Regulation (EU) 2024/1689, m. 8-27 (Chapter III: *High-Risk AI Systems*), özellikle m. 8 (yüksek riskli sistemlere ilişkin yükümlülükler), m. 9 (risk yönetim sistemi), m. 10 (veri ve veri yönetimi), m. 11 (teknik dokümantasyon), m. 12 (kayıt tutma), m. 14 (insan gözetimi) ve m. 15 (doğruluk, sağlık ve siber güvenlik).

elements of the legal safeguards governing such decisions. Accordingly, high-risk AI systems must be capable of being monitored by competent public authorities or authorised persons, who must be able, where necessary, to intervene, disregard their outputs, or stop the systems. At the same time, such systems are required to meet certain standards of accuracy, robustness, and cybersecurity and to be protected against risks arising from errors or data manipulation. In this respect, the Artificial Intelligence Act may be understood as seeking to safeguard not only technological security in algorithmic decision-making processes but also principles of administrative oversight, such as transparency and accountability (Articles 14–15).

Algorithmic transparency does not merely entail the complete disclosure of a system's source code or technical architecture. It also requires that the data, criteria, and inferential processes through which a decision is generated be meaningfully understandable to public authorities, the persons affected by the decision, and supervisory or review bodies. Although the technical complexity of algorithmic systems and the ways in which they are used by institutions may create different forms of opacity, transparency in this context can be achieved only in conjunction with explainability, accountability, and human oversight.⁴ This approach demonstrates that, particularly where public authorities rely on machine-learning-based systems, an automated output cannot replace the statement of reasons for an administrative decision. Public authorities remain responsible for explaining the outcome generated by the system by reference to the relevant legal and factual grounds.

8. Administrative Liability in the Context of Transparency and Accountability

The European Union Artificial Intelligence Act does not make the use of high-risk AI systems by public authorities subject solely to technical standards. On the contrary, it recognises the principles of transparency and accountability as fundamental conditions for the lawful operation of such systems. In this context, transparency does not require the complete disclosure of an algorithm's source code or technical architecture. Rather, it requires access to information that enables an appropriate understanding of the system's intended purpose, operational limitations, performance characteristics, level of accuracy, and the manner in which its outputs should be interpreted. Transparency thus makes it possible to understand the effects, grounds, subject matter, and purpose of an enforceable administrative decision. It therefore constitutes a functional safeguard that ensures the

⁴ Jenna Burrell, "How the Machine 'Thinks': Understanding Opacity in Machine Learning Algorithms", *Big Data & Society*, C. 3, S. 1, 2016, s. 2-6; Sandra Wachter / Brent Mittelstadt / Luciano Floridi, "Why a Right to Explanation of Automated Decision-Making Does Not Exist in the General Data Protection Regulation", *International Data Privacy Law*, C. 7, S. 2, 2017, s. 81-90.

intelligibility and reviewability of the algorithmic decision-making process. This approach does not seek the absolute disclosure of technical systems; instead, it aims to render the decision-making process sufficiently visible and traceable to permit effective legal review. This may help mitigate the risks that the “black-box”⁵ nature of algorithmic decisions may pose to fundamental rights.

Accountability, which complements transparency, is given concrete expression in the Artificial Intelligence Act, particularly through the obligations imposed in relation to high-risk AI systems. Obligations such as establishing a risk-management system, maintaining technical documentation and event logs, and ensuring administrative oversight are designed as institutional mechanisms that enable algorithmic decisions to be reviewed retrospectively and responsibility to be established where necessary. In this framework, the Act does not establish a separate regime of technical liability based solely on the outcomes generated by an AI system. Instead, by imposing ongoing monitoring, control, and record-keeping obligations on providers and deployers, it ensures that algorithmic decision-making processes are assessed within the applicable legal liability regime. Transparency and accountability thus emerge not merely as technical requirements intended to ensure the reliability of high-risk AI systems but as fundamental elements of the European Union’s human-centric approach to artificial intelligence.⁶

Under the Artificial Intelligence Act, liability is addressed not merely as a legal consequence attached to the outcome produced by an AI system but within a broader framework of obligations that must be fulfilled throughout the system’s life cycle. Accordingly, the Act imposes varying levels of duties of care, oversight, and record-keeping on providers, deployers, and, in particular, public authorities acting in these capacities. In the event of a potential infringement of rights, the legal assessment therefore concerns not only the accuracy of the algorithmic output but also whether the risk-management system was properly implemented, the required technical documentation was prepared, effective human oversight was ensured, and the system’s use was duly recorded. This approach demonstrates that, in algorithmic decision-making processes, the Artificial Intelligence Act establishes liability within a holistic governance model based on preventive compliance and accountability, rather than a conventional outcome-based model. The Act thus seeks to safeguard the reliability of algorithmic decisions not only

⁵ Ahmet Yayla, *İdare Hukuku Bakımından Yapay Zekâ: İdarenin Faaliyetleri, Yapay Zekâlı İdari İşlemler ve Sorumluluk*, 2. bs., Seçkin Yayıncılık, Ankara, 2026, s. 113-127.

⁶ *European Law Institute, Artificial Intelligence (AI) and Public Administration: Developing Impact Assessments and Public Participation for Digital Democracy (Event Report)*, 25 Kasım 2021, <https://www.europeanlawinstitute.eu>, E.T.: 16.06.2026.

through technical standards but also through continuous oversight, transparency, and institutional accountability mechanisms.

Conclusion

The use of algorithmic decision-making systems by public authorities enables public services to be delivered more rapidly, consistently, and on the basis of data. However, it also gives rise to new legal issues concerning the intelligibility and reviewability of administrative decision-making processes. Through its risk-based approach, particularly in relation to high-risk AI systems, the EU Artificial Intelligence Act seeks to establish a system of legal safeguards that does not treat these issues merely as matters of technical safety. Within this framework, the legitimacy of an algorithmic decision depends not only on the accuracy of the outcome generated but also on whether the data and criteria on which the decision is based can be explained, the limitations of the system are known, and authorised persons can intervene where necessary. Consequently, an automatically generated output cannot, in itself, constitute the statement of reasons for an administrative decision; the decision-making process must be meaningful, traceable, and amenable to effective review.

Under the framework established by the Act, accountability and liability do not constitute an outcome-oriented mechanism that becomes operative only after an infringement has occurred. Rather, the system is structured around preventive obligations. For public authorities, duties relating to risk management, oversight, record-keeping, and control serve both to prevent infringements of fundamental rights and to provide a basis for establishing liability where an infringement occurs. Transparency and accountability are therefore not ancillary principles governing the use of high-risk AI systems but constitutive elements of the European Union's human-centric and trustworthy AI model.

References

Avrupa Parlamentosu ve Konseyi, Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 Laying Down Harmonised Rules on Artificial Intelligence (Artificial Intelligence Act), *Official Journal of the European Union*, L 1689, 12.07.2024.

Burrell, Jenna, "How the Machine 'Thinks': Understanding Opacity in Machine Learning Algorithms", *Big Data & Society*, C. 3, S. 1, 2016, s. 1-12.

Coglianese, Cary / Lehr, David, "Regulating by Robot: Administrative Decision Making in the Machine-Learning Era", *Georgetown Law Journal*, C. 105, S. 5, 2017, s. 1147-1223.

European Law Institute, *Artificial Intelligence (AI) and Public Administration: Developing Impact Assessments and Public Participation for Digital Democracy (Event Report)*, 25.11.2021.

Wachter, Sandra / Mittelstadt, Brent / Floridi, Luciano, “Why a Right to Explanation of Automated Decision-Making Does Not Exist in the General Data Protection Regulation”, *International Data Privacy Law*, C. 7, S. 2, 2017, s. 76-99.

Yayla, Ahmet, *İdare Hukuku Bakımından Yapay Zekâ: İdarenin Faaliyetleri, Yapay Zekâlı İdari İşlemler ve Sorumluluk*, 2. bs., Seçkin Yayıncılık, Ankara, 2026.

Yeung, Karen, “Algorithmic Regulation: A Critical Interrogation”, *Regulation & Governance*, C. 12, S. 4, 2018, s. 505-523.

The Legal Nature of Crypto-Assets and Investor Protection in Digital Financial Markets

Jordan Delev¹

Abstract

The emergence of crypto-assets has created new legal challenges regarding the legal classification of these new digital financial assets, the manner of their regulation and the protection of investors. The lack of harmonized legal standards for investors has long meant a significant risk, which includes market instability, fraud and market manipulation. In this direction, at the European Union level, with the adoption of the Markets in Crypto-Assets (MiCA) Regulation, a significant step was taken towards establishing an integral legal framework for protection against distortions in financial markets and investor protection. The main focus of this paper is a doctrinal comparative analysis of the legal nature of crypto-assets and their impact on investor protection in digital markets. The paper uses the comparative method to compare the legal frameworks of the centralized model of the European Union and the fragmented model of the United States. Additionally, the paper analyzes the role of international organizations (IOSCO, FSB and ESMA) in creating the global regulatory framework, by introducing mandatory disclosure obligations through white papers for crypto-assets, preventing market abuse and coordinated cross-border supervisory cooperation. The paper concludes that it is necessary to construct a multi-layered structure that provides a balanced regulatory approach that, on the one hand, guarantees investor protection, legal certainty, market transparency, financial stability, and, on the other hand, encourages technological innovation within the rapidly growing crypto-asset ecosystem.

Keywords: Crypto-assets; Investor Protection; MiCA Regulation; Digital Financial Markets; Financial Regulation

¹ Professor Dr., Dean, International Vision University, Faculty of Law, Gostivar, N. Macedonia
jordan.delev@vision.edu.mk, ORCID: 0000-0003-3852-0565

Introduction

In the last decade, financial markets have been directly affected by the global digital transformation. As a result of this transformation, crypto-assets have emerged, creating investment markets that include numerous individual and institutional investors. From a legal perspective, crypto-assets do not represent a single legal category. This poses a problem in legal classification, which is extremely important in determining the rules for issuance, trading, deposit, compensation and execution. Unlike conventional financial instruments, which are highly regulated, crypto-assets are often outside these regulatory frameworks.

The European Union (EU) has taken a step towards filling the legal gap by adopting Regulation (EU) 2023/1114 on markets in crypto-assets (MiCA), which entered into force on 29 June 2023 and became fully applicable from 30 December 2024. The European Union's approach is aimed at creating a functional and relatively comprehensive framework, which applies to crypto-assets that are not yet covered by existing financial services law, and excludes financial instruments under MiFID II. However, unlike the EU, the United States of America (US) has a fragmented regulatory framework that includes laws, banking supervision, and anti-money laundering rules. (Jaffri, 2026)

This paper analyzes the doctrinal approaches to the legal classification of crypto-assets and the contemporary protection mechanisms available to investors in digital financial markets. Particular importance is given to the regulatory framework established by MiCA and international regulatory standards, as well as the remaining legal challenges for investor protection.

The Legal Nature and Classification of Crypto-Assets

Modern financial law is faced with the challenge of legal categorization of crypto-assets. This issue is directly affected by the economic function and technological characteristics of crypto-assets, but also by the legal approach adopted in the jurisdiction of the country in which they exist. The question of the legal nature of crypto-assets is also subject to evaluation from the perspective of private law and public law. While private law focuses on whether crypto-assets can be owned, transferred, pledged, public law emphasizes the question of whether they are a regulated financial product. Scientific observations in this field are in the direction of accepting crypto-assets as property, but with a clear emphasis that they do not fit into the traditional concepts of tangible, movable property. (Chan, 2023)

The EU approach through MiCA defines crypto-assets as “a digital representation of value or rights which may be transferred and stored electronically, using distributed ledger technology or similar technology”. It is evident that a wide range of instruments is defined, while avoiding categorizing crypto-assets with any existing legal category. The three main categories recognized by MiCA are: (i) asset-referenced tokens (ARTs), which maintain a stable value by reference to a basket of assets; (ii) electronic money tokens (EMTs), referencing a single official currency; and (iii) all other crypto-assets not otherwise regulated under EU financial services law. (Hallak, 2023) This *numerus clausus* approach with a precise definition of the scope is a significant legal achievement, but it is not complete. Because certain crypto-assets such as non-fungible tokens (NFTs), decentralised finance (DeFi) protocols, and algorithmically stabilised tokens have an uncertain position within the boundaries of the MiCA definition and remain outside its scope. The applied regulatory perimeter creates difficulty in defining crypto-assets, by setting precise boundaries to ensure legal certainty, but on the other hand there is an unstoppable flow of innovation, which must be legislatively integrated. (ESMA, 2023)

The approach applied in the US is drastically more fragmented because a token can be a security if sold as an investment contract, it can be treated as a commodity for the purposes of the Commodity Futures Trading Commission (CFTC), as a virtual currency under the guidelines of the Financial Crimes Enforcement Network (FinCEN), or a controllable electronic record under the commercial law of the state where Article 12 of the Uniform Commercial Code (UCC) Amendments of 2022 was adopted. The framework set out in this way indicates different directions, which often overlap. (SEC, 2026)

The central question that dominates from a private law perspective is whether crypto-assets can be the subject of property rights. Classical civil law theory opposes the categorization of rights over crypto-assets as rights in rem, i.e. as property rights, especially in civil law systems that traditionally require tangible or explicit legal recognition. However, courts in common law systems recognize crypto-assets as a separate, third category of property rights, capable of giving rise to equity claims. (Chan, 2023) The academic discussion is that the applicability of the rules established in property law, both in common law and in classical civil law systems, depends less on the technical characteristics of crypto-assets than on the need to ensure efficient claim of the assets in insolvency, collateralisation and inheritance. The recognition of property rights over crypto-assets has an impact on the position of investors, as it allows them to assert priority claims in the matter of misuse of their assets in insolvency proceedings. (Aksoy, 2023) An additional argument for legal recognition of property rights over crypto-assets is not only regulatory confidence in terms of investor protection, but also tax treatment and securities regulation. (Otabor-Olubor, 2025)

In the attempt to classify crypto-assets, an alternative approach arises, prompted by the question of whether a particular token can be treated as a financial instrument within the meaning of the Markets in Financial Instruments Directive II (MiFID II, Directive 2014/65/EU). According to MiFID II, security tokens that grant rights analogous to dividends, voting participation or profit sharing can qualify as transferable securities. This approach entails serious investor protection obligations that apply to traditional securities markets. (Tomczak, 2022) The categorization of which crypto-assets can qualify as financial instruments is determined by joint guidelines of the European supervisory authorities, the European Banking Authority (EBA), the European Insurance and Occupational Pensions Authority (EIOPA) and the European Securities and Markets Authority (ESMA), issued pursuant to Article 97(1) of MiCAR, which provide a standardized classification test intended to promote regulatory convergence and prevent arbitrage behavior. (EBA, EIOPA, ESMA, 2024)

Investor Protection Challenges in Digital Financial Markets

The growth of crypto-asset markets has imposed the biggest regulatory challenge in the name of investor protection. Investors as a concerned category in traditional financial markets benefit from extensive disclosure obligations, prudential supervision, compensation schemes and well-established legal remedies, but in crypto-asset markets investors are forced to operate in fragmented and incomplete regulatory environments. As a result, individual investors in particular are often exposed to financial and legal risks.

Investor protection under MiCA includes at its core the mandatory publication of a white paper for crypto-assets prior to any public offering or admission to trading. The mandatory elements of the white paper are: comprehensive information about the issuer, the project, the rights and obligations associated with the crypto-asset, the underlying technology and the associated risks. This approach based on mandatory disclosure mirrors the logic of securities regulation. (Hallak, 2023)

One of the most critical areas addressed by MiCA is the segregation of client assets. MiCA directly imposes on crypto-asset service providers (CASPs) an obligation to hold client assets and crypto-assets in segregated accounts, ensuring that they are protected in the event of the provider's insolvency and are not accessible to the provider's creditors. (van der Linden, Shirazi, 2023) This design of the rules is in line with criticisms directed at unregulated exchanges, where client assets were commingled and effectively misused. (Delev, Jakupova Domazet, 2025)

In order to comprehensively protect investors, MiCA establishes a market abuse regime specifically tailored to crypto-asset markets, prohibiting insider trading, unlawful disclosure of internal information and market manipulation. These provisions confirm that the integrity of digital financial markets cannot be assumed. (Langenbucher, 2024)

The comparative analysis of EU insider trading law notes that MiCA adopts an information-based approach, prohibiting trading based on inside information. A critical analysis of MiCA's market abuse provisions identifies important interpretative challenges in applying the new rules to primary categories of crypto-assets, particularly unbacked tokens whose valuations are not based on identifiable fundamental factors. These interpretative difficulties highlight the need for continued regulatory guidance and capacity-building for enforcement. (Barczentewicz, de Gândara Gomes, 2024)

In the US, fragmentation is reflected in the way that security tokens trigger registration obligations under federal securities law; derivatives fall under the CFTC; money transmission and anti-money laundering obligations involve FinCEN and state licensing; and banks can offer custody provided that banking supervision is respected. (SEC, 2020) In the US, the Securities Investor Protection Corporation (SIPC) protects only securities within the statutory definition and does not protect non-security crypto assets. Even unregistered crypto-assets with investment contracts do not qualify for SIPC protection. Protection is strongest when the asset is a security and is held within a broker-dealer or fund. Securities and Exchange Commission (SEC) rules strengthen custodial obligations, but for non-security crypto-assets, the position is far less adequate. (SIPC, 2026) This gap is important because hacking, frozen accounts, and failed transfers remain common investor complaints. Therefore, a coherent investor protection model should go beyond mere disclosure and require either mandatory private insurance, an industry-funded compensation pool, or a combination of both. (Arner, et al., 2024)

The fact that crypto-asset markets are borderless makes domestic or regional regulation inherently incomplete. Crypto-asset providers often combine offshore incorporation, globally accessible web interfaces, fragmented group structures and mixed regulated/unregulated services. The Financial Stability Board (FSB) global regulatory framework, expressed through recommendations resulting from diagnosed regulatory failures, addresses governance transparency, risk management, data reporting, conflict of interest management and segregation of client assets. (FSB, 2023) The International Organization of Securities Commissions (IOSCO) also released 18 policy recommendations for crypto and digital asset markets. IOSCO's 2025 Thematic Review found that, while progress has been made, the crypto-asset ecosystem "still harbors risks related to investor protection and market integrity" and identified cross-border regulatory cooperation as a critical area for improvement. (IOSCO, 2025)

The most prominent challenges related to investor protection in digital financial markets include the decentralized financial nature of crypto-assets, regulatory fragmentation, and arbitrariness in action.

The decentralized nature of finance, which creates financial services through automated smart contracts without centralized intermediaries, presents a structural

challenge to investor protection frameworks that rely on the identification of responsible parties. The lack of an issuer, service provider and administrator, the lack of conventional regulation for authorization, disclosure and oversight reduce the legal certainty of the digital market. ESMA's analysis in the EU identified this liability problem as a source of significant risk for investors, compounded by vulnerabilities in smart contracts, the concentration of governance tokens and the absence of recourse mechanisms for investors who suffer losses. (ESMA, 2023)

The existence of different regulatory approaches has encouraged regulatory arbitrage, as operators migrate to more lenient jurisdictions to minimize compliance costs. IOSCO noted that regulatory fragmentation remains an obstacle to coherent investor protection, particularly as new business models for crypto-assets emerge that do not fit neatly into existing definitions. (IOSCO, 2023)

Conclusion

The legal nature of crypto-assets is a significant topic in contemporary financial law that requires appropriate regulatory positioning. The doctrinal debate is aimed at allocating new digital instruments, such as crypto-assets, to legal categories that have developed before the beginning of the digital revolution. EU law offers a relatively coherent answer to certain questions, while certain private law problems remain incomplete. On the other hand, US law offers strong protection where securities law is clearly applied, but otherwise leaves investors in a poorly defined and fragmented field.

MiCA introduces a pragmatic and functional taxonomy, which represents a workable legislative compromise, but its limitations on scope leave significant gaps in investor protection. The FSB and IOSCO recommendations establish a global normative framework that complements MiCA, reinforcing the principle that investor protection in digital financial markets requires not only domestic regulation, but also sustained cross-border supervisory cooperation. Effective investor protection in digital markets would be achieved through a layered model in which legal classification, custody integrity, prudential supervision, compensation and cross-border cooperation are treated as an integrated form that is constantly being upgraded and strengthened.

References

- Aksoy, P.Ç. (2023). The applicability of property law rules for crypto assets: considerations from civil law and common law perspectives. *Law, Innovation and Technology*. 15(1). <https://doi.org/10.1080/17579961.2023.2184140>
- Arner, D. W., Zetsche, D. A., Buckley, R. P., and Kirkwood, J. M. (2024). The Financialisation of Crypto: Designing an International Regulatory Consensus. *Computer Law & Security Review* 53: 105970. <https://doi.org/10.1016/j.clsr.2024.105970>

Barcentewicz, M., de Gândara Gomes, A. (2024). Crypto-Asset Market Abuse Under EU MiCA. *European Journal of Risk Regulation*, 1–18. <https://doi.org/10.1017/err.2024.80>

Chan, T. (2023). The nature of property in cryptoassets. *Legal Studies*, 43(3), 480–498. <https://doi.org/10.1017/lst.2022.53>

Delev, J., Jakupova Domazet, N. Legal Framework of Crypto-Assets and Their Legal Challenges. *Balkan and Near Eastern Journal of Social Sciences*. 11(03). 65-71. https://www.ibaness.org/bnejss/2025_11_03/08_Delev_and_Domazet.pdf

European Banking Authority, European Insurance and Occupational Pensions Authority, European Securities and Markets Authority. (2024). Consultation Paper on Draft Guidelines on templates for explanations and opinions, and the standardized test for the classification of crypto-assets, under Article 97(1) of Regulation (EU) 2023/1114. EBA, EIOPA, ESMA. <https://www.eba.europa.eu/sites/default/files/2024-07/1de342e1-71c0-4b61-bb98-420e8251bfea/Consultation%20paper%20on%20draft%20ESAs%20Guidelines%20on%20Art%2097%20MiCAR.pdf>

European Securities and Markets Authority. (2023). Decentralised Finance in the EU: Developments and risks. ESMA. https://www.esma.europa.eu/sites/default/files/2023-10/ESMA50-2085271018-3349_TRV_Article_Decentralised_Finance_in_the_EU_Developments_and_Risks.pdf

Financial Stability Board. (2023). High-level Recommendations for the Regulation, Supervision and Oversight of Crypto-Asset Activities and Markets: Final report. FSB. <https://www.fsb.org/uploads/P170723-2.pdf>

Hallak, I. (2023). Markets in crypto-assets (MiCA). European Parliamentary Research Service (EPRS). [https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/739221/EPRS_BRI\(2022\)739221_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/739221/EPRS_BRI(2022)739221_EN.pdf)

International Organization of Securities Commissions. (2023). Final Report with Policy Recommendations for Decentralized Finance (DeFi). IOSCO. <https://www.iosco.org/library/pubdocs/pdf/ioscopd754.pdf>

International Organization of Securities Commissions. (2025). Thematic Review Assessing the Implementation of IOSCO Recommendations for Crypto and Digital Asset Markets: Final Report. IOSCO. <https://www.iosco.org/library/pubdocs/pdf/IOSCOPD801.pdf>

Jaffri, A. M. (2026). Regulating crypto assets in the United States: balancing regulatory effectiveness, investor protection, and cross-border challenges. *Capital Markets Law Journal*, 21 (2), 1-12. <https://doi.org/10.1093/cmlj/kmag015>

Langenbucher, K. C. (2024). Insider Trading in European Law – from financial instruments to crypto-assets. *European Corporate Governance Institute - Law Working Paper No. 763/2024*. <https://dx.doi.org/10.2139/ssrn.4771059>

Otabor-Olubor, I. (2025). Property Rights, Money and the Future of Cryptocurrency. *International Journal of Digital Law and Governance*, 2(2), 253-287. <https://doi.org/10.1515/ijdlg-2025-0011>

Securities Investor Protection Corporation. (2026). What SIPC Protects: Official explanation of coverage limits for digital and crypto assets. SIPC. <https://www.sipc.org/for-investors/what-sipc-protects>

Tomczak, T. (2022). Crypto-Assets and Crypto-Assets' Subcategories under MiCA Regulation. *Capital Markets Law Journal*. 17(3). 365–382. <https://doi.org/10.1093/cmlj/kmac008>

United States Securities and Exchange Commission. (2020). SEC Charges Ripple and Two Executives with Conducting \$1.3 Billion Unregistered Securities Offering. SEC. <https://www.sec.gov/newsroom/press-releases/2020-338>

United States Securities and Exchange Commission. (2026). Framework for 'Investment Contract' Analysis of Digital Assets [Superseded by Application of the Federal Securities Laws to Certain Types of Crypto Assets and Certain Transactions Involving Crypto Assets (Mar. 17, 2026)]. SEC. <https://www.sec.gov/about/divisions-offices/division-corporation-finance/framework-investment-contract-analysis-digital-assets>

Van der Linden, T., Shirazi, T. (2023). Markets in crypto-assets regulation: Does it provide legal certainty and increase adoption of crypto-assets? *Financial Innovation* 9:22. <https://doi.org/10.1186/s40854-022-00432-8>

The Legal Nature of Standard Computer Program Transfer Agreements Enabling Permanent Use: An Assessment under Turkish Contract and Copyright Law

Turgut Alp Demirci¹

Abstract

Standard computer programs are routinely supplied to end users under standardized agreements labeled “licenses,” which grant a permanent right of use against a one-off payment. How such agreements are to be characterized within the system of the Turkish Code of Obligations remains contested: doctrine has proposed the direct or analogous application of sales law, the mixed-contract construction, the creation of a usufruct, and the copyright license. Employing the doctrinal method, this paper reconstructs and critically assesses these views against the Turkish statutory framework, in particular the Code of Obligations No. 6098 and the Law on Intellectual and Artistic Works No. 5846. The analysis rests on a preliminary finding: the computer program is an intangible intellectual product, and the data carrier is merely an ancillary instrument of performance whose legal fate follows that of the program. On this basis, the sale and usufruct characterizations prove untenable, since neither a complete transfer of the transferor’s legal position nor a real right over a corporeal thing occurs, while the mixed-contract view describes rather than characterizes the transaction. The paper concludes that the agreement constitutes a non-exclusive copyright license whose statutory gaps—notably delivery and liability for defects—must be filled by the analogous application of the rules on the sale of movables.

Keywords: computer programs; standard software transfer agreements; license contract; characterization of contracts; Turkish Code of Obligations; copyright law

¹ Istanbul University Faculty of Law, Department of Information and Technology Law, Istanbul, Türkiye. E-mail: turgut.demirci@istanbul.edu.tr. ORCID iD: 0009-0007-1165-3559. Corresponding author.

1. Introduction

The emergence of software as an independent economic asset has confronted the classical law of obligations with a persistent problem of characterization. Standard (off-the-shelf) computer programs are distributed to a mass market under terms drafted unilaterally by the producer, typically against a one-off payment and for an unlimited period.² Although such agreements are almost universally entitled “license agreements,” Turkish doctrine agrees that the nomen iuris chosen by the parties does not determine the legal nature of a contract: decisive is the parties’ real and common intention, to be ascertained under Article 19 of the Turkish Code of Obligations No. 6098 (TCO) in light of the reliance (trust) theory and of objective criteria such as the characteristic performance and the duration of the relationship.³ The very history of the “license” label counsels caution: before computer programs enjoyed settled copyright protection, producers employed the term in order to retain control over the software and to impose use restrictions on the acquirer, thereby lending the program the appearance of a right effective against third parties.⁴

The question is of considerable practical consequence. Whether the rules on sale, lease, usufruct, or license govern the relationship determines, among other things, the form of the contract, the modalities of delivery, the remedies available for defects, and the validity of the restrictions imposed on the user. This paper therefore examines the characterization, under Turkish law, of agreements by which a standard computer program is permanently made available to an end user, and evaluates their relationship with copyright law under the Law on Intellectual and Artistic Works No. 5846 (LIA).

2. Methods

The study employs the doctrinal (dogmatic) method of legal research. First, the relevant statutory framework was analyzed: the TCO, the LIA, the Turkish Civil Code No. 4721 governing real rights, and the Consumer Protection Law No. 6502 (CPL).

²For the first official definition of the computer program, see World Intellectual Property Organization, *Model Provisions on the Protection of Computer Software* (Geneva: WIPO, 1978), 9.

³Fikret Eren, *Borçlar Hukuku Genel Hükümler* [Law of Obligations: General Provisions], 29th ed. (Ankara: Yetkin Yayınları, 2024), 395; Necip Kocayusufpaşaoğlu, *Borçlar Hukukuna Giriş, Hukukî İşlem, Sözleşme* [Introduction to the Law of Obligations, Juridical Act, Contract], 7th ed. (İstanbul: Filiz Kitabevi, 2017), 132 et seq.; İbrahim Kaplan, *Hakimin Sözleşmeye Müdahalesi* [Judicial Intervention in the Contract] (Ankara: Kadioğlu Matbaası, 1987), 44 et seq.

⁴Nuri Erişgin, “Standart Bilgisayar Programının Son Kullanıcıya Sürekli Kazandırılmasını Amaçlayan Sözleşmenin Hukukî Niteliği” [The Legal Nature of the Contract Aimed at the Permanent Acquisition of a Standard Computer Program by the End User], *Ankara Üniversitesi Hukuk Fakültesi Dergisi* 52, no. 4 (2003): 45; Şener Dalyan, “Bilgisayar Programlarının Fikri Hukukta Korunması” [The Protection of Computer Programs under Copyright Law] (PhD diss., Ankara University, 2008), 241.

Second, the competing characterizations advanced in Turkish and Swiss-influenced scholarship—sale applied directly or by analogy, mixed contract, usufruct, and license—were systematically reconstructed.⁵ Their assessment was preceded by the preliminary question of the subject matter of performance, which conditions every further step of the analysis. Third, each view was tested for internal coherence and for the practical consequences it produces with respect to form, delivery, liability for defects, and user restrictions. The inquiry is confined to standard programs supplied for permanent use; custom-made software, fixed-term arrangements, and maintenance or support contracts fall outside its scope.⁶

3. Results

3.1. The Subject Matter of Performance

The decisive preliminary finding concerns the nature of the program as the subject of performance. One strand of scholarship regards the program, once fixed on a data carrier, as embodied in a corporeal thing and therefore subject to the law governing tangibles.⁷ The better view holds that the program is an intangible, functional intellectual product. Three considerations support it. First, the same program may be supplied on a physical carrier, pre-installed on hardware, or downloaded online; in the last case no corporeal object changes hands at all, yet the economic content of the transaction is identical. Second, under Article 57(1) LIA the transfer of ownership of the original or of copies does not, absent agreement to the contrary, carry with it the author's economic rights—proof that the rights in the carrier and the rights in the work are legally distinct.⁸ Third, like a canvas whose significance derives entirely from the painting fixed upon it, the carrier draws its economic value from the program it embodies; it is an ancillary instrument of performance whose legal fate follows that of the program, and not conversely.⁹

⁵Erişgin, "Sözleşmenin Hukukî Niteliği," 47 et seq.; Mustafa Fadıl Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri (Paket Yazılım Sözleşmeleri)* [Standard Computer Program Transfer Contracts (Package Software Contracts)] (İstanbul: Türkiye Bilişim Vakfı Yayınları, 1999), 69 et seq.

⁶On the typology of software contracts, see Erişgin, "Sözleşmenin Hukukî Niteliği," 44–45.

⁷Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 93, 95; for the intangible conception adopted here, Nuri Erişgin, "Standart Yazılım Devrini Amaçlayan Sözleşmelerde Edimin Konusu Olarak Bilgisayar Programı" [The Computer Program as the Subject Matter of Performance in Contracts Aimed at the Transfer of Standard Software], *Ankara Üniversitesi Hukuk Fakültesi Dergisi* 48, no. 1 (1999): 222 et seq.

⁸Şafak N. Erel, *Türk Fikir ve Sanat Hukuku* [Turkish Law of Intellectual and Artistic Works], 3rd ed. (Ankara: Yetkin Yayınları, 2009), 279.

⁹Erişgin, "Edimin Konusu," 240 n. 126; Erişgin, "Sözleşmenin Hukukî Niteliği," 60–61.

3.2. The Sale Characterizations

Against this background, the sale characterizations prove untenable, even though Turkish law construes the object of sale broadly: the notion of the “thing sold” in Article 207 TCO extends beyond corporeal objects, and Article 3(h) CPL expressly counts software prepared for use in the electronic environment among “goods.”¹⁰ A sale is directed at the definitive transfer of the seller’s legal position and the buyer’s acquisition of full power of disposal. In the supply of a standard program, however, the transferor retains the program and continues to exploit it commercially; a complete transfer of a legal position never takes place.¹¹ The standard restrictions imposed on the user—prohibitions on reproduction beyond a backup copy, on modification, rental, or onward transfer—are equally incompatible with the position of a buyer.¹² Construing the transaction as a sale of the copyright itself would, moreover, expose countless informally concluded contracts to invalidity for want of the written form prescribed by Article 52 LIA—a plainly unreasonable result.¹³ Finally, the warranty regime of sales law was conceived for corporeal objects and fits only imperfectly a product which, by its nature, can hardly ever be entirely free of defects.¹⁴

3.3. The Usufruct Theory

The usufruct theory fails at its premise, since it presupposes that the program acquires the quality of a thing upon fixation.¹⁵ Even if a usufruct over the carrier were assumed, the carrier’s negligible economic value and the online-download scenario leave the alleged real right without a determinate object. The principle of clarity governing real rights requires that the creation of a usufruct be stipulated unequivocally; standard terms containing mere use restrictions do not satisfy that requirement. Nor does practice know any obligation of the user to preserve and return the object—users may delete the program at will, and suppliers claim neither restitution nor compensation—which is irreconcilable with the restitutionary structure of usufruct.¹⁶

¹⁰Fahrettin Aral and Hasan Ayrancı, *Borçlar Hukuku: Özel Borç İlişkileri* [Law of Obligations: Particular Contractual Relationships], 18th ed. (Ankara: Yetkin Yayınları, 2025), 102, 109 et seq.; Haluk Tandoğan, *Borçlar Hukuku: Özel Borç İlişkileri*, vol. 1 (Ankara, 1977), 79; on Article 3(h) CPL, Dalyan, “Bilgisayar Programlarının,” 243.

¹¹Erişgin, “Sözleşmenin Hukukî Niteliği,” 54.

¹²Erişgin, “Sözleşmenin Hukukî Niteliği,” 55; *contra* Dalyan, “Bilgisayar Programlarının,” 245; Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 75.

¹³Erişgin, “Sözleşmenin Hukukî Niteliği,” 54; cf. Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 111 (holding that contracts for the permanent transfer of standard programs need not be made in writing).

¹⁴Erişgin, “Sözleşmenin Hukukî Niteliği,” 54.

¹⁵Erişgin, “Sözleşmenin Hukukî Niteliği,” 51.

¹⁶Erişgin, “Sözleşmenin Hukukî Niteliği,” 57–58; Erişgin, “Edimin Konusu,” 231.

3.4. The Mixed-Contract View

The mixed-contract construction captures the composite character of system-supply arrangements that combine the program with adaptation, training, or support obligations.¹⁷ For the standard, permanent supply of an off-the-shelf program, however, it describes rather than characterizes the relationship: it does not identify the rules governing the core performance itself and thus postpones, rather than answers, the question of characterization.

3.5. Objections to the License View

The license view, finally, faces objections of its own. The causa of the grant—the underlying transaction by which the authorization to use is conferred—remains unspecified.¹⁸ The parallel grant of identical rights to thousands of users sits uneasily with a licensing doctrine oriented towards exclusivity,¹⁹ and the frequent disregard, in practice, of the form requirements attending dispositions over economic rights adds further friction. Nor does the technical reproduction involved in loading the program into memory prove a license by itself, since that act belongs to the user's statutorily guaranteed minimum of lawful use.²⁰

4. Discussion and Conclusion

The findings support a two-tier solution. At the level of characterization, the agreement granting permanent use of a standard program is a license contract rooted in copyright law: the user acquires neither ownership nor a limited real right, but a permanent, non-exclusive authorization—a simple license (ruhsat) within the meaning of Articles 48(2) and 56 LIA—to benefit from the program's problem-solving functionality.²¹ So understood, the principal objections against the license view lose their force. The mass, parallel grant of identical use rights, irreconcilable with an exclusivity-

¹⁷Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 71, 74–81; Aral and Ayrancı, *Borçlar Hukuku*, 84, 88 et seq.; Dalyan, “Bilgisayar Programlarının,” 245–246.

¹⁸Erişgin, “Sözleşmenin Hukukî Niteliği,” 59.

¹⁹Hasan Kadir Yılmaztekin, “Fikir ve Sanat Eserleri Kanunu Uyarınca Eser Sahipliği ve Hak Sahipliği ile Bunların Tecavüz Davaları Bağlamında Davacı Sıfatına Etkileri” [Authorship and Right Ownership under the Law on Intellectual and Artistic Works and Their Effects on Standing in Infringement Actions], *Adalet Dergisi*, no. 65 (2020): 527.

²⁰Serhat Kaypakoğlu, *Bilgisayar Programlarının Hukuki Korunması* [The Legal Protection of Computer Programs] (İzmir: İpekçi Yayınları, 1997), 137; Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 60–61.

²¹Erel, *Türk Fikir ve Sanat Hukuku*, 217, 306; Nuşin Ayiter, *Hukukta Fikir ve Sanat Ürünleri* [Intellectual and Artistic Products in Law] (Ankara: Sevinç Matbaası, 1981), 211; Saibe Oktay Özdemir, *Sinai Haklara İlişkin Lisans Sözleşmeleri ve Rekabet Hukuku Düzenlemelerinin Lisans Sözleşmelerine Uygulanması* [License Contracts concerning Industrial Property Rights and the Application of Competition Law to License Contracts] (İstanbul: Beta Yayınları, 2002), 23.

oriented conception, is precisely what the simple license contemplates. And the reproduction inherent in loading and running the program need not be construed as the essence of the grant, for it falls—together with error correction, the making of a backup copy, and decompilation for purposes of interoperability—within a mandatory core of user entitlements that cannot be excluded by contract.²²

At the level of the applicable rules, the *causa* objection is answered through gap-filling. The LIA regulates the license only fragmentarily and contains no provisions on delivery or on liability for defects. These gaps are to be closed by the analogous application of the TCO rules on the sale of movables, which, among the statutory contract types, are most congruent with a transaction directed at the definitive, remunerated, and permanent conferral of a benefit.²³ Sales law thus applies not because the contract is a sale, but because—and only insofar as—its rationale fits the permanent character of the grant; provisions presupposing corporeality or restitution remain inapplicable. On this construction, the restrictions imposed on the user are neither anomalies nor evidence of a real right, but ordinary determinations of the scope of the license, subject to review under the rules on standard terms and consumer protection and ineffective where they encroach upon the mandatory core just described.

The characterization defended here also supplies the doctrinal baseline for contemporary distribution models: subscription-based access and purely digital supply differ from the permanent transfer in duration and in the mode of performance, not in the intangible nature of their subject matter. In conclusion, standard computer program transfer agreements enabling permanent use are to be characterized as copyright license contracts whose statutory lacunae—above all delivery and liability for defects—must be filled by the analogous application of the law on the sale of movables, to the extent compatible with the nature of the transaction.

References

Aral, Fahrettin, and Hasan Ayrancı. *Borçlar Hukuku: Özel Borç İlişkileri* [Law of Obligations: Particular Contractual Relationships]. 18th ed. Ankara: Yetkin Yayınları, 2025.

Ayiter, Nuşin. *Hukukta Fikir ve Sanat Ürünleri* [Intellectual and Artistic Products in Law]. Ankara: Sevinç Matbaası, 1981.

Dalyan, Şener. “Bilgisayar Programlarının Fikri Hukukta Korunması” [The Protection of Computer Programs under Copyright Law]. PhD diss., Ankara University Institute of Social Sciences, 2008.

²²Kaypakoğlu, *Bilgisayar Programlarının Hukuki Korunması*, 137; Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 60–61.

²³Erişgin, “Sözleşmenin Hukukî Niteliği,” 64; for the alternative characterization as a *sui generis* or mixed contract, Yıldırım, *Standart Bilgisayar Program Devir Sözleşmeleri*, 74–81.

Erel, Şafak N. *Türk Fikir ve Sanat Hukuku* [Turkish Law of Intellectual and Artistic Works]. 3rd ed. Ankara: Yetkin Yayınları, 2009.

Eren, Fikret. *Borçlar Hukuku Genel Hükümler* [Law of Obligations: General Provisions]. 29th ed. Ankara: Yetkin Yayınları, 2024.

Erişgin, Nuri. “Standart Bilgisayar Programının Son Kullanıcıya Sürekli Kazandırılmasını Amaçlayan Sözleşmenin Hukukî Niteliği” [The Legal Nature of the Contract Aimed at the Permanent Acquisition of a Standard Computer Program by the End User]. *Ankara Üniversitesi Hukuk Fakültesi Dergisi* 52, no. 4 (2003): 43–68.

Erişgin, Nuri. “Standart Yazılım Devrini Amaçlayan Sözleşmelerde Edimin Konusu Olarak Bilgisayar Programı” [The Computer Program as the Subject Matter of Performance in Contracts Aimed at the Transfer of Standard Software]. *Ankara Üniversitesi Hukuk Fakültesi Dergisi* 48, no. 1 (1999): 219–250.

Kaplan, İbrahim. *Hakimin Sözleşmeye Müdahalesi: Sözleşmenin Yorumu, Sözleşmenin Tamamlanması, Sözleşmenin Değişen Hal ve Şartlara Uyarlanması* [Judicial Intervention in the Contract]. Ankara: Kadioğlu Matbaası, 1987.

Kaypakoğlu, Serhat. *Bilgisayar Programlarının Hukuki Korunması* [The Legal Protection of Computer Programs]. İzmir: İpekçi Yayınları, 1997.

Kocayusufpaşaoğlu, Necip. *Borçlar Hukukuna Giriş, Hukukî İşlem, Sözleşme* [Introduction to the Law of Obligations, Juridical Act, Contract]. 7th ed. İstanbul: Filiz Kitabevi, 2017.

Oktay Özdemir, Saibe. *Sınai Haklara İlişkin Lisans Sözleşmeleri ve Rekabet Hukuku Düzenlemelerinin Lisans Sözleşmelerine Uygulanması* [License Contracts concerning Industrial Property Rights and the Application of Competition Law to License Contracts]. İstanbul: Beta Yayınları, 2002.

Tandoğan, Haluk. *Borçlar Hukuku: Özel Borç İlişkileri*. Vol. 1. Ankara, 1977.

World Intellectual Property Organization. *Model Provisions on the Protection of Computer Software*. Geneva: WIPO, 1978.

Yıldırım, Mustafa Fadıl. *Standart Bilgisayar Program Devir Sözleşmeleri (Paket Yazılım Sözleşmeleri)* [Standard Computer Program Transfer Contracts (Package Software Contracts)]. İstanbul: Türkiye Bilişim Vakfı Yayınları, 1999.

Yılmaztekin, Hasan Kadir. “Fikir ve Sanat Eserleri Kanunu Uyarınca Eser Sahipliği ve Hak Sahipliği ile Bunların Tecavüz Davaları Bağlamında Davacı Sıfatına Etkileri” [Authorship and Right Ownership under the Law on Intellectual and Artistic Works and Their Effects on Standing in Infringement Actions]. *Adalet Dergisi*, no. 65 (2020).

The Legal Nature of Crypto Assets under Digital Transformation: A Comparative Analysis and Regulatory Framework

İbrahim Hakkı Akpınar ¹

Abstract

This study evaluates the complex legal nature of crypto assets within the framework of modern private law, focusing on recent international regulatory trends and the emerging legal landscape in Turkish law. As digital transformation accelerates, defining the exact legal taxonomy of crypto assets becomes critical for transaction security, property rights, and regulatory compliance. This paper systematically analyzes the technical foundations of blockchain technology, including cryptography, decentralization, and smart contracts, to assess how these features challenge traditional legal doctrines. A comparative methodology is employed to evaluate the classification of crypto assets across multiple paradigms: as corporeal property (goods), securities, financial instruments, commodities, fiat currency, or independent digital assets. The analysis closely examines the European Union's Markets in Crypto-Assets (MiCA) Regulation as a benchmark for comprehensive supranational legislation, contrasting it with the fragmented, primarily restrictive framework currently observed in Turkish law (e.g., Central Bank regulations and recent capital markets amendments). The results demonstrate that while crypto assets share hybrid characteristics with commodities and intangible rights, they ultimately constitute a distinct category of digital property that requires a *sui generis* holistic legislative framework rather than piecemeal analogical applications.

¹ Research Assistant in Private Law in *İstanbul Ticaret University*, Email: ihakpinar@ticaret.edu.tr, ORCID: 0009-0000-9323-1606

Keywords: Crypto Assets, Blockchain, Private Law, MiCA, Digital Property, Turkish Law.

1. Introduction

The dawn of the twenty-first century has witnessed an unprecedented acceleration in digital transformation, profoundly affecting global economic systems and traditional legal doctrines. The primary driver of this disruption is the emergence of crypto assets, built upon decentralized ledger technology (DLT), commonly known as blockchain. Operating without a central clearing authority, these digital instruments have evolved from fringe cryptographic experiments into highly capitalized financial mechanisms utilized by both retail and institutional investors. However, their rapid proliferation has significantly outpaced the evolution of statutory frameworks, leading to a profound jurisprudential dilemma regarding their precise legal classification.

In the early phases of their existence, regulatory interest in crypto assets was heavily skewed toward criminal law and tax compliance. Because of the relative anonymity and cross-border fluidity inherent in public blockchains, early adoption was occasionally associated with illicit activities, such as the infamous Silk Road marketplace or massive domestic exchange failures like the Thodex incident in Turkey. These high-profile crises catalyzed state interventions, forcing governments to establish initial anti-money laundering (AML) and counter-terrorist financing (CFT) protocols. Nevertheless, addressing these digital assets solely through the lens of prohibitive or punitive public law leaves core private law issues unresolved. Determining how crypto assets fit within the law of obligations, property law, and execution frameworks remains one of the most pressing intellectual challenges for legal scholars today.

This paper seeks to systematically analyze the legal nature of crypto assets by synthesizing their technical architecture with comparative private law doctrines. The study addresses a fundamental question: Can crypto assets be seamlessly integrated into established legal categories—such as corporeal property, securities, commodities, or fiat currency—or do they demand an entirely new legal taxonomy as independent digital property? By evaluating international legislative benchmarks, specifically the European Union's Markets in Crypto-Assets (MiCA) Regulation, alongside the piecemeal statutory updates introduced in Turkish law, this study outlines a path forward for harmonizing technological innovations with comprehensive legal security.

2. Methods

To comprehensively evaluate a phenomenon that sits at the intersection of advanced computer science and classical jurisprudence, this study utilizes a dual-methodological framework. First, a technical-functional analysis is applied to deconstruct the operational

mechanics of blockchain systems. Legal definitions must not be formulated in an academic vacuum; they must accurately reflect the underlying engineering realities of the technology. Therefore, this research examines the core components of public ledgers, including cryptographic hash functions (such as the SHA-256 algorithm), decentralized consensus mechanisms, smart contract execution parameters, and the structural differences between cold (offline) and hot (online) digital wallets managed by Crypto Asset Service Providers (CASPs).

Second, the study implements a comparative and analytical legal methodology. This involves mapping the technical attributes of crypto assets onto the statutory frameworks and judicial precedents of multiple jurisdictions. The paper critically evaluates continental European property law principles, which traditionally mandate the requirement of 'corporeality' (cismanilik) for an asset to qualify as an object of property rights. Furthermore, the paper executes a comparative statutory analysis by evaluating the comprehensive, harmonized approach adopted by the European Union through its MiCA framework against the fragmented, sector-specific, and largely restrictive regulatory models seen in emerging markets, with a specific focus on recent legislative updates enacted by the Capital Markets Board (SPK) and the Central Bank of the Republic of Turkey (TCMB).

3. Results

The technical and comparative assessment reveals that crypto assets possess a unique, hybrid nature that resists clean categorization under traditional legal classifications. The results of analyzing these assets under various legal paradigms are detailed below:

3.1. The Corporeal Property (Goods) Paradigm

Under classical civil law doctrines, such as those governing the Turkish Civil Code (TMK) and the Swiss Civil Code, an item must exhibit physical, three-dimensional corporeality (cismanilik) to be deemed an 'object' (eşya) capable of supporting real or proprietary rights (ayni hak). Because crypto assets exist solely as decentralized entries on a digital ledger, they lack physical form. Consequently, the dominant view in private law theory rejects the direct classification of crypto assets as corporeal property. However, alternative interpretations suggest that the law must adapt. For instance, certain jurisdictions have expanded property frameworks to include controllable digital forces or energies. While a minority view argues for a broad interpretation of property to preserve transaction security, the consensus indicates that without explicit statutory extension, crypto assets cannot support classical zilyetlik (possessory rights) or absolute proprietary protections.

3.2. Financial Instruments and Securities Classification

Classifying crypto assets as securities or financial instruments yields mixed outcomes depending on the specific characteristics of the asset and the jurisdiction. Under standard capital markets legislation, a security must represent an underlying membership or creditor right, provide periodic yields, and be issued in series via standardized procedures. Traditional crypto assets like Bitcoin do not possess these traits; they offer no debt claims or corporate voting rights. However, the regulatory landscape changes significantly when evaluating utility tokens or asset-backed tokens. The U.S. Securities and Exchange Commission (SEC) has aggressively utilized investment contract frameworks (e.g., the Howey Test) to sweep many crypto assets into the securities net to protect investors. In contrast, European and Turkish capital market frameworks generally treat native crypto assets as separate from traditional securities, unless they are intentionally structured as fractionalized investment contracts or derivatives.

3.3. The Currency and Commodity Paradigms

Although colloquially termed 'cryptocurrencies,' these instruments fail to meet the macroeconomic criteria of legal tender or functional money. Classic currency must serve as a universal medium of exchange, a standard unit of account, and a stable store of value. Due to extreme market volatility, crypto assets cannot effectively function as a unit of account. Furthermore, statutory rules frequently restrict their use as payment instruments; for example, the TCMB explicitly prohibits the use of crypto assets in payment services. On the other hand, the commodity paradigm has gained substantial traction globally. Jurisdictions such as the United States (via the CFTC) view crypto assets as digital commodities because their value is determined entirely by market supply and demand, and their extraction requires significant expenditure of capital and labor (mining), mirroring the economic attributes of precious metals like gold.

4. Discussion and Conclusion

The findings of this study underscore a widening gap between rapid technological innovation and traditional legislative frameworks. The comparative analysis demonstrates that attempt to force crypto assets into pre-existing legal boxes—whether as tangible property, classical securities, or standard fiat currency—creates systemic contradictions and severe legal uncertainty. The European Union's implementation of the MiCA Regulation marks a profound paradigm shift. By moving away from restrictive, piecemeal prohibitions and instead establishing a comprehensive, unified framework, MiCA successfully categorizes various types of tokens (such as asset-referenced tokens and e-money tokens) while introducing rigorous transparency, licensing, and consumer protection standards. This supranational framework proves that digital innovation is best governed through proactive, specialized legislation rather than forced analogies.

In contrast, the current regulatory stance in Turkish law reflects a reactive and overly cautious approach. While the 2024 amendments to the Capital Markets Law (SPK) introduced critical foundational definitions and established mandatory licensing requirements for domestic platforms, the broader legal system remains plagued by fragmentation. The Central Bank's outright prohibition on utilizing crypto assets for payments reflects an attempt to safeguard monetary sovereignty, yet it fails to address the underlying private law realities of these assets. When a dispute arises regarding the inheritance, seizure, or contractual transfer of a crypto asset, practitioners are left without clear guidance because civil and property statutes remain silent on the status of independent intangible digital property.

In conclusion, this study argues that crypto assets must be legally recognized as a distinct, *sui generis* category of digital property. Future legislative perspectives must transition away from purely defensive public law restrictions and focus on establishing robust private law protections. Lawmakers should introduce specific amendments to civil codes and enforcement acts, explicitly defining the mechanisms for transferring, securing, and inheriting digital assets. By establishing a balanced, clear, and comprehensive statutory framework that mirrors the harmonized approach of global standards, jurisdictions can effectively mitigate the systemic risks of the digital age while fostering an environment that encourages responsible technological and engineering innovation.

References

- Aksu, M. (2007). *Bilgisayar Programlarının Fikri Mülkiyet Hukukunda Korunması*. İstanbul: Beta Yayıncılık.
- Central Bank of the Republic of Turkey (TCMB). (2021). Regulation on the Non-Use of Crypto-Assets in Payments. Official Gazette, Date: 16.04.2021, No: 31456.
- Demir, F. (2024). *Kripto Varlıklardan Elde Edilen Gelirlerin Vergilendirilmesi* (4th ed.). İstanbul: Filiz Kitabevi.
- European Banking Authority (EBA). (2019). Report with advice for the European Commission on crypto-assets. Paris: EBA.
- European Central Bank (ECB). (2019). *Crypto-Assets: Implications for Financial Stability, Monetary Policy, and Payments*. Occasional Paper Series, Frankfurt.
- European Union. (2023). Regulation (EU) 2023/1114 of the European Parliament and of the Council on markets in crypto-assets (MiCA). Official Journal of the European Union.
- İmamoğlu, D. A. (2024). *Kripto Para Birimleri ve Türk Hukukunda Düzenlenmesi* (5th ed.). Ankara: Seçkin Yayınevi.
- Oğuzman, K., Oktay Özdemir, S., & Seliçi, Ö. (2024). *Eşya Hukuku* (26th ed.). İstanbul: Filiz Kitabevi.

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education
Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Özkan Taş, R. (2025). Dijital Varlıklar Üzerindeki Hakkın Hukuki Niteliği (1st ed.). İstanbul: Oniki Levha Yayıncılık.

Republic of Turkey. (2024). Law Amending the Capital Markets Law (Law No. 7518). Official Gazette, Date: 02.07.2024, No: 32590.

The Legal Taxonomy of R&D Contracts within the Framework of Sui Generis Obligations*

Ömer Fatih GÜRCAN**

Abstract

This study evaluates the complex legal nature of Research and Development (R&D) contracts within the framework of modern obligations law, establishing an analytical classification system between joint and reciprocal R&D models. As technological innovation becomes the primary driver of corporate competitiveness, the traditional bilateral models of statutory contracts fall short in addressing the core elements of modern R&D processes, such as profound technical uncertainty, creative risk-sharing, and intricate intellectual property dynamics. Grounded in the criteria established by the OECD's Frascati Manual and domestic law, this paper defines the core requirements of R&D activities—novelty, creativity, uncertainty, systematic structure, and transferability. The methodology categorizes these agreements into joint R&D contracts, which function as simple partnerships, and reciprocal R&D contracts, which operate as commercial exchange frameworks under two distinct branches: result-oriented service models and conduct-oriented proxy models. The results demonstrate that reciprocal R&D contracts cannot be reduced to mixed or standard statutory frameworks due to the overriding principle of scientific independence and heightened duties of loyalty, confirming their status as independent, sui generis obligations requiring custom legislative approaches.

Keywords: R&D Contracts, Sui Generis Obligations, Frascati Manual, Simple Partnership, Intellectual Property, Private Law.

DOI: <https://doi.org/10.5281/zenodo.22040267>

I. THE CONCEPT OF R&D AND ITS LEGAL FRAMEWORK

The concept of R&D is crucial for determining the legal nature of R&D contracts. The concept of R&D has been defined and its framework established by the Frascati Manual published by the OECD. According to this guide, R&D is “creative work undertaken on a systematic basis to increase the stock of knowledge—comprising knowledge of man, culture and society—and to use this stock to devise new applications”¹.

The definition set out in Article 2(1)(a) of the Law on the Support of Research, Development and Design Activities is also consistent with the definition in the Frascati Manual. Indeed, this provision also highlights the importance of R&D activities in expanding the body of knowledge and their significance in designing new applications. Furthermore, the relevant provision emphasises the uncertainty, systematic nature, and original and scientific character of R&D activities in terms of their outcomes.

In accordance with the Frascati Guide, there are essential criteria for R&D activities. These criteria are that the activity must be innovative, creative, involve uncertainty, be systematic, and have the potential to be transferred and/or replicated². These conditions must be met cumulatively³.

It is necessary to briefly explain the essential criteria for understanding R&D activities. Accordingly, the criterion of innovation is the requirement that the activity makes a new contribution to the body of knowledge in the relevant field⁴. Given its creative nature, the activity cannot simply be a repetition of established rules⁵. The activity must be of a creative nature⁶. The characteristic feature that distinguishes an R&D contract from a work agreement or an agency agreement is its capacity to bear uncertainty. In this context, it cannot be determined with certainty whether the intended outcome will be achieved when the contract is concluded, or, if it is to be achieved, how much time and cost this will entail⁷. The systematic nature of R&D, however, rules out the possibility of a positive outcome being achieved by chance. In accordance with this characteristic, R&D

* The author acknowledges the use of artificial intelligence tools for the translation of the text from Turkish into English.

**Research Assistant at Istanbul Sabahattin Zaim University, Email: omer.gurcan@izu.edu.tr | ORCID: 0009-0005-4585-1938.

¹ OECD, Frascati Kılavuzu Araştırma ve Deneysel Geliştirme Taramaları İçin Önerilen Standart Uygulama, trans. Tübitak, Ankara, Tübitak, 2002, para. 63.

² OECD, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, Paris, OECD publishing, 2015, p. 45, para. 2.7.

³ Ibid., p. 46, para. 2.13; Kemal Erdoğan, Araştırma - Geliştirme Sözleşmesi, Ankara, Adalet Yayınevi, 2022, p. 90.

⁴ Erdoğan, p. 90 et seq.

⁵ OECD, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, p. 47, para. 2.17.

⁶ Erdoğan, p. 93.

⁷ OECD, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, p. 47, para. 2.18; Erdoğan, p. 93 et seq.

is a process that involves a dedicated budget, the employment of staff, and the adherence to a specific plan and scientific methods⁸. The final characteristic is the potential for transferability and/or reproducibility. According to this characteristic, the knowledge gained from R&D activities must be transferable to others. The scope of transferable knowledge also includes information derived from activities that have ended in failure. This knowledge must be rendered in such a way that it can be licensed and objectively reproduced⁹.

II. ELEMENTS AND TYPES OF R&D CONTRACTS

R&D contracts are not a type of contract specifically regulated by law within the context of the law of obligations. In other words, they are innominate contracts¹⁰. These contracts have arisen as a result of the needs generated by commercial life and technological developments. In practice, these contracts are divided into two categories: joint R&D contracts and reciprocal R&D contracts.

A. Joint R&D Agreement and Its Elements

In a joint R&D agreement, two or more enterprises or organisations come together to develop a new product or technology. Through this collaboration, they aim to carry out R&D activities jointly and to share the costs, risks and outcomes equally or in agreed proportions¹¹. The most important feature distinguishing it from a reciprocal R&D contract is that the parties act as a single entity (a single party) towards a common goal¹². In contrast, in a reciprocal R&D agreement, as will be explained below, the parties assume opposing roles as creditor and debtor.

For a joint R&D agreement to exist, three elements—which can be regarded as essential—must all be present. These are a common objective, an obligation to contribute capital, and collaboration.

B. Reciprocal R&D Agreement and Its Elements

In a reciprocal R&D agreement, the parties may be referred to as the party carrying out the R&D and the party commissioning the R&D¹³. Under a reciprocal R&D agreement, the party carrying out the R&D undertakes to conduct research and development activities and to transfer or grant the rights to the product or knowledge resulting from these activities to the party commissioning the R&D. In return, the party

⁸ OECD, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, p. 47, para. 2.19; Erdoğan, p. 97.

⁹ OECD, Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities, p. 48, para. 2.20; Erdoğan, pp. 97-98.

¹⁰ Emel Badur, Gülmelihat Doğan, “Fikri Haklar Açısından Araştırma Geliştirme Sözleşmeleri”, HBV-HFD, Vol. 26, No: 3, 2022, p. 83; Erdoğan, p. 27; Faruk Dıvarcı, Araştırma ve Geliştirme(Ar-Ge) Sözleşmeleri, Ankara, Yetkin Yayınları, 2021, p. 36.

¹¹ Rekabet Kurumu, Rekabet Terimleri Sözlüğü, 6th ed., Ankara, Rekabet Kurumu, 2019, p. 48.

¹² Dıvarcı, p. 13.

¹³ Erdoğan, p. 46.

commissioning the R&D undertakes to finance this process¹⁴. These obligations of the parties constitute the principal obligation.

1. Types of Reciprocal R&D Agreements

This contract is divided into two categories. These are the reciprocal R&D contract where the obligation arises from the performance of a specific act (R&D Order) and the reciprocal R&D contract where the obligation arises from the mere act of performance (R&D Agency Agreement).

a. Result-Oriented Reciprocal R&D Agreements

This agreement is concluded in instances where the realization of a target product or technology resulting from the R&D activity is foreseeable. Under this contract, the performing party does not merely undertake R&D activities but also assumes an obligation of result, whereby it is contractually bound to develop the subject product and deliver it to the commissioning party¹⁵.

b. Reciprocal R&D Agreements Based on an Obligation of Means

This agreement is concluded in circumstances where the realization of a target product or technology remains uncertain. Under this contract, the performing party does not guarantee the success of the R&D activity; rather, it assumes an obligation of means. In other words, the party commits to performing the research with the requisite professional diligence, in accordance with the established scientific and technical standards of the relevant field¹⁶. In this respect, such agreements exhibit a close resemblance to service or agency contracts, which are primarily characterized by the obligation of means.

III. LEGAL NATURE OF R&D AGREEMENTS

The legal nature of joint R&D agreements differs significantly from that of reciprocal R&D agreements.

A. Legal Nature of Joint R&D Agreements

As previously stated, a joint R&D agreement is a contract whereby two or more undertakings or institutions commit to pooling capital and acting in concert to achieve a common objective¹⁷. The parties share the profits, losses, and risks. For this reason, it can be argued that a joint R&D agreement possesses the legal nature of a simple partnership¹⁸. Even in cases where the parties conduct R&D activities jointly solely for scientific purposes without any economic expectation, such an agreement may still be classified as a simple partnership, provided that the other requisite conditions are met¹⁹.

B. Legal Nature of Reciprocal R&D Agreements

¹⁴ Dıvarcı, p. 14.

¹⁵ Erdoğan, p. 48; Dıvarcı, p. 14.

¹⁶ Dıvarcı, p. 15; Erdoğan, p. 48.

¹⁷ See supra part II, A.

¹⁸ Erdoğan, p. 169; Dıvarcı, p. 20.

¹⁹ Dıvarcı, p. 21.

In a reciprocal R&D agreement, the parties do not share a common objective. The performing party undertakes to conduct R&D activities aimed at developing a new product or technology, while the commissioning party assumes the obligation to pay a consideration in return. This agreement is distinguished based on whether an obligation of result or an obligation of means is undertaken.

A minority view in legal doctrine characterizes the reciprocal R&D agreement as a mixed contract in a broad sense. According to this perspective, the commissioning party seeks to benefit from the results obtained through the R&D activity. Financing R&D solely for scientific purposes is considered inconsistent with the realities of commercial life. Therefore, the license and know-how provisions, which govern the transfer of intellectual property rights derived from the R&D project, are viewed as essential components of the agreement. The inclusion of these license and know-how elements, in addition to the performance element typical of a contract for work or a mandate contract—which constitutes the primary performance obligation of the R&D performer—renders the reciprocal R&D agreement a mixed contract²⁰.

In contrast, the majority opinion in legal doctrine classifies the reciprocal R&D agreement as a *sui generis* contract, independent of existing nominate contract types²¹. There is no consensus in legal doctrine regarding *sui generis* contracts. According to one view, *sui generis* contracts are those that contain only partially, or do not contain at all, the essential elements of typical contracts regulated by law²². Accordingly, for a contract to be characterized as *sui generis*, it must inherently possess unique elements. In other words, such contracts must exhibit a “novel structure”²³. According to another view, *sui generis* contracts arise from the combination of elements not regulated by law, aimed at creating a new contractual form²⁴. In our view, *sui generis* contracts are agreements that establish unique structures containing elements which are, either in part or in whole, unregulated by statutory law.

²⁰ Erdoğan, p. 161-162.

²¹ Dıvarcı, p. 38; Badur, Doğan, p. 84; Sema Çörtoğlu Koca, “Milletlerarası Özel Hukukta Araştırma-Geliştirme(Ar-Ge) Sözleşmelerine Uygulanacak Hukuk”, Ankara Barosu Fikri Mülkiyet Hukuku ve Rekabet Hukuku Dergisi, Vol. 9, No: 3, 2009, p. 100.

²² Haluk Tandoğan, Borçlar Hukuku Özel Borç İlişkileri, Vol. I/1, Kendisine Özgü Yapısı Olan ve Karma Sözleşmeler, Satış ve Çeşitleri, Trampa, Bağışlama, 6.th ed., 2008, p. 13; Aydın Zevkliler, Emre Gökyayla, Borçlar Hukuku Özel Borç İlişkileri, 20th ed., İstanbul, Vedat Kitapçılık, 2020, p. 12; Cevdet Yavuz, Faruk Acar, Burak Özen, Türk Borçlar Hukuku Özel Hükümler, Vol. 1, 11th ed., İstanbul, Beta Yayınevi, 2022, p. 35.

²³ Fahrettin Aral, Hasan Ayrancı, Borçlar Hukuku Özel Borç İlişkileri, 12th ed., Ankara, Yetkin Yayınları, 2019, p. 56.

²⁴ Fikret Eren, Borçlar Hukuku Özel Hükümler, 9th ed., Ankara, Yetkin Yayınları, 2021, para.3245; Rona Serozan, Borçlar Hukuku Özel Bölüm, prep. Başak Baysal, Kerem Cem Sanlı, 4th ed., İstanbul, On İki Levha Yayıncılık, 2019, para. 260, para. 350; O. Gökhan Antalya, “Borçlar Hukuku Genel Hükümler Vol.1”, 2nd ed., Ankara, Seçkin Hukuk, 2019, para. 1330; Mustafa Alper Gümüş, Borçlar Hukuku Özel Hükümler Kısa Ders Kitabı, 5th ed., İstanbul, Filiz Kitabevi, 2020, pp. 8-9; Mustafa Alper Gümüş, Borçlar Hukuku Özel Hükümler, Vol. I, 3rd ed., İstanbul, Vedat Kitapçılık, 2013, p. 9; Erden Kuntalp, Karışık Muhtevalı Akit (Karma Sözleşme), 2nd ed., Ankara, Banka ve Ticaret Hukuku Araştırma Enstitüsü, 2013, p. 14.

R&D activities are inherently variable due to scientific, technical, and economic exigencies. Given the high degree of risk, uncertainty, and the imperative of innovation associated with these activities, characterizing them as mixed contracts would not be appropriate²⁵. Indeed, these attributes constitute sui generis characteristics which cannot be found in nominate (typical) contracts.

By the very nature of R&D agreements, the parties are obliged to mutually share trade secrets and know-how, and to keep each other fully informed. Consequently, they are required to exercise a level of diligence and loyalty that exceeds the standard obligations typically associated with mandate, service, or contract for work agreements²⁶.

In our view, it can be argued that reciprocal R&D agreements incorporate unique elements that are not present in typical (nominate) contracts regulated by law, which prevents them from being reduced to a mere hybrid of existing contractual types. Given their independent and original nature, and in accordance with the definition of sui generis contracts we have adopted, reciprocal R&D agreements should undoubtedly be characterized as sui generis contracts.

References

- Antalya, O. G. (2019). *Borçlar Hukuku Genel Hükümler* (Vol. 1, 2nd ed.). Ankara: Seçkin Yayıncılık.
- Aral, F., & Ayrancı, H. (2019). *Borçlar Hukuku Özel Borç İlişkileri* (12th ed.). Ankara: Yetkin Yayınları.
- Badur, E., & Doğan, G. (2022). "Fikri Haklar Açısından Araştırma Geliştirme Sözleşmeleri". *Hacı Bayram Veli Üniversitesi Hukuk Fakültesi Dergisi (HBV-HFD)*, 26(3), 77-118.
- Çörtoğlu Koca, S. (2009). "Milletlerarası Özel Hukukta Araştırma-Geliştirme (Ar-Ge) Sözleşmelerine Uygulanacak Hukuk". *Ankara Barosu Fikri Mülkiyet Hukuku ve Rekabet Hukuku Dergisi*, 9(3), 97-114.
- Dıvarcı, F. (2021). *Araştırma ve Geliştirme (Ar-Ge) Sözleşmeleri*. Ankara: Yetkin Yayınları.
- Eren, F. (2021). *Borçlar Hukuku Özel Hükümler* (9th ed.). Ankara: Yetkin Yayınları.
- Erdoğan, K. (2022). *Araştırma - Geliştirme Sözleşmesi*. Ankara: Adalet Yayınevi.
- Gümüş, M. A. (2013). *Borçlar Hukuku Özel Hükümler* (Vol. 1, 3rd ed.). İstanbul: Vedat Kitapçılık.
- Gümüş, M. A. (2020). *Borçlar Hukuku Özel Hükümler Kısa Ders Kitabı* (5th ed.). İstanbul: Filiz Kitabevi.
- Kuntalp, E. (2013). *Karışık Muhtevalı Akit (Karma Sözleşme)* (2nd ed.). Ankara: Banka ve Ticaret Hukuku Araştırma Enstitüsü.
- OECD (2002). *Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development*. Paris: OECD Publishing.

²⁵ Badur, Doğan, p. 84.

²⁶ Erdoğan, pp. 160-161.

- OECD (2015). *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development*. Paris: OECD Publishing.
- Rekabet Kurumu (2019). *Rekabet Terimleri Sözlüğü* (6th ed.). Ankara: Rekabet Kurumu.
- Serozan, R. (2019). *Borçlar Hukuku Özel Bölüm* (Prepared by B. Baysal & K. C. Sanlı, 4th ed.). İstanbul: On İki Levha Yayıncılık.
- Tandoğan, H. (2008). *Borçlar Hukuku Özel Borç İlişkileri* (Vol. I/1, 6th ed.). İstanbul: Vedat Kitapçılık.
- Yavuz, C., Acar, F., & Özen, B. (2022). *Türk Borçlar Hukuku Özel Hükümler* (Vol. 1, 11th ed.). İstanbul: Beta Yayınevi.
- Zevkliler, A., & Gökyayla, E. (2020). *Borçlar Hukuku Özel Borç İlişkileri* (20th ed.). İstanbul: Vedat Kitapçılık.

Data Protection and Digital Evidence: An Assessment of the Turkish Constitutional Court's Ruling on the Annulment of Article 134 of the Code of Criminal Procedure (Case No. 2023/128 E. and Decision No. 2026/36 K.) in the Light of German Criminal Procedure Law

Tahsin Furkan Çiçek¹

Abstract

The development of digital technologies has made digital evidence one of the most important tools for establishing the material truth in criminal proceedings. However, the legal issues surrounding digital evidence don't end with its acquisition. Increasing attention has been directed towards the rules governing the retention, processing, transfer and erasure of the personal data contained in such evidence, particularly from the perspective of the protection of fundamental rights. In its decision to annul Article 134 of the Turkish Code of Criminal Procedure (TCCP), the Constitutional Court assessed the provision under Article 20 of the Constitution, noting that whilst the provision regulated the procedure for obtaining digital data, it didn't contain sufficient legal safeguards regarding the subsequent processing of the data obtained following the trial. This study examines the reasoning behind both the majority and dissenting opinions in the aforementioned decision; These findings are then compared with the provisions of the German Code of Criminal Procedure (§§ 483–491 StPO) concerning the processing, storage, erasure, restriction of processing and periodic review of personal data. In this context, it is demonstrated that the data management model adopted in German law establishes a comprehensive protection regime covering not only the acquisition of digital evidence but also the entire data lifecycle. The study argues that is that the current provisions in Turkish law are limited to the stage of accessing digital data; conversely, there is a need for a systematic normative framework governing the

¹ Phd in Law, Department of Criminal Law and Criminal Procedure Law, Faculty of Law, Istanbul Sabahattin Zaim University. E-mail: tahsin.cicek@izu.edu.tr. ORCID: 0000-0001-7310-5303. Corresponding author.

retention, erasure, restriction of processing, and supervision of the personal data obtained, as well as the data subjects' judicial remedies. Accordingly, the study concludes by proposing legislative reforms to restructure Article 134 of the Code of Criminal Procedure, drawing on the data management system under German law and European data protection standards.

Keywords: Digital Evidence, Personal Data Protection, Article 134 of the Turkish Code of Criminal Procedure, Turkish Constitutional Court, Article 483–491 of the German Code of Criminal Procedure, Data Governance.

1. The Importance of Digital Evidence

Today, digital evidence has become one of the most important sources of evidence in criminal proceedings. The SIRIUS Electronic Evidence Situation Reports, published by the European Commission and Europol, indicate that digital data plays a decisive role in approximately 80% of criminal investigations, particularly in organized crime, terrorism, drug trafficking, child sexual exploitation and cybercrime². The central issue, therefore, is not whether digital evidence may be relied upon, but which constitutional and statutory safeguards should protect individuals' private life and personal data throughout its acquisition, retention, processing and destruction.

2. Assessment of the Turkish Constitutional Court's Decision

2.1. General Overview

By its decision of 12 February 2026 (E.2023/128, K.2026/36), the Turkish Constitutional Court annulled Article 134 of the TCCP on the ground that it failed to provide adequate legal safeguards for the protection of personal data³. While Article 134 regulates the procedure for the search, copying and seizure of digital data, it contains no rules on how the personal data obtained will subsequently be processed, how long it will be retained, by what procedure it will be deleted, or what rights data subjects hold. The Court's the constitutional deficiency lay not the acquisition of digital evidence or its admissibility in criminal proceedings, but the insufficiency of the data protection regime governing the personal data obtained. The annulment doesn't, by itself, render evidence

² SIRIUS Project, *SIRIUS EU Electronic Evidence Situation Report 2024* (The Hague, November 2024), 16.

³ Constitutional Court of the Republic of Türkiye, Decision No. E.2023/128, K.2026/36, 12 February 2026, accessed July 20, 2026, <https://normkararlarbilgibankasi.anayasa.gov.tr/kbb/pages/search/NormDenetimi?id=a2JiOmVhMTU1YmY5LWI5MzYtY2VlOS0zZDU2LWUyNTM3YmQ3ODNlNg&type=NormDenetim>

obtained under Article 134 unlawful, nor does it set aside final convictions or reopening concluded criminal proceedings.

2.2. Legal Arguments of the Majority Opinion

The Court identified four principal deficiencies in Article 134: no rules on retention duration or destruction procedure; no designated authority to assess erasure or restriction requests; no procedural safeguards for these processes; and no effective judicial remedy for data subjects⁴. These gaps leave Article 134 incompatible with Article 20(3) of the Constitution, which requires that the principles and procedures for personal data protection be regulated by law. Article 16 of Directive (EU) 2016/680 similarly grants a right to erasure or restriction once the processing purpose lapses, permitting restriction instead of erasure only where evidentiary necessity persists. It is precisely this normative gap that formed the basis of the Court's finding that Article 134 failed to satisfy the constitutional requirement of proportionality.

2.3. Legal Arguments of the Dissenting Opinion

The dissenting opinion maintains data retention necessary for ordinary and extraordinary remedies, arguing that preserving evidence to establish the truth ultimately serves the data subject as well. It notes that existing legislation already addresses retention, that Article 137(3) of the TCCP could apply by analogy to acquittal or non-prosecution decisions and that the Court had previously rejected similar objections.

2.4. Our Assessment of the Constitutional Court's Decision

In our view, the majority opinion is correct. Article 20(3) of the Constitution requires a comprehensive legal framework covering not only acquisition but retention, processing, transfer, erasure and restriction of processing. Article 134 contains no rule on the fate of data after acquittal or non-prosecution. The constitutional problem, therefore, lies not in the safeguards over acquisition, but in the absence of any legal regulation of subsequent processing. Combating crime effectively can't justify disregarding the constitutional protection of personal data.

3. General Assessment of the Annulled Provision of Article 134 of the TCCP

The Constitutional Court deferred the annulment's entry into force to 25 February 2027. Should the legislature enact a new legal framework within this period, the statutory basis for search, copying and seizure measures under Article 134 will cease to exist, exposing evidence obtained thereunder to lawfulness of evidence under Article 20 of the

⁴ Constitutional Court of the Republic of Türkiye, Decision No. E.2023/128, K.2026/36, §§ 64–66.

Constitution and Article 206(2)(a) of the TCCP — a scenario that could generate significant practical difficulties.

3.1. Negative Aspects of Article 134 of the TCCP

First, Article 134 has become outdated in light of technological developments. Its reference to "computer records" has been interpreted broadly to include smartphones, cloud services and AI-based applications, creating legal uncertainty⁵. Second, full forensic imaging of entire devices has become the de facto standard, leading to the collection of personal data unrelated to the offence⁶ and raising concerns under the principle of proportionality reflected in ECtHR case law and Directive (EU) 2016/680. Third, Article 134 contains no rules on the return, erasure or destruction of personal data following an acquittal, a decision of non-prosecution, or the discontinuance of criminal proceedings⁷.

3.2. Positive Aspects of Article 134 of the TCCP

Article 134 also has significant strengths. As a rule, the measure requires prior judicial authorization, while prosecutorial orders in urgent cases must be approved within twenty-four hours or the data must be destroyed. The requirements of strong suspicion based on concrete evidence and the absence of alternative means ensure proportionality⁸ and provide stronger safeguards than many comparable legal systems. Moreover, Article 134(5), requiring that a copy of the data be provided to the suspect, reinforces the right of defence by enabling verification of the integrity of the evidence and the presentation of counter-evidence⁹.

⁵ For a detailed discussion, see N. Ateş Benek, "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma," *Ceza Hukuku ve Kriminoloji Dergisi—Journal of Penal Law and Criminology* 10, no. 2 (2022): 375 ff., 407.

⁶ Olgun Değirmenci, "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma Koruma Tedbirinde (CMK m. 134), 7145 Sayılı Kanunla Yapılan Değişikliklerin Değerlendirilmesi," *Terazi Hukuk Dergisi* 13, no. 147 (2018): 151.

⁷ Salih Keskin, "Bilişim Suçlarında Ceza Muhakemesi Kanununun 134. Maddesindeki Hükümlerin Uygulanmasında Yaşanan Aksaklıklar," *Kırklareli Üniversitesi Sosyal Bilimler Dergisi* 11, no. 2 (2021): 662–663.

⁸ Osman Gazi Ünal, *Bilgisayarlarda Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma* (Master's thesis, Gazi University, Institute of Social Sciences, Ankara, 2011), 102.

⁹ Gökhan Yaşar Duran, "Ceza Muhakemesi Kanunu'nda (CMK) Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma (CMK m.134)," *Bahçeşehir Üniversitesi Hukuk Fakültesi Dergisi* 14, nos. 173–174 (2019): 231; Batuhan Aktaş, "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma Tedbiri Üzerine Bir İnceleme," *İnönü Üniversitesi Hukuk Fakültesi Dergisi* 12, no. 1 (2021): 230 ff.

4. Protection of Digital Evidence under German Law

4.1. The 2008 Decision of the German Federal Constitutional Court

In its Online-Durchsuchung decision of 27 February 2008 (1 BvR 370/07), the German Federal Constitutional Court recognized a “right to the confidentiality and integrity of information technology systems,” holding that covert access to IT systems is permissible only where a concrete danger exists, the measure is ordered by a judge, and the core area of private life remains protected¹⁰. Although the Turkish Constitutional Court decision doesn’t recognize a new fundamental right, both courts share the premise that digital privacy requires dedicated constitutional safeguards.

4.2. Sections 483–491 of the German Code of Criminal Procedure: A Comprehensive Data Retention Regime

German criminal procedure law protects personal data through a comprehensive data-management regime covering not only the acquisition of digital evidence but also its processing, retention, transfer, supervision and deletion. Sections 483–491 StPO, which form the legal basis of this approach, regulate the entire life cycle of personal data obtained in the course of criminal proceedings; the reform of 20 November 2019 restructured these provisions in line with EU Directive 2016/680 and the GDPR, thereby strengthening the data protection safeguards¹¹.

As a rule, Section 489 StPO prohibits indefinite retention: data must be deleted once its processing purpose lapses or retention is no longer necessary. Mandatory review periods (*Prüffristen*)¹²— ten years for adults, five for juveniles, three following acquittal or non-prosecution and two for children without criminal responsibility — ensure periodic reassessment of necessity rather than fixing absolute retention terms¹³.

Deletion is not, however, absolute. Section 489(6) StPO and Section 58 of the Federal Data Protection Act permit restricting processing instead — where necessary for scientific research, technically impossible to delete, harmful to the data subject’s own interests or disproportionately burdensome¹⁴. Restricted data may generally be used only for that purpose, though renewed access is permitted to resolve a genuine evidentiary

¹⁰ For further details, see Bundesverfassungsgericht (BVerfG), Judgment of the First Senate of 27 February 2008, 1 BvR 370/07 and 1 BvR 595/07, BVerfGE 120, 274, ECLI:DE:BVerfG:2008:rs20080227.1bvr037007, accessed July 20, 2026.

¹¹ Rolf Hannich, ed., *Karlsruher Kommentar zur Strafprozessordnung*, 9th ed. (Munich: C.H. Beck, 2023), commentary by Gieg, para. 1.

¹² KK-StPO/Gieg, 9th ed., § 489, para. 3.

¹³ KK-StPO/Gieg, 9th ed., § 489, para. 3.

¹⁴ KK-StPO/Gieg, 9th ed., § 489, para. 4.

difficulty (*Beweisnot*)¹⁵. This balances data protection against the effectiveness of criminal justice.

4.3. Problems of the German System

The German regime nonetheless attracts criticism. Its “mixed data systems” (*Mischdateisysteme*) under Section 483(3) allow data obtained for criminal investigation and for danger prevention to be held in the same database, weakening purpose limitation (*Zweckbindung*) and complicating oversight¹⁶. Under Sections 484(2) and 489, data may also be retained on the basis of “residual suspicion” (*Restverdacht*) even after acquittal or non-prosecution, unless innocence is affirmatively established — a practice criticized as inconsistent with the presumption of innocence¹⁷. In practice, individuals are effectively required to demonstrate their own innocence to obtain erasure, a further point of criticism¹⁸.

5. Reform of Article 134 of the TCCP: Assessment of the Legislative Bill and Reform Proposals

Following the annulment, Article 15 of Bill No. 2/3737 (the “12th Judicial Package”) proposed amending Article 134. While preserving its first five paragraphs, it introduced a sixth paragraph requiring data obtained under the measure to be kept in judicial custody and destroyed fifteen years after a final non-prosecution decision or judgment, while allowing data subjects to request earlier deletion where retention was no longer justified. Although Article 15 was removed during the parliamentary deliberations and was therefore not enacted under Law No. 7589, the bill remains significant as an indication of the legislature's intended response to the Constitutional Court's judgment. By granting data subjects the right to request the erasure of their personal data, the bill represents an important step towards addressing the normative deficiencies in the protection of personal data identified by the Constitutional Court in its annulment judgment.

However, unlike Sections 483–491 StPO, it regulates only retention and destruction, leaving the broader framework for the processing, transfer and restriction of personal data unaddressed. Its principal weakness is the fixed fifteen-year retention period, which applies irrespective of the outcome of the proceedings or the nature of the

¹⁵ KK-StPO/Gieg, 9th ed., § 489, para. 4.

¹⁶ Jürgen Graf, ed., *Beck'scher Online-Kommentar Strafprozessordnung (BeckOK StPO)*, 59th ed. (Munich: C.H. Beck, updated April 1, 2026), commentary by Wittig, § 483, para. 8.

¹⁷ Christoph Knauer, Hans Kudlich, and Hartmut Schneider, eds., *Münchener Kommentar zur Strafprozessordnung*, 2nd ed. (Munich: C.H. Beck, 2024), commentary by Singelnstein, § 484, para. 17.

¹⁸ MüKoStPO/Singelnstein, § 484, para. 17.

offence, raising concerns under the presumption of innocence and the right not to be stigmatized. A German-style *Prüffristen* model, based on periodic review rather than a fixed retention period, would be preferable. Turkish law should also replace the outdated concept of "computer record" with "information system", provide rights of access, restriction of processing and effective judicial remedies and extend these safeguards to the prosecution stage.

In conclusion, although the bill represents a meaningful response to the Constitutional Court's judgment, Article 134 should ultimately be restructured, following the model of Sections 483–491 StPO, into a comprehensive data-management regime governing the entire life cycle of personal data.

References

Aktaş, Batuhan. "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma Tedbiri Üzerine Bir İnceleme." *İnönü Üniversitesi Hukuk Fakültesi Dergisi* 12, no. 1 (2021): 211–239.

Ateş Benek, N. "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma." *Ceza Hukuku ve Kriminoloji Dergisi–Journal of Penal Law and Criminology* 10, no. 2 (2022): 375–411.

Bundesverfassungsgericht (BVerfG). Judgment of the First Senate of 27 February 2008, 1 BvR 370/07 and 1 BvR 595/07. *BVerfGE* 120, 274. ECLI:DE:BVerfG:2008:rs20080227.1bvr037007.

Constitutional Court of the Republic of Türkiye. Decision No. E.2023/128, K.2026/36. 12 February 2026. Accessed July 20, 2026. <https://normkararlarbilgibankasi.anayasa.gov.tr/kbb/pages/search/NormDenetimi?id=a2JiOmVhMTU1YmY5LWI5MzYtY2VlOS0zZDU2LWUyNTM3YmQ3ODNlNg&type=NormDenetimi>.

Değirmenci, Olgun. "Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma Koruma Tedbirinde (CMK m. 134), 7145 Sayılı Kanunla Yapılan Değişikliklerin Değerlendirilmesi." *Terazi Hukuk Dergisi* 13, no. 147 (2018): 146–155.

Duran, Gökhan Yaşar. "Ceza Muhakemesi Kanunu'nda (CMK) Bilgisayarlarda, Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma (CMK m.134)." *Bahçeşehir Üniversitesi Hukuk Fakültesi Dergisi* 14, nos. 173–174 (2019): 173–241.

Graf, Jürgen, ed. *Beck'scher Online-Kommentar Strafprozessordnung (BeckOK StPO)*. 59th ed. Munich: C.H. Beck, updated April 1, 2026.

Hannich, Rolf, ed. *Karlsruher Kommentar zur Strafprozessordnung*. 9th ed. Munich: C.H. Beck, 2023.

Keskin, Salih. "Bilişim Suçlarında Ceza Muhakemesi Kanununun 134. Maddesindeki Hükümlerin Uygulanmasında Yaşanan Aksaklıklar." *Kırklareli Üniversitesi Sosyal Bilimler Dergisi* 11, no. 2 (2021): 649–667.

The Impact of Technological Innovations on Law in the Digital Age and Future Perspectives in Engineering Education
Almalyk State Technical Institute, Almalyk, Uzbekistan, 22 July 2026

Knauer, Christoph, Hans Kudlich, and Hartmut Schneider, eds. *Münchener Kommentar zur Strafprozessordnung*. 2nd ed. Munich: C.H. Beck, 2024.

SIRIUS Project. *SIRIUS EU Electronic Evidence Situation Report 2024*. The Hague, November 2024.

Ünal, Osman Gazi. *Bilgisayarlarda Bilgisayar Programlarında ve Kütüklerinde Arama, Kopyalama ve Elkoyma*. Master's thesis, Gazi University, Institute of Social Sciences, Ankara, 2011.

The Impact of Artificial Intelligence on Turkish Joint Stock Companies Law

Mustafa Yasan¹

Abstract

Artificial intelligence is a reality of our time, one that cannot be explained without law. Corporate law is among the areas of law most affected by artificial intelligence. Joint-stock companies are considered the locomotive of corporate law and a type of company with an extremely broad scope of influence. Artificial intelligence technologies have begun to show their effect in a very wide range of areas, from the establishment and management of joint-stock companies to general assembly meetings and auditing. Many issues that are currently being debated and challenged have the potential to become accepted facts by legal systems in the near future. The Turkish legal system is also following these developments in line with the European Union vision.

Keywords: Artificial intelligence, Turkish company law, Joint stock companies in Turkish law, Corporate governance, Digitalisation, AI and company law

1. Introduction

Artificial intelligence (AI) is transforming company law. The Turkish Commercial Code No. 6102 (TCC) is based on human-centered, traditional management models. Although the TCC allows electronic meetings, AI technologies offer greater potential for change. The active role of AI in corporate management, decision-making, and auditing

¹ Prof. Dr., Balıkesir University Faculty of Law, mustafa.yasan@balikesir.edu.tr,
ORCID: 0000-0003-0741-9720

challenges traditional liability regimes and conceptual boundaries of Turkish company law.

AI is evolving beyond automation to serve as an autonomous "decision-maker" capable of replacing company bodies. This study examines current and potential effects of AI on Turkish corporate law. It addresses the legal nature of AI, "electronic personality" (e-personhood) debates, autonomous boards (DAOs), board members' liability, the prudent businessman criterion, and the Business Judgment Rule. Furthermore, shareholder rights, minority protection, the changing role of auditors, and potential implications of the European Union (EU) AI Act on Turkish law are evaluated from a *de lege ferenda* perspective.

2. The Legal Nature Of Artificial Intelligence and the "Personality" Debates

According to Article 8 of the Turkish Civil Code (TCiC), every person has legal capacity, and Article 47 grants legal personality to organized groups or asset pools (Koç, 2023). This classic dichotomy between natural and legal persons is insufficient for AI's autonomous capabilities (Ber, 2022; Gülel, 2023; Kubat, 2026). In Turkish corporate law doctrine, three main theories explain AI's legal nature (Kılıçarslan, 2019):

Property/Instrument Theory: Views AI as an advanced instrument subject to property law. Decisions made and damages caused are considered direct actions of the company or its board (Gülel, 2023).

Digital Agent Theory: Explains AI's autonomous actions within the framework of representation under the Turkish Code of Obligations (TCO), directly binding the represented company.

Electronic Personality Theory: Argues that AI should acquire limited personality through a legal fiction, enabling it to potentially become a shareholder or board member (Ber, 2022; Kubat, 2026).

In positive law, AI remains an object of rights (property) (Kılıçarslan, 2019; Koç, 2023; Yünlü, 2024). However, its autonomous structure mimics the "declaration of will" mechanism, making classical property law insufficient (Godwin, Lee and Langford, 2021).

3. AI in Corporate Management and the Digitalization of Boards of Directors

AI participation in management processes involves three main stages based on autonomy (Petrin, 2024):

Supportive AI: Systems analyzing data, providing consultancy.

Collaborative AI: Systems working alongside human board members, influencing decisions without voting rights (Möslein, 2021; Daeenabi, 2025).

Autonomous AI (DAO): Decentralized organizations managing companies entirely through smart contracts and algorithms (Möslein, 2021; Daeenabi, 2025).

Under Turkish law, AI cannot be a board member *de lege lata*. Article 359 of the TCC requires board members to be fully competent natural persons or legal entities. Transferring decision-making authority to AI violates the board's "non-transferable duty of supervision" under Article 375/1-e of the TCC (Aksakal, 2024). However, no legal obstacle prevents managers from using AI as a supportive tool to analyze data, determine corporate strategies, and verify decisions (Uğurerkan, 2024).

4. The Board of Directors' Duty of Care and the Business Judgment Rule

The integration of artificial intelligence (AI) as a management tool is reshaping the scope of directors' duties of care and loyalty under Article 369/1 of the Turkish Commercial Code (TCC). The traditional standard of "the diligence of a prudent manager" acquires new dimensions in the AI era (Kaya, 2021). A director who completely disregards big data analyses and strategic reports generated by AI may be deemed to have breached the duty of care. Conversely, blindly approving AI-generated reports without any critical scrutiny also constitutes a breach of this duty (Akin, 2022).

Directors are obligated to question algorithmic outputs, verify the reliability of underlying databases, and retain human judgment in final decision-making. At this juncture, the Business Judgment Rule — widely accepted in legal doctrine and jurisprudence—becomes relevant. For a board decision to be protected from judicial review and executive liability, it must be based on reasonable information, free from conflicts of interest, and made in good faith for the best interests of the company (Uğurerkan, 2024).

The required process follows a logical sequence: (1) integration of AI data, (2) executive review of algorithmic outputs, (3) human judgment and risk analysis, and (4) protection under the Business Judgment Rule upon completion of these steps. Directors

should benefit from this protection even if outcomes prove erroneous, provided they have properly investigated the AI system's limitations, error margins, and data quality (Kaya, 2021). AI utilization falls within the directors' "right and obligation to be informed," yet it must not serve as a shield that absolves human responsibility.

5. Damages Arising from Artificial Intelligence Use and Board Liability

When a company suffers losses due to erroneous AI decisions, cybersecurity vulnerabilities, or inaccurate market predictions, the legal liability of board members arises under Article 553 of the TCC. Turkish company law applies the principle of fault-based liability. Therefore, directors cannot be held automatically liable for harms caused by AI systems. Liability requires proof of negligence in selecting (*culpa in eligendo*), instructing (*culpa in instruendo*), or supervising (*culpa in custodiendo*) the AI technology (Uğurerkan, 2024).

Beyond civil liability, gross negligence in AI integration processes may trigger criminal responsibility under Article 562 of the TCC. Examples include failing to detect AI manipulation of financial statements or neglecting to prevent the leakage of trade secrets through AI algorithms, both of which may expose directors to criminal sanctions (Karadeniz, 2023). To clarify accountability, companies must establish clear internal guidelines on AI use and define precise job descriptions for relevant roles.

6. Digitalization of Shareholder Rights and Minority Protections

The convergence of artificial intelligence and blockchain technologies is fundamentally transforming the exercise of shareholder rights. The electronic general assembly (EGAS) system, governed by Article 1527 of the TCC, can automate voting processes through integrated AI algorithms. Shareholders may appoint "AI proxies" that vote autonomously in line with predefined investment policies (Akın, 2022).

This digitalization offers both opportunities and risks for minority shareholder protection. AI enables minority shareholders to better exercise their rights to information and inspection (Article 437 TCC) by providing real-time analysis of financial data. Algorithms capable of instantly detecting irregular transactions can accelerate redress mechanisms. However, controlling shareholders may manipulate AI systems to their advantage, leading to systematic violations of minority rights. Such practices are likely to generate new disputes, including share acquisition impediments under Article 491 et seq. of the TCC and capital increases that breach the principle of good faith.

7. The Evolving Role of Company Auditors in Digital Transformation

The audit of joint-stock companies, regulated under Article 397 and subsequent provisions of the TCC, is among the areas most profoundly affected by AI technologies. Traditional auditing relies on sampling and examination of historical financial data. In contrast, AI possesses the capacity to review all financial transactions, accounting records, and invoices in real time. This shift transforms auditors from passive “reporters of the past” to proactive “predictors of future risks.”

AI-powered audit tools facilitate immediate detection of fraudulent transactions, tax evasion risks, and accounting manipulations. Nevertheless, this enhanced capability also heightens auditors’ legal responsibilities. Auditors who fail to utilize AI tools or ignore the warning signals they generate may face increased liability for damages under Article 404 of the TCC. Auditors are furthermore required to oversee the independence of algorithmic systems and the integrity of input data (Akin, 2022).

In conclusion, the incorporation of AI into corporate governance introduces significant opportunities alongside new responsibilities. It necessitates a redefinition of core principles—duty of care, accountability, and oversight—while preserving the centrality of human judgment and ethical responsibility (Ergül, 2025).

8. European Union Artificial Intelligence Act (AI Act) and Its Implications for Turkish Law – De Lege Ferenda Perspective

The European Union’s Artificial Intelligence Act (AI Act) adopts a risk-based approach, classifying AI systems according to their potential harm (Arezzo, 2026). AI applications in corporate management, human resources, and financial risk assessment are typically categorized as high-risk, subjecting them to stringent requirements regarding transparency, human oversight, cybersecurity, and data governance (Custers, Fosch-Villaronga, 2022; Ananthan, Thangam, Manickam, Kapepa and Woods, 2026).

From a *de lege ferenda* perspective, Turkish company law should draw on this regulatory framework during its modernization process. Special provisions should be incorporated into the Turkish Commercial Code (TCC) or supporting legislation to establish minimum standards, accreditation mechanisms, and algorithmic transparency obligations for AI systems used in joint-stock companies. Rather than prohibiting AI outright, Turkish law should integrate robust corporate governance principles to mitigate risks and enhance legal certainty (Aksakal, 2024).

Key proposals include: introducing a “digital duty of care” into Article 369 alongside the prudent manager standard; explicitly defining directors’ oversight duties

concerning AI and algorithms, including cybersecurity, impartiality, and explainability; permitting boards to appoint AI-based digital advisors while maintaining the prohibition on AI serving as board members; and clarifying board responsibility for AI-generated decisions (Aksakal, 2024).

Further recommendations involve creating a limited “electronic legal entity” model for autonomous subsidiaries or DAOs, allowing commercial registry registration upon mandatory AI professional liability insurance and guarantee fund requirements (Barfield and Pagallo, 2018). This approach would recognize DAOs as a new generation of commercial entities, avoiding their classification as ordinary partnerships and the resulting unlimited liability risks (Arezzo, 2026). Such reforms would help Turkish corporate law remain competitive in the comparative landscape.

Conclusion

Artificial intelligence technologies are a reality that challenges the traditional boundaries of Turkish joint-stock company law and dictates an inevitable digital transformation. The absence of an independent legal personality or board membership status for artificial intelligence under the current legal system does not eliminate its de facto power in company management. Artificial intelligence has become an integral part of managers' obligation to act as prudent businesspeople and to be informed. To prevent future violations of rights and confusion of responsibilities, Turkish company law doctrine should discuss the theories of "electronic personality" and "digital agent" more deeply, and legislators should implement de lege ferenda regulations compatible with EU artificial intelligence legislation that prioritize transparency and human oversight. The sustainability of companies and the success of corporate governance principles depend on crowning this technological transformation with a sound legal foundation.

References

- Akın, İ. (2022). Dijital gelişmelerin şirketler hukuku üzerindeki etkisi. *Türk-Alman Üniversitesi Hukuk Fakültesi Dergisi*, 4(1), 3–26.
- Aksakal, Ö. (2026, 16 Temmuz). *Yönetim kurulunda yapay zeka - yapay zekanın yönetim kuruluna entegrasyonu hakkında bir inceleme*. Av. Ömer Aksakal Hukuk Bürosu. <https://www.avomeraksakal.com/post/y%C3%B6netim-kurulunda-yapay-zeka-yapay-zekan%C4%B1n-y%C3%B6netim-kuruluna-entegrasyonu-hakk%C4%B1nda-bir-i-ncelme>
- Ananthan, S., Thangam, D., Manickam, T., Kapepa, O. and Woods, A. (2026). *Rethinking responsibility at the intersection of AI and corporate liability*. IGI Global Scientific Publishing.
- Arezzo, E. (2026). *Navigating the (legal) challenges of the artificial intelligence era: Intellectual property, competition law and corporate law*. Kluwer Law International.

Barfield, W. and Pagallo, U. (2018). *Research handbook on the law of artificial intelligence*. Edward Elgar Publishing.

Ber, A. S. (2022). Yapay zekânın hukuki statüsü ve kişilik hakkı kapsamında değerlendirilmesi. *Dicle Üniversitesi Adalet Meslek Yüksekokulu Dicle Adalet Dergisi*, 6(1), 57–100.

Custers, B. and Fosch-Villaronga, E. (2022). *Law and artificial intelligence regulating AI applying AI in legal practice*. Springer.

Daeenabi, I. M. (2025). Beyond human oversight: Corporate law and the case for AI directors. *UC Law Journal*, 76(4), 1271–1306.

Ergül, E. (2025). *Avrupa yapay zeka hukuku*. Adalet Yayınevi.

Godwin, A., Lee, P. W. and Langford, R. T. (2021). *Technology and corporate law*. Edward Elgar Publishing.

Gülel, H. (2023). *Hukuki açıdan yapay zeka*. Adalet Yayınevi.

Kara Kılıçarslan, S. (2019). Yapay zekanın hukuki statüsü ve hukuki kişiliği üzerine tartışmalar. *Yıldırım Beyazıt Hukuk Dergisi*, 4(2), 363–389.

Karadeniz, S. (2023). Yapay zekânın anonim şirket yönetim kuruluna üyeliği ve üyelikten doğan sorumluluğunun değerlendirilmesi. *Türkiye Adalet Akademisi Dergisi*, 14(54), 255–288.

Karatepe Kaya, M. (2021). Yapay zekanın şirket yönetimine olası katkılarının Türk şirketler Hukuku kapsamında değerlendirilmesi ve yapay zekanın hukuki statüsünün belirlenmesinde şirketler hukukundan çıkartılabilecek dersler. *Ankara Hacı Bayram Veli Üniversitesi Hukuk Fakültesi Dergisi*, 25(3), 69–106.

Koç, E. G. (2023). Yapay zekanın hukuki statüsüne yönelik yaklaşımlar ve genel bir değerlendirme. M. Aksu (Ed.), *Yapay zeka ve hukuk içinde* (s. 311–312). On İki Levha Yayıncılık.

Kubat, M. (2026). *Yapay zekâ tarafından üretilen eserlerin korunması*. Yetkin Yayınevi.

Möslein, F. (2021). Yönetim kurulu toplantı odasındaki robotlar: Yapay zeka ve şirketler hukuku (S. Bora Çınar, Çev.). *İstanbul Hukuk Mecmuası*, 79(2), 699–728.

Petrin, M. (2024). The impact of AI and new technologies on corporate governance and regulation. *Singapore Journal of Legal Studies*, 90–106.

Uğurerkan, Ç. S. (2024). *Artificial intelligence impact on corporate law and management*. Yetkin Yayınevi.

Yünlü, S. (2024). Üretici yapay zekâ kaynaklı norm ve kişi bazlı hukuki sorumluluk. *Adalet Dergisi*, (72), 501–542.

The Issue of the Legal Nature of Digital Services Taxes: an Assessment from the Perspectives of Double Taxation and Fiscal Sovereignty

Kaan Erkan¹

Abstract

Digitization of economic activities has rendered traditional approaches to international tax law, which base taxing authority on the criteria of physical presence and a permanent establishment, arguable. In response to problems regarding the taxation of activities digitally, many countries have unilaterally implemented Digital Services Taxes (DSTs). Since DSTs are structured on the basis of gross revenue, unlike income taxes levied in many countries, they have sparked debate over whether they fall within the scope of existing Double Taxation Treaties (DTTs). However, the classification of DSTs under DTTs raises significant debates regarding the fiscal sovereignty of states, particularly in terms of limiting the taxing authority of countries. The assessment of DSTs, which countries have established in their domestic laws as a tax distinct from income tax, in light of existing DTTs raises the risk that multinational companies could be taxed in more than one country for the same economic activity. This study analyzes the limits of states' sovereign taxing authority, unilateral DST measures, the points of conflict between these measures and bilateral or multilateral international obligations. The study discusses how to strike

¹ LL.M. Student in Public Law, Kocaeli University, E-mail: kaanerkanhukuk@gmail.com, ORCID ID: 0009-0007-1245-7533

a delicate balance between states' desire to protect their sovereign rights and international law's ideal of preventing double taxation.

Keywords: Fiscal Sovereignty, Digital Services Taxes (DSTs), Double Taxation, Tax Treaties (DTTs)

1. Introduction

The territorial application of tax laws refers to the geographical scope within which states exercise their taxing powers and determine which income is subject to taxation. Traditionally, the allocation of taxing rights has been governed by two fundamental principles: the principle of personality and the principle of territoriality. "The principle of territoriality requires a state to tax all persons within its territorial boundaries, regardless of their nationality, whereas the principle of personality refers to a state's taxation of its own nationals even if they reside abroad" (Bilici, 2022, p. 18).

These principles have historically constituted the foundation of states' fiscal sovereignty. Under traditional economic conditions, factors such as residence, nationality, and the place where business activities were physically carried out provided clear and predictable criteria for allocating taxing rights. However, the rapid expansion of the digital economy has weakened the connection between economic activity and physical presence, making traditional international tax rules increasingly inadequate for taxing digital economic activities.

OECD has also acknowledged these challenges, emphasizing that international tax rules based on physical presence and permanent establishment face significant difficulties in addressing the taxation of digital economic activities (OECD, 2015).

In response, countries such as Türkiye, France, the United Kingdom, Italy, and Spain have introduced DSTs to tax revenues derived from digital activities. These measures aim to protect fiscal sovereignty, promote tax fairness, and address the challenges of base erosion and profit shifting identified under the OECD Base Erosion and Profit Shifting (BEPS) Project (OECD, 2015).

Nevertheless, the unilateral implementation of DSTs has given rise to significant legal issues, particularly concerning double taxation. Since DSTs are generally imposed on gross revenues rather than corporate income, they are often considered to fall outside the scope of existing DTTs. As a result, multinational enterprises may be taxed both in the market jurisdiction through DSTs and in their state of residence through corporate

income tax, raising questions regarding the allocation of taxing rights and the effectiveness of existing treaty mechanisms (OECD, 2020).

Accordingly, this study examines the emergence and legal nature of DSTs and evaluates their implications for DTTs and states' fiscal sovereignty within the framework of international tax law.

2. Method

This study adopts a doctrinal legal research methodology. It is based on the examination of primary legal sources, including domestic legislation concerning Digital Services Taxes, Double Taxation Treaties, the OECD Model Tax Convention, and OECD reports on the taxation of the digital economy. The study also draws upon secondary sources, including academic literature on fiscal sovereignty, international tax law, and digital taxation.

The analysis employs legal interpretation and doctrinal analysis to examine the legal nature of Digital Services Taxes, their relationship with existing Double Taxation Treaties, and their implications for the allocation of taxing rights and states' fiscal sovereignty under international tax law.

3. Results and Discussion

3.1. The Legal Nature of Digital Services Taxes and the Risk of Double Taxation

The legal nature of DSTs has become one of the most debated issues in international tax law. At the heart of this debate lies the question of whether DSTs should be characterized as taxes on income or as a distinct category of direct taxes independent of income taxes. This distinction is crucial in determining whether such taxes fall within the scope of DTTs.

The scope of Double Taxation Treaties is defined in Article 2 of the OECD Model Tax Convention, which generally applies to taxes on income and on capital. Since Digital Services Taxes are, in most jurisdictions, levied on gross revenues rather than corporate profits, divergent views have emerged in the literature as to whether they qualify as "taxes on income" for treaty purposes (OECD, 2017). "In light of the classifications made regarding the legal nature of the Digital Services Tax, it is not easy to include this type of tax within any category" (Ergür, 2025, p. 24).

If DSTs are considered to fall outside the scope of DTTs, multinational enterprises may be subject to both DSTs in the market jurisdiction where digital services are supplied

and corporate income tax in their state of residence on the same economic activity. This situation has the potential to undermine one of the fundamental objectives of international tax law, namely the prevention of double taxation. The OECD has likewise noted that unilateral DSTs may increase international tax disputes and create a greater risk of double taxation (OECD, 2020).

On the other hand, proponents of DSTs argue that these measures seek to address the tax gap arising from the inability of existing international tax rules to adequately capture the digital economy. The current international tax framework, which relies on the requirement of physical presence, often prevents market jurisdictions from taxing substantial economic activities carried out by digital businesses. Accordingly, states consider the taxation of revenues generated from digital activities to be a legitimate exercise of their fiscal sovereignty. In this respect, the OECD's Two-Pillar Solution also recognizes the need to allocate greater taxing rights to market jurisdictions in response to the challenges posed by the digital economy (OECD, 2021).

Accordingly, the debate over the legal nature of DSTs extends beyond a purely technical issue of tax law. It reflects the broader challenge of balancing states' fiscal sovereignty with the allocation of taxing rights under the international tax treaty framework. Therefore, determining the legal status of Digital Services Taxes in relation to existing DTTs remains a key issue for the future development of the international tax system.

3.2. Fiscal Sovereignty and the Unilateral Implementation of Digital Services Taxes

The unilateral adoption of DSTs reflects states' efforts to preserve their fiscal sovereignty in response to the challenges posed by the digital economy. Fiscal sovereignty refers to the authority of states to determine their own tax systems and to levy taxes within the limits of international law. However, the increasing ability of multinational digital enterprises to generate significant revenues in market jurisdictions without establishing a taxable physical presence has considerably weakened the effectiveness of this authority under the traditional international tax framework (OECD, 2015).

From this perspective, many states regard DSTs as an interim mechanism designed to protect their tax bases until a multilateral solution is fully implemented. In particular, market jurisdictions argue that digital businesses derive substantial economic value from user participation and consumer markets within their territories and should therefore contribute to public revenues, regardless of the absence of a permanent establishment.

Accordingly, the unilateral introduction of DSTs has been justified as a legitimate exercise of fiscal sovereignty aimed at ensuring a fair allocation of taxing rights.

Nevertheless, unilateral DSTs have also attracted significant criticism. Since these measures are generally adopted outside the existing treaty framework, they may create inconsistencies in the allocation of taxing rights, increase the risk of double taxation, and give rise to international tax disputes (OECD, 2020). For this reason, the OECD has emphasized that unilateral measures should be regarded as temporary solutions pending the implementation of a coordinated international framework.

The OECD's Two-Pillar Solution represents an important step toward reconciling states' fiscal sovereignty with the need for greater international tax coordination. In particular, Pillar One seeks to reallocate a portion of taxing rights to market jurisdictions, thereby addressing one of the principal shortcomings of the traditional permanent establishment concept while reducing the need for unilateral DSTs. (OECD, 2021).

Accordingly, the debate surrounding DSTs extends beyond their legal characterization. It also reflects the broader tension between states' sovereign right to tax economic activities within their jurisdictions and the need to preserve coherence and legal certainty within the international tax system.

4. Conclusion

The rapid development of the digital economy has challenged the traditional principles governing the allocation of taxing rights in international tax law. As digital business models enable multinational enterprises to generate significant economic value without maintaining a physical presence in market jurisdictions, the existing international tax framework has become increasingly inadequate in addressing the taxation of digital activities.

This study has demonstrated that the legal characterization of DSTs remains one of the most controversial issues in contemporary international tax law. Since these taxes are generally levied on gross revenues rather than corporate income, uncertainty persists as to whether they fall within the scope of existing DTTs. This uncertainty may increase the risk of double taxation while also creating inconsistencies in the allocation of taxing rights between residence and market jurisdictions.

At the same time, the unilateral implementation of DSTs reflects states' efforts to safeguard their fiscal sovereignty and protect their tax bases against the challenges created by digitalization. Although such measures may be regarded as legitimate from the perspective of fiscal sovereignty, they also demonstrate the limitations of unilateral solutions in an increasingly interconnected global economy.

Accordingly, the future of the international tax system depends on achieving an appropriate balance between states' sovereign taxing powers and the need for coordinated international rules. In this respect, the OECD's Two-Pillar Solution represents an important step toward addressing the tax challenges arising from digitalization. Nevertheless, its long-term effectiveness will ultimately depend on its consistent implementation and broad international acceptance.

References

- Bilici, N. (2022). *Vergi hukuku* [Tax law]. Savaş Yayınevi.
- Ergür, O. K. (2025). Dijital hizmet vergisi: Türk vergi sistemine etkileri ve uygulama alanları [Digital service tax: Its effects on the Turkish tax system and areas of application]. *Ankara Hacı Bayram Veli Üniversitesi Hukuk Fakültesi Dergisi*, 29(4), 1975–2025. <https://doi.org/10.34246/ahbvuhfd.1672756>
- OECD. (2015). *Addressing the tax challenges of the digital economy, Action 1 - 2015 final report*. OECD Publishing. <https://doi.org/10.1787/9789264241046-en>
- OECD. (2017). *Model tax convention on income and on capital: Condensed version 2017*. OECD Publishing. https://doi.org/10.1787/mtc_cond-2017-en
- OECD. (2020). *Tax challenges arising from digitalisation – Report on Pillar One blueprint*. OECD Publishing. <https://doi.org/10.1787/beba0634-en>
- OECD. (2021). *Statement on a two-pillar solution to address the tax challenges arising from the digitalisation of the economy*. OECD Publishing. <https://www.oecd.org/tax/beps/statement-on-a-two-pillar-solution-to-address-the-tax-challenges-arising-from-the-digitalisation-of-the-economy-october-2021.pdf>