IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

MINING 5.0 TRANSITION IN EMERGING ECONOMIES: A SOCIO-TECHNICAL FRAMEWORK FOR HUMAN-CENTRIC AIOT ADOPTION AT COAL INDIA LIMITED

Shivam Kushwaha[1] and Ram Chandra Chaurasia[2]

[1] M.Tech Scholar, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

[2] Associate Professor, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

Abstract: The mining industry is undergoing a profound shift toward Mining 5.0, emphasizing human-centric design, sustainability, and intelligent collaboration between humans and autonomous systems. This paper proposes a socio-technical framework for human-centric AIoT (Artificial Intelligence of Things) adoption in emerging economies, with a focused case on Coal India Limited (CIL). Drawing on Industry 5.0 principles, the framework integrates collaborative robotics, digital twins, edge AI, and ethical governance to address the unique challenges of legacy infrastructure, skill gaps, regulatory complexities, and workforce transition in Indian coal mining. Through a systematic literature review and analysis of global and Indian case studies (Rio Tinto, BHP, CIL Digi-Coal), the study identifies critical barriers including cybersecurity risks, data privacy concerns, algorithmic bias, and potential job displacement. It advocates a balanced approach that prioritizes operator well-being, reskilling programs, and inclusive implementation pathways. The proposed framework outlines phased adoption strategies, performance metrics, and policy recommendations aligned with DGMS guidelines and Atmanirbhar Bharat initiatives. Findings highlight that successful Mining 5.0 transition requires harmonizing technological innovation with social and ethical considerations to achieve enhanced safety, productivity, and sustainability.

Keywords: Mining 5.0, AIoT, human-centric design, socio-technical framework, Coal India Limited, emerging economies, digital twins, ethical AI, Industry 5.0, sustainable mining

I. INTRODUCTION

The rapid integration of Artificial Intelligence of Things within the mining sector marks a strategic departure from traditional Industry 4.0 automation toward a Cyber-Physical-Social Systems paradigm (Chen et al., 2023; Singh et al., 2024; Singh et al., 2025). This transition necessitates a shift beyond mere operational efficiency to address the critical mandate of human-machine collaboration and sustainable resource management (Yang et al., 2023). For Coal India Limited, this evolution requires navigating the unique constraints of emerging economies, where successful adoption depends less on pure technological capacity and more on the workforce's ability to appropriate and adapt to these sophisticated industrial shifts (Capet et al., 2026). By fostering an environment where human creativity synergizes with AIoT-driven intelligence, Coal India Limited can effectively transition toward the "Operator 5.0" model, which prioritizes the augmentation of worker capabilities through intelligent, real-time data streams (Rožanec et al., 2022; Fazlollahtabar, 2025). This framework specifically addresses the pressing need to reconcile the operational requirements of the Indian mining landscape characterized by rugged terrain and logistical hurdles with the socio-technical imperative for inclusive, human-centric design (Pratap., 2025; Togara, Madahana and Olugu, 2026). Such an approach must bridge the prevailing digital divide by integrating fatigue monitoring and predictive maintenance tools directly into the daily workflows of frontline employees (Lingaraja and G, 2025; Tripathi & Chaurasia, 2025; Giri & Chaurasia, 2025).

Furthermore, this study aims to address the current lack of integrated frameworks in the Indian context by harmonizing organizational readiness with the specific socio-technical realities of the mining workforce (Bhattacharyya and Shah, 2021; Togara, Madahana and Olugu, 2026; Yadav & Chaurasia, 2025a). By developing a systematic, six-step framework for AIoT implementation, this research offers granular guidance to translate abstract Industry 5.0 principles into daily design practices that elevate worker well-being and long-term engagement (Passalacqua et al., 2024). This transformation further emphasizes the necessity of understanding the psychological dimensions of worker autonomy and AI trust to ensure that the adoption of intelligent systems does not alienate the existing labor force (Lund et al., 2024; Passalacqua et al., 2024). The framework is also relevant to environmental and energy performance. Recent research on AIoT-enabled methane prediction demonstrates how intelligent sensing and predictive analytics can be applied to underground coal mining to reduce methane emissions and improve carbon-footprint performance (Singh & Chaurasia, 2026).

Such applications demonstrate that Mining 5.0 can extend beyond productivity and safety toward environmental sustainability and carbon management. Consequently, the proposed framework emphasizes the intentional integration of human ethical judgment and cognitive insight with autonomous AIoT components to move beyond the constraints of pure automation (Gomaa, 2026), (Thompson-Bahm, Teixeira and Lobo, 2025). thereby creating a symbiotic ecosystem where machines handle hazardous, high-precision tasks while workers retain agency over complex decision-making processes (Aouedi et al., 2024). This strategic alignment with Industry 5.0 values is essential for navigating the transition from purely automated infrastructure to sustainable, collaborative manufacturing (Lo et al., 2024; Narkhede et al., 2024). By aligning operators' competencies with this new smart factory context, the organization can transcend traditional automation to cultivate an augmented operator paradigm that leverages deep, multi-level cooperation (Longo, Nicoletti and Padovano, 2017). Such an integration requires mapping emerging technological advancements such as collaborative robotics and cyber-physical systems to the specific occupational safety and ethical requirements of the mining sector (Hammad et al., 2025).

Furthermore, the adoption of digital twins and sophisticated scenario engineering provides a robust foundation for predicting potential operational bottlenecks before they manifest in real-world extraction cycles (Chen et al., 2024; Tripathi & Chaurasia, 2025a). The application of intelligent technologies can also be extended to mine environmental monitoring, mine closure, post-closure monitoring, and sustainability assessment. Recent research on integrated geospatial frameworks demonstrates the potential of remote sensing and GIS for monitoring post-closure mining landscapes (Bisen & Chaurasia, 2025). Similarly, contemporary mine-closure research emphasizes the need for systematic risk assessment and long-term monitoring throughout the mine life cycle (Bisen & Chaurasia, 2026). These applications strengthen the sustainability dimension of Mining 5.0.

This proactive stance shifts the paradigm from simple safety compliance toward a holistic enhancement of employee well-being, where real-time monitoring of physical and psychological states informs smarter resource allocation (Davila-Gonzalez and Martín, 2024; Singh, Chaurasia, & Beg, 2025). The transition also requires consideration of working conditions. Mining 5.0 technologies should not be implemented solely to maximize production; rather, they should contribute to improved occupational safety, working conditions, productivity, and worker well-being. Recent research examining working conditions under the OSHWC Code, 2020, highlights the importance of integrating occupational safety considerations with the emerging smart-mining environment (Tiwari & Chaurasia, 2026). This evolution necessitates a multi-dimensional diagnostic approach that evaluates readiness not only through technological benchmarks but also through the integration of socio-technical pillars (Djebbouri et al., 2025). This strategy recognizes that human centricity is achieved by empowering industrial operators to enhance their individual competencies in collaboration with advanced digital technologies (Alves, Lima and Gaspar, 2023). Integrating these systemic perspectives allows Coal India Limited to bridge the current gap between technological deployment and the socio-cultural evolution of its workforce, ultimately positioning robots as collaborative partners rather than mere tools (Górny, 2023), (Dacre et al., 2024; Yadav & Chaurasia, 2025; Yadav & Chaurasia, 2025a).

By facilitating this cognitive symbiosis, the organization can evolve its Cyber-Physical Systems to function as active decision-support interfaces that proactively enhance problem-solving literacy and operational planning (Ghobakhloo et al., 2024). Although significant progress has been made in Mining 4.0 technologies, the transition to Mining 5.0 remains largely conceptual and underdeveloped. Existing literature predominantly focuses on technological aspects of AIoT, digital twins, and automation in developed economies (e.g., Rio Tinto and BHP operations in Australia), with limited attention to human-centric design, socio-technical integration, and ethical implications central to Industry 5. There is a notable scarcity of comprehensive frameworks that simultaneously address the unique challenges of emerging economies, such as legacy infrastructure, skill gaps, regulatory constraints, cultural resistance, and potential job displacement.

In the Indian context, while Coal India Limited (CIL) has initiated digital transformation through Digi-Coal and related pilots, studies offering integrated socio-technical models for human-centric AIoT adoption remain fragmented and insufficient. Most research overlooks the complex interplay between technological implementation, workforce well-being (Operator 5.0), ethical governance, and contextual adaptation in large-scale public sector undertakings like CIL. In present study Fig. 1 & Fig. 2 illustrate how human, technological, organizational, and sustainability dimensions interact during the transition from Mining 4.0 to Mining 5.0.

Figure 1. To illustrate how human, technological, organizational, and sustainability dimensions interact during the transition from Mining 4.0 to Mining 5.0.

Figure 2. Evolution from Mining 4.0 to Mining 5.0

2. Literature Review

The foundational discourse surrounding Industry 5.0 emphasizes a transition from the system-centric optimization typical of Industry 4.0 toward a paradigm defined by human-centricity, resilience, and sustainability (Gaffinet et al., 2025). While Industry 4.0 primarily prioritized business productivity through autonomous smart factories, the subsequent shift toward Industry 5.0 re-centers the progress of industrial advancement on the collaborative synergy between human expertise and machine intelligence (Adel, 2022). This paradigm shift underscores the importance of ethical design and the prompt integration of safety standards to ensure that autonomous smart methods remain dependable within complex production environments (Yitmen and Almusaed, 2024). Central to this evolution is the implementation of Operator Digital Twins, which leverage biometric data to monitor the physical and emotional states of workers, thereby ensuring that industrial applications are responsive to the intrinsic needs of the human workforce (Villani et al., 2024). Furthermore, this transition fosters the emergence of the "Resilient Operator 5.0," whose skill sets are significantly augmented by real-time information systems, enabling them to navigate increasingly complex socio-technical challenges (Simeone et al., 2023). The sustainability dimension of Mining 5.0 is equally important. Mining operations increasingly need to address energy efficiency, carbon emissions, environmental degradation, mine closure, and post-mining land use. AIoT-based environmental monitoring can provide continuous information for proactive environmental management. Similarly, geospatial technologies can facilitate long-term monitoring of mining landscapes and post-closure conditions (Bisen & Chaurasia, 2025).

The development of intelligent mining systems should also consider the entire mining production chain. Blast fragmentation, equipment productivity, haulage efficiency, and downstream processing are interconnected components of mining performance. Optimizing these components using digital technologies can contribute to the broader Mining 5.0 objective of intelligent and sustainable resource utilization (Tiwari et al., 2025a; Tiwari et al., 2025b).

This evolution aligns with the core objectives of SDG 9, shifting the industrial focus from mere technological output to the cultivation of resilient, inclusive infrastructure that proactively integrates worker welfare into the digital production architecture (Costa, 2024). At the core of these frameworks lies the Human-Cyber-Physical System, a composite architecture where interactions among human, cyberspace, and physical assets are orchestrated to optimize collaborative problem-solving across all manufacturing phases (Lou et al., 2024). These systems utilize machine learning and 5G-enabled Industrial Internet of Things to establish a cognitive pillar of human-machine integration, effectively augmenting situational awareness and decision-making capabilities (Alimam et al., 2023). Implementing this architecture requires shifting organizational priorities from purely profit-driven innovation toward a model that embeds worker welfare, inclusivity, and empowerment as foundational components of industrial design (Dehbozorgi et al., 2024). This socio-technical realignment mandates that digital infrastructures be governed by organizational routines that prioritize the enhancement of human capital, ensuring that technology serves as a tool for scalable uniqueness rather than simple replacement (Aheleroff et al., 2022; Sahin and Çark, 2026). Additionally, this framework facilitates the integration of motion analysis systems to evaluate musculoskeletal workload, thereby optimizing workstation design to support the physical ergonomics of the operator.

3. Methodology

This study adopts a qualitative research design based on a Systematic Literature Review (SLR) and conceptual framework development approach to investigate the transition from Mining 4.0 to Mining 5.0 in emerging economies. The research aims to develop a socio-technical framework for human-centric adoption of Artificial Intelligence of Things (AIoT) technologies within Coal India Limited (CIL), India's largest coal-producing organization. Given that Mining 5.0 is an emerging concept with limited empirical studies available in the mining sector, a systematic review methodology was considered appropriate for synthesizing existing knowledge and identifying research gaps. The study follows established guidelines for systematic reviews proposed by Tranfield et al. (2003) and Kitchenham (2004), ensuring transparency, reproducibility, and methodological rigor. The research process consists of four major phases: literature identification, screening and selection, thematic analysis, and framework development. The methodology integrates technological, organizational, human, and policy perspectives to capture the complex socio-technical nature of Mining 5.0 transformation (Singh et al., 2024; Yadav & Chaurasia, 2025a; Bisen et al., 2025; Bisen & Chaurasia, 2026).

3.1 Systematic Literature Review (SLR) Process

The systematic literature review was conducted to identify relevant studies related to Industry 5.0, Mining 4.0, smart mining technologies, AIoT systems, digital twins, collaborative robotics, and human-centric industrial transformation. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework.

3.2 Data Analysis and Thematic Synthesis

The selected studies were analyzed using thematic content analysis. This approach enabled the identification of recurring concepts, technological trends, implementation challenges, and human-centered considerations associated with Mining 5.0.

The thematic analysis was conducted in three stages:

Stage 1: Open Coding

Key concepts and findings from each article were extracted and coded. Examples included:

- AI adoption
- Worker augmentation
- Digital twins
- Autonomous systems
- Cybersecurity
- Sustainability
- Skills development

Stage 2: Theme Development

The codes were grouped into broader thematic categories. Five dominant themes emerged:

1. Smart and connected mining infrastructure.
2. AIoT-enabled decision support systems.
3. Human-machine collaboration.
4. Governance and ethical considerations.
5. Sustainability and resilience.

Stage 3: Framework Integration

The identified themes were synthesized into a unified socio-technical framework. Relationships among technological, organizational, and human dimensions were mapped to understand how Mining 5.0 technologies can be successfully implemented in emerging economies.

Despite methodological rigor, the study has certain limitations. First, the framework is primarily conceptual and requires empirical validation through field implementation. Second, the rapid evolution of AI and Industry 5.0 technologies may result in new developments beyond the scope of the reviewed literature. Third, access to proprietary operational data from mining organizations was limited, restricting quantitative analysis.

Nevertheless, the methodology provides a robust foundation for understanding Mining 5.0 transformation and offers a structured approach for future empirical investigations in emerging economy contexts.

Results

Case Study: CIL manages a diverse portfolio of mining operations, including large-scale opencast mines, underground mines, coal washeries, transportation networks, and coal handling plants spread across multiple Indian states. The company's annual production exceeds 750 million tonnes, supplying coal primarily to thermal power plants, steel industries, cement manufacturers, and other industrial sectors. Given its strategic importance and vast operational footprint, Coal India Limited represents an ideal case study for examining the transition toward Mining 5.0 in an emerging economy context. The mining environment in India presents unique challenges such as varying geological conditions, aging infrastructure, labor-intensive operations, environmental concerns, and stringent safety requirements. These challenges make digital transformation both necessary and complex. As India pursues modernization initiatives under the Digital India and Atmanirbhar Bharat programs, CIL has increasingly invested in digital technologies aimed at improving operational efficiency, safety performance, environmental monitoring, and decision-making capabilities.

1. Current Digital Transformation Initiatives

Over the last decade, Coal India Limited has undertaken several digital transformation initiatives that align with the principles of Mining 4.0. These efforts have focused primarily on operational monitoring, automation, data management, and real-time decision support.

2. Digi-Coal Initiatives

One of the most significant modernization efforts is the implementation of Digi-Coal initiatives across various subsidiaries. These programs seek to improve transparency, operational visibility, and resource management through the integration of digital technologies. Many opencast mines utilize GPS-enabled fleet management systems to track the movement of dumpers, excavators, and transportation vehicles in real time. These systems help optimize dispatch operations, reduce idle time, improve fuel efficiency, and enhance productivity.

3. Drone-Based Surveying and Mapping

CIL has increasingly adopted unmanned aerial vehicles (UAVs) for mine surveying, stockpile measurement, land-use monitoring, and environmental assessment. Drone-based surveys significantly reduce survey time while improving measurement accuracy and operational planning. Integrated ERP systems have been deployed to streamline procurement, inventory management, financial operations, human resource management, and production planning. These systems provide centralized access to operational information and support data-driven decision-making. Advanced surveillance technologies, including CCTV networks and remote monitoring systems, have been installed at several mining sites. These systems assist in operational supervision, security management, and regulatory compliance. Environmental Monitoring Platforms Continuous environmental monitoring systems are being deployed to track air quality, dust levels, noise emissions, water quality, and other environmental indicators. Real-time environmental data supports compliance with regulatory requirements and sustainability objectives.

4 DGMS-Supported Safety Digitalization

The Directorate General of Mines Safety (DGMS) has played an important role in encouraging the adoption of digital safety technologies throughout the Indian mining industry.

Several digital safety initiatives are currently being implemented or piloted within CIL operations, including:

- Real-time gas monitoring systems in underground mines.
- Automated environmental sensing networks.
- Digital incident reporting platforms.

- Remote communication systems.
- Emergency response management tools.
- Workforce tracking technologies.

These technologies contribute to proactive hazard identification and improved emergency preparedness. However, their deployment remains fragmented across operations and is yet to achieve enterprise-wide integration.

5 Gap Analysis: Current State versus Mining 5.0 Vision

Although CIL has made significant progress toward Mining 4.0 adoption, substantial gaps remain before achieving a fully human-centric Mining 5.0 ecosystem.

Artificial Intelligence and Predictive Analytics

Current digital systems primarily focus on monitoring and reporting functions. Advanced AI applications such as predictive maintenance, autonomous decision support, predictive safety analytics, and intelligent resource optimization remain limited. Mining 5.0 requires AI systems capable of augmenting human decision-making rather than merely collecting data. The adoption of digital twins within CIL remains at an early stage. Most operational systems function independently without integrated virtual representations of mining assets, processes, and environments. Mining 5.0 envisions enterprise-wide digital twins capable of simulating production scenarios, predicting failures, and supporting strategic planning. Current automation initiatives focus largely on mechanization and remote monitoring. Collaborative robotics (cobots), augmented reality systems, wearable intelligence platforms, and Operator 5.0 concepts have not yet been widely implemented. This represents a significant opportunity for future transformation. The transition toward Mining 5.0 requires new competencies in artificial intelligence, data analytics, digital systems management, and cyber-physical operations. Existing workforce training programs remain largely focused on conventional mining practices. Significant investment in digital skill development will be necessary.

Many current digital initiatives prioritize operational efficiency rather than worker experience. Mining 5.0 emphasizes human well-being, cognitive support, safety enhancement, and worker empowerment. Integrating these principles into technology design remains a critical challenge.

Opportunities for Mining 5.0 Adoption

Coal India Limited possesses substantial opportunities to become a global leader in Mining 5.0 implementation among emerging economies.

Safety Enhancement

AIoT-enabled monitoring systems can significantly improve mine safety through predictive hazard detection and real-time risk assessment. Advanced methane prediction models, geotechnical monitoring systems, wearable safety devices, and AI-assisted emergency response platforms can reduce accident risks and enhance worker protection.

Productivity Improvement

Digital twins, edge computing platforms, and predictive analytics can optimize equipment utilization, fleet dispatching, maintenance scheduling, and production planning. These technologies can minimize downtime and improve overall operational efficiency.

Sustainability and Environmental Performance

Mining 5.0 technologies can support sustainable mining practices through intelligent energy management, emissions monitoring, water conservation, and waste reduction. AI-driven optimization systems can contribute to lower carbon footprints and improved environmental compliance.

Workforce Empowerment

The Operator 5.0 concept provides opportunities to augment human capabilities rather than replace workers. Technologies such as augmented reality, wearable devices, digital assistants, and collaborative robots can improve decision-making, reduce physical strain, and enhance workplace safety.

Strategic Competitiveness

By adopting a human-centric Mining 5.0 framework, CIL can strengthen its global competitiveness while supporting India's broader objectives of technological self-reliance, sustainable industrial growth, and digital transformation.

Overall, Coal India Limited has established a strong foundation for digital transformation through its ongoing Mining 4.0 initiatives. However, achieving the vision of Mining 5.0 will require a more integrated socio-technical approach that balances technological innovation with workforce development, ethical governance, sustainability, and human-centered design principles. Such a transition has the potential to transform CIL into a benchmark for smart, safe, and sustainable mining in emerging economies.

Discussion

The transition to Mining 5.0 at Coal India Limited (CIL) and in other emerging economies represents a paradigm shift from the technology-driven efficiency of Mining 4.0 toward a human-centric, resilient, and sustainable model. This shift integrates advanced AIoT (Artificial Intelligence of Things) systems with socio-technical considerations, emphasizing joint optimization of technical subsystems (AI-driven automation, real-time monitoring, predictive analytics) and social subsystems (workforce empowerment, skills development, organizational culture, and community well-being). The proposed socio-technical framework highlights that successful human-centric AIoT adoption requires balancing technological capabilities with human factors such as trust in AI systems, reskilling programs, and inclusive decision-making. At CIL, ongoing digital initiatives including Digi-Coal for safety and operations, IoT-based real-time monitoring, ERP implementations, and partnerships with firms like Accenture and Tech Mahindra demonstrate progress toward this integration. However, these efforts remain largely in a Mining 4.0 phase, focused on automation and data collection, with limited emphasis on collaborative human-AI workflows characteristic of Mining 5.0.

Implications for Emerging Economies

Emerging economies like India face unique opportunities and challenges in this transition. On the positive side, Mining 5.0 can enhance productivity to meet ambitious targets (e.g., CIL’s 1 billion tonnes coal production goal), improve occupational safety in hazardous underground environments, reduce environmental footprints through optimized resource use and predictive maintenance, and support broader economic goals such as energy security and just transitions. Human-centric AIoT can empower workers by shifting them from repetitive, high-risk tasks to supervisory, creative, and problem-solving roles, potentially fostering inclusive growth and reducing social resistance.

For emerging economies more broadly, successful adoption could strengthen global supply chains for critical minerals needed in the clean energy transition while promoting sustainable development. However, without a socio-technical lens, these technologies risk exacerbating inequalities: displacing low-skilled labor without adequate reskilling, widening urban-rural or headquarters-field divides, and creating new dependencies on foreign technology providers.

Barriers to Transition

Several interconnected barriers hinder progress:

- Technological and Infrastructure Gaps: Poor connectivity in remote or underground mines, high implementation costs, legacy systems, and data quality/silo issues limit scalable AIoT deployment.
- Human and Organizational Factors: Workforce resistance due to fear of job loss, skill mismatches, low digital literacy among frontline workers, and cultural inertia in large public-sector entities like CIL.
- Regulatory and Policy Challenges: Fragmented governance, slow adaptation of safety/environmental standards to new technologies, and insufficient incentives for human-centric innovation.
- Socio-Economic and Environmental Constraints: High capital requirements, limited local R&D and manufacturing capabilities, and the need to balance coal dependency with sustainability commitments in energy-transitioning economies.

These barriers are amplified in emerging contexts compared to advanced mining nations due to resource constraints and institutional complexities.

Success Factors

Drawing from the proposed framework and empirical insights, key enablers include:

- Strong leadership commitment and cross-functional collaboration.
- Comprehensive change management with participatory design involving workers.
- Targeted investments in education, training, and lifelong learning programs.
- Public-private partnerships for technology transfer and infrastructure.
- Adaptive governance that integrates ethical AI principles, data privacy, and social impact assessments.
- Pilot projects demonstrating tangible benefits in safety, productivity, and worker satisfaction to build momentum.

Conclusion

This study concludes that the transition to Mining 5.0 at CIL and similar contexts in emerging economies demands more than technological upgrades. It requires a deliberate socio-technical approach that places humans at the center of AIoT ecosystems. The proposed framework offers a structured pathway for joint optimization, addressing technological, organizational, human, environmental, and policy dimensions simultaneously. While CIL has made notable strides in digitalization, realizing the full potential of human-centric Mining 5.0 will depend on overcoming persistent barriers through systemic interventions. Successful implementation can position India as a leader in responsible mining, contributing to both economic resilience and sustainable development goals. Ultimately, Mining 5.0 is not merely about smarter machines but about creating more humane, inclusive, and sustainable mining operations.

References

1. Adel, A. (2022) "Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas," *Journal of Cloud Computing Advances Systems and Applications*, 11(1), pp. 40–40. doi:10.1186/s13677-022-00314-5.
2. Aheleroff, S. *et al.* (2022) "Toward sustainability and resilience with Industry 4.0 and Industry 5.0," *Frontiers in Manufacturing Technology*, 2. doi:10.3389/fmtec.2022.951643.
3. Alimam, H. *et al.* (2023) "The resurrection of digital triplet: A cognitive pillar of human-machine integration at the dawn of industry 5.0," *Università Politecnica delle Marche (Università Politecnica delle Marche)*, 35(10), pp. 101846–101846. doi:10.1016/j.jksuci.2023.101846.
4. Alves, J., Lima, T.M. and Gaspar, P.D. (2023) "Is Industry 5.0 a Human-Centred Approach? A Systematic Review," *Processes*, 11(1), pp. 193–193. doi:10.3390/pr11010193.
5. Aouedi, O. *et al.* (2024) "A Survey on Intelligent Internet of Things: Applications, Security, Privacy, and Future Directions," *IEEE Communications Surveys & Tutorials*, pp. 1–1. doi:10.1109/comst.2024.3430368.
6. Bhattacharyya, S.S. and Shah, Y. (2021) "Emerging technologies in Indian mining industry: an exploratory empirical investigation regarding the adoption challenges," *Journal of Science and Technology Policy Management*, 13(2), pp. 358–381. doi:10.1108/jstpm-03-2021-0048.
7. Capet, T. *et al.* (2026) "Human-Centered Industrial Transition: A Human-Technology-Organization Acceptance Model for Industry 5.0 — Conceptual Framework and Research Protocol," *Procedia Computer Science*, 277, pp. 762–771. doi:10.1016/j.procs.2026.02.117.
8. Chen, L. *et al.* (2023) "Mining 5.0: Concept and Framework for Intelligent Mining Systems in CPSS," *IEEE Transactions on Intelligent Vehicles*, 8(6), pp. 3533–3536. doi:10.1109/tiv.2023.3285417.
9. Chen, L. *et al.* (2024) "Smart Mining With Autonomous Driving in Industry 5.0: Architectures, Platforms, Operating Systems, Foundation Models, and Applications," *IEEE Transactions on Intelligent Vehicles*, 9(3), pp. 4383–4393. doi:10.1109/tiv.2024.3365997.
10. Costa, E. (2024) "Industry 5.0 and SDG 9: a symbiotic dance towards sustainable transformation," *Sustainable Earth Reviews*, 7(1). doi:10.1186/s42055-024-00073-y.
11. Dacre, N. *et al.* (2024) "Advancing sustainable manufacturing: a systematic exploration of Industry 5.0 supply chains for sustainability, human-centricity, and resilience," *Production Planning & Control*, pp. 1–30. doi:10.1080/09537287.2024.2380361.
12. Davila-Gonzalez, S. and Martín, S. (2024) "Human Digital Twin in Industry 5.0: A Holistic Approach to Worker Safety and Well-Being through Advanced AI and Emotional Analytics," *Sensors*, 24(2), pp. 655–655. doi:10.3390/s24020655.
13. Dehbozorgi, M.H. *et al.* (2024) "Human in the loop: revolutionizing industry 5.0 with design thinking and systems thinking," *Proceedings of the Design Society*, 4, pp. 245–254. doi:10.1017/pds.2024.27.
14. Djebbouri, K.B. *et al.* (2025) "I5.0-MM : Beyond Automation Toward Human-Centric Sustainable Manufacturing," *Sustainable Development* [Preprint]. doi:10.1002/sd.70584.
15. Fazlollahtabar, H. (2025) "Industry 5.0 paradigm transformation adoption in developing countries: an analytical game theoretic model," *Scientific Reports*, 15(1). doi:10.1038/s41598-025-16089-z.

16. Gaffinet, B. *et al.* (2025) "Human Digital Twins: A systematic literature review and concept disambiguation for industry 5.0," *Computers in Industry*, 166, pp. 104230–104230. doi:10.1016/j.compind.2024.104230.

17. Ghobakhloo, M. *et al.* (2024) "Beyond Industry 4.0: a systematic review of Industry 5.0 technologies and implications for social, environmental and economic sustainability," *Asia-Pacific Journal of Business Administration*, 17(4), pp. 889–914. doi:10.1108/apjba-08-2023-0384.

18. Gomaa, A.H. (2026) "Industry 5.0 in Engineering and Manufacturing: A Comprehensive Review and Strategic Framework," *Journal of Engineering Advancements*, pp. 16–28. doi:10.38032/jea.2026.01.002.

19. Górny, A. (2023) "Developing Industry 5.0 To Effectively Harness Production Capacities," *Management Systems in Production Engineering*, 31(4), pp. 456–463. doi:10.2478/mspe-2023-0052.

20. Hammad, M. *et al.* (2025) "From Industry 4.0 to 5.0: leveraging AI and IoT for sustainable and human-centric operations," *International Journal of Industrial Engineering and Operations Management*, pp. 1–19. doi:10.1108/ijieom-04-2025-0070.

21. Lingaraja, B.M. and G, S. (2025) "AI for Inclusive Industrial Growth: Social Work Interventions for Improving Quality of Work Life among Mining Truck Drivers.," *International Journal For Multidisciplinary Research*, 7(6). doi:10.36948/ijfmr.2025.v07i06.64586.

22. Lo, H.-W. *et al.* (2024) "Evaluating the Interrelationships of Industrial 5.0 Development Factors Using an Integration Approach of Fermatean Fuzzy Logic," *Journal of Operations Intelligence*, 2(1), pp. 95–113. doi:10.31181/jopi21202416.

23. Longo, F., Nicoletti, L. and Padovano, A. (2017) "Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context," *Computers & Industrial Engineering*, 113, pp. 144–159. doi:10.1016/j.cie.2017.09.016.

24. Lou, S. *et al.* (2024) "Human-Cyber-Physical System for Industry 5.0: A Review From a Human-Centric Perspective," *IEEE Transactions on Automation Science and Engineering*, 22, pp. 494–511. doi:10.1109/tase.2024.3360476.

25. Lund, E. *et al.* (2024) "Mining 4.0 and its effects on work environment, competence, organisation and society – a scoping review," *Mineral Economics*, 37(4), pp. 827–840. doi:10.1007/s13563-024-00427-0.

26. Narkhede, G. *et al.* (2024) "Industry 5.0 and sustainable manufacturing: a systematic literature review," *Benchmarking An International Journal*, 32(2), pp. 608–635. doi:10.1108/bij-03-2023-0196.

27. Passalacqua, M., Cabour, G., *et al.* (2024) "Human-Centered AI for Industry 5.0 (HUMAI5.0)," in *Chapman and Hall/CRC eBooks*. Informa, pp. 260–274. doi:10.1201/9781003320791-27.

28. Passalacqua, M., Pellerin, R., *et al.* (2024) "Human-centred AI in industry 5.0: a systematic review," *SPIRE - Sciences Po Institutional REpository*, 63(7), pp. 2638–2669. doi:10.1080/00207543.2024.2406021.

29. Pratap., E.H. (2025) "Smart Mining Systems for Indian Terrain: A Proposed Solution for Productivity, Sustainability, and Security," *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT*, 9(8), pp. 1–9. doi:10.55041/ijsrem51757.

30. Rožanec, J.M. *et al.* (2022) "Human-centric artificial intelligence architecture for industry 5.0 applications," *International Journal of Production Research*, 61(20), pp. 6847–6872. doi:10.1080/00207543.2022.2138611.

31. Sahin, O. and Çark, Ö. (2026) "Beyond Industry 4.0: Enabling Technologies and the Socio-Technical Foundations of Industry 5.0," in *Özgür Yayınları eBooks*. doi:10.58830/ozgur.pub1231.c4973.

32. Simeone, A. *et al.* (2023) "A human-cyber-physical system for Operator 5.0 smart risk assessment," *The International Journal of Advanced Manufacturing Technology*, 129, pp. 2763–2782. doi:10.1007/s00170-023-12481-z.

33. Thompson-Bahm, H., Teixeira, J.E. and Lobo, R.C.G. (2025) "Enhancing sustainability and human centricity through emerging technologies from Industry 4.0 to Industry 5.0: An integrative literature review," *Corporate Governance and Sustainability Review*, 9(3), pp. 90–90. doi:10.22495/cgsrv9i3p7.

34. Togara, T.P., Madahana, M.C.I. and Olugu, E.U. (2026a) "Overcoming barriers to the adoption of technology in the mining industry to enhance safety and productivity: A scoping review," *EPJ Web of Conferences*, 347, pp. 3002–3002. doi:10.1051/epjconf/202634703002.

35. Togara, T.P., Madahana, M.C.I. and Olugu, E.U. (2026b) "Overcoming barriers to the adoption of technology in the mining industry to enhance safety and productivity: A scoping review," *Springer Link (Chiba Institute of Technology)* [Preprint]. doi:10.1051/epjconf/202634703002/pdf.

36. Villani, V. *et al.* (2024) "A Digital Twin Driven Human-Centric Ecosystem for Industry 5.0," *IEEE Transactions on Automation Science and Engineering*, 22, pp. 11291–11303. doi:10.1109/tase.2024.3410703.

37. Yang, J. *et al.* (2023) "On Intelligent Mining With Parallel Intelligence," *IEEE Transactions on Intelligent Vehicles*, 8(10), pp. 4296–4300. doi:10.1109/tiv.2023.3316132.

38. Yitmen, İ. and Almusaed, A. (2024) "Synopsis of Industry 5.0 Paradigm for Human-Robot Collaboration," in *Artificial intelligence*. IntechOpen. doi:10.5772/intechopen.1005583.

39. Bisen, V., & Chaurasia, R. C. (2026). Risk assessment plan for mine closure. *International Journal of Sciences and Innovation Engineering, 3*(4), 2534–2551. https://doi.org/10.70849/ijsci03042618848

40. Bisen, V., Chaurasia, R. C., Daharwal, V., Tiwari, G., Kiran, A. V., & Singh, K. (2025). An integrated geospatial framework for post-closure mine site monitoring: A synthesis of remote sensing and GIS methodologies. *Journal of Civil and Environmental Engineering (IJCEE), 13*(9), 210–220. https://doi.org/10.1018/IJCEE.2025.13.9.8169

41. Giri, V. K., & Chaurasia, R. C. (2025). A comprehensive study on equipment utilization and haulage efficiency in open-cast mining. *International Journal of Innovative Research in Technology, 12*(4).

42. Singh, G., Chaurasia, R. C., & Beg, I. A. (2025). Risk assessment and safety management in underground coal excavation: A case study analysis. *International Journal on Science and Technology (IJSAT), 16*(3).

43. Singh, G., Singh, S. K., Chaurasia, R. C., & Jain, A. K. (2024). The present and future prospect of artificial intelligence in the mining industry. *Industrial Engineering Journal, 53*(4), 1–10.

44. Tripathi, S. K., & Chaurasia, R. C. (2025). Exploring peak productivity achievable with continuous miners. *International Journal of Innovative Research in Technology, 12*(3).

45. Tripathi, S. K., & Chaurasia, R. C. (2025). Investigation into optimum production by continuous miner. *International Research Journal of Modernization in Engineering Technology and Science, 7*(4).

46. Yadav, I., & Chaurasia, R. C. (2025). A comprehensive review of coal mining: Techniques, environmental impacts, health and safety issues, and sustainable future prospects. *International Journal of Sciences and Innovation Engineering, 2*(12), 1186–1197. https://doi.org/10.70849/ijsci02121281167

47. Yadav, I., & Chaurasia, R. C. (2025). Coal mining: Techniques, impacts, and future prospects. International Journal for Multidisciplinary Research, 7(4).

48. Tiwari, G., Chaurasia, R. C., Bisen, V., Daharwal, V., Kiran, A. V., & Singh, K. (2025). Blast design for obtaining desired rock fragmentation. *Journal of Civil and Environmental Engineering, 13*(7), 227–240. https://doi.org/10.1018/IJCEE.2025.13.7.850

49. Tiwari, G., Chaurasia, R. C., Bisen, V., Daharwal, V., Kiran, A. V., & Singh, K. (2025). Linking blast fragmentation to energy efficiency and downstream productivity in opencast mining. Journal of Civil and Environmental Engineering, 13(9), 203–209. https://doi.org/10.1018/IJCEE.2025.13.9.8168

50. Singh, R., & Chaurasia, R. C. (2026). AI-IoT enabled methane emission prediction and carbon footprint reduction in underground coal mines: A case study. International Journal of Creative and Open Research in Engineering and Management, 2(7). https://doi.org/10.55041/ijcope.v2i7.044

51. Tiwari, G., & Chaurasia, R. C. (2026). Study of working conditions and their impact on occupational safety and productivity of miners: An analysis under OSHWC Code, 2020 in the era of smart mining. International Journal of Scientific Research and Technology, 3(7), 177–189.