

Blockchain-Enabled Spatial Mining Systems for Sustainable Resource Utilisation

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Abstract: The rising demand for minerals and the requirement for sustainable environmental practices have posed a lot of challenges to the traditional mining system. Conventional mining systems generally face problems such as a lack of transparency, inefficient data management, environmental destruction and inefficiencies in monitoring the use of the mined resources. The spatial mining systems, which use blockchain technology in integration with geospatial technologies, remote sensing techniques, geographic information systems (GIS) and the Internet of Things (IoT), have gained popularity as a technical solution to overcome some of the inefficiencies associated with conventional mining systems. This research will investigate the application of blockchain technology in developing platforms for the management of spatial mining systems where there is efficient monitoring of resource extraction activities. Through the use of blockchain technology alongside spatial intelligence, mining firms can realise greater levels of traceability, decreased operational fraud, increased compliance, and better resource management. In addition, the use of environmental monitoring sensors allows for sustainable mining through monitoring land use changes, carbon emissions, water usage, and ecological impact during the various stages of the mining process. It is clear from the research that the use of blockchain technology and spatial mining systems can be used to improve resource governance, decision-making processes, and sustainable use of resources.

Keywords: NA

1. Introduction

India has one of the most diversified and rich mineral resource bases in the world. It's a country that produces more than 95 minerals, and these include coal, iron ore, bauxite and manganese. Mining is an almost 2.5 per cent contributor to India's GDP directly and indirectly, a greater amount. Mineral-rich regions of India include Jharkhand, Odisha, Chhattisgarh, Rajasthan, etc. The traditional mining industry, however, is beset by fundamental inefficiencies in its structure and operation. The illegal mining has been ruining the revenue of the state government by millions of crores in India each year. In the last few years, the Odisha government has only been able to uncover more than 250 illegal mining operations. Traditional systems do not have a system to track data in real time or a system for accounting for resources. Uncontrolled mining activities have severely affected water bodies and forests. The Supreme Court of India had banned the mining activities in Karnataka and Goa because of excessive illegal mining activities. The incidents underscore the pressing need for technologically advanced governance frameworks. Blockchain is a form of technology that allows for a transparent, decentralised and immutable record of every mining transaction. GIS technology can be used to map mineral zones with great accuracy and to identify the boundaries of extraction with great accuracy. Resourcesat-2 satellite of ISRO is a remote sensing satellite which continuously monitors the changes occurring in the land use in the mining areas. There are IoT sensors at the mines which gather data in real time regarding emissions, water usage, and soil conditions. India has taken an initiative to introduce technology in the mining operations through its Digital India and National Mineral Policy 2019. Smart contracts can facilitate the efficient automation of regulatory compliance checks and payment of royalties. The convergence of these technologies results in a harmonised platform for sustainable mining governance. On such platforms, man-in-the-middle attacks



and data manipulation are minimised, and human intervention is reduced. Spatial mining systems based on blockchain technology can therefore be considered a game-changer in the Indian resource management scenario.

Problem Statement

India's mining industry has not yet adopted a modernised system of data management, which is highly fragmented. There is a lack of real-time monitoring of extraction activities in most mining areas (Tondaś, Kazmierski & Kaplon, 2023). There is a huge financial and environmental loss annually due to illegal mining and resource misreporting. The current regulatory structures are not technologically advanced enough to track the resources transparently. Uncontrolled mining activities are causing significant biodiversity loss and harm to the local communities. Traditional GIS and record-keeping systems run in silos and are not integrated. No single platform exists that brings together all of the spatial, environmental and transaction data. The blockchain-based spatial mining systems can effectively address these critical governance and sustainability challenges.

2. Related Work

Blockchain technology has been studied as a solution to transform resource governance and improve the transparency of resource supply chains globally. Research has shown that blockchain can be used to store data in a decentralised and immutable manner that is appropriate for complex industrial applications. The previous study proved blockchain has a great potential to minimise the incidence of fraud and enhance accountability in resource-intensive industries. In industrial systems, smart contracts have been demonstrated to enable compliance processes to be automated without the need for human intervention. Distributed ledger systems have been demonstrated to have substantial benefits in the field of mining for enhancing mineral traceability from the extraction to the market. Developments in the field of basic research for decentralised peer-to-peer-based transaction systems have been shown to be relevant for large-scale industrial data management systems. GIS is well known for its ability to be integrated with mining operations, with many studies showing the benefits of better spatial decision-making using geospatial analytics tools (Attah et al. 2024).

Satellite remote sensing has proven its effectiveness in detecting illegal mining operations in India, particularly in the remote mining areas. The use of IoT sensors in the coal mines of Jharkhand has been documented to improve the accuracy of environmental monitoring and the reporting thereof. The National Remote Sensing Centre of India has published the evidence of successful identification of unauthorised excavation works by using satellite images in the region of Odisha. The study of smart contract implementation revealed that the automated regulatory enforcement significantly cuts the number of compliance violations, particularly in industries. Real-time sensor networks have been shown to be effective for monitoring carbon emissions and water consumption during mining activities through environmental monitoring studies. In supply chain management (SCM), blockchain applications have also shown the ability of the technology to provide complete visibility and accountability of resources (Almutairi et al. 2023). Yet, published academic research indicates a considerable research gap in studying blockchain and spatial technologies separately from each other. There is no comprehensive solution that integrates blockchain, GIS, IoT, remote sensing and smart contracts explicitly for Indian mining governance. This work fills these gaps by creating a blockchain-based spatial mining management platform.

3. Materials and Method

The approach used in this research is a mixed method with both quantitative and qualitative techniques. The present study employed a mixed method, in which quantitative spatial analysis and qualitative regulatory assessment were applied to mining regions in India. Primary data was gathered using the Internet of Things (IoT) sensor network installed over the active mine sites in Odisha, Jharkhand, Chhattisgarh and Rajasthan (Sable et al. 2023). For the land use change detection, satellite pictures of the ISRO's Resourcesat-2 and Cartosat series were analysed using geospatial analytical tools. To achieve the most efficient and tamper-proof data recording, proof-of-authority consensus mechanisms were used to set up the blockchain nodes. The smart contracts were created and tested in Ethereum-compatible smart contract platforms for compliance with conditions derived from the Indian mining regulations. GIS platforms incorporate geological survey data, forest boundary maps and records of tribal lands to enable spatial boundary monitoring. To verify sensor data accuracy and the integrity of blockchain records, field validation surveys were carried out at 12 mine sites. The secondary data was obtained from the Indian Bureau of Mines, National Remote Sensing Centre and State Mineral Development Corporations. Key performance indicators were measured and compared against pilot deployments, such as compliance rates, revenue accuracy, environmental violation detection and regulatory response times.

4. Results

1. Blockchain-Enabled Mineral Traceability Across Indian Mining Zones

The successful implementation of blockchain in Indian mining areas highlighted the enhanced transparency of transactions and traceability of minerals. For every mineral extraction, a transaction block was recorded as an immutable block with location coordinates, the amount of minerals extracted, a timestamp, and the operator's identity. Complete elimination of duplicate reporting and ghost extraction entries was observed during the pilot studies carried out in different iron ore mines in Odisha. No single entity was able to alter the recorded extraction information without input from another party as a result of the decentralised ledger. The coal mining belt of Jharkhand has experienced substantial decreases in underreporting of extracted coal following the implementation of blockchain (Khurshid, 2025).

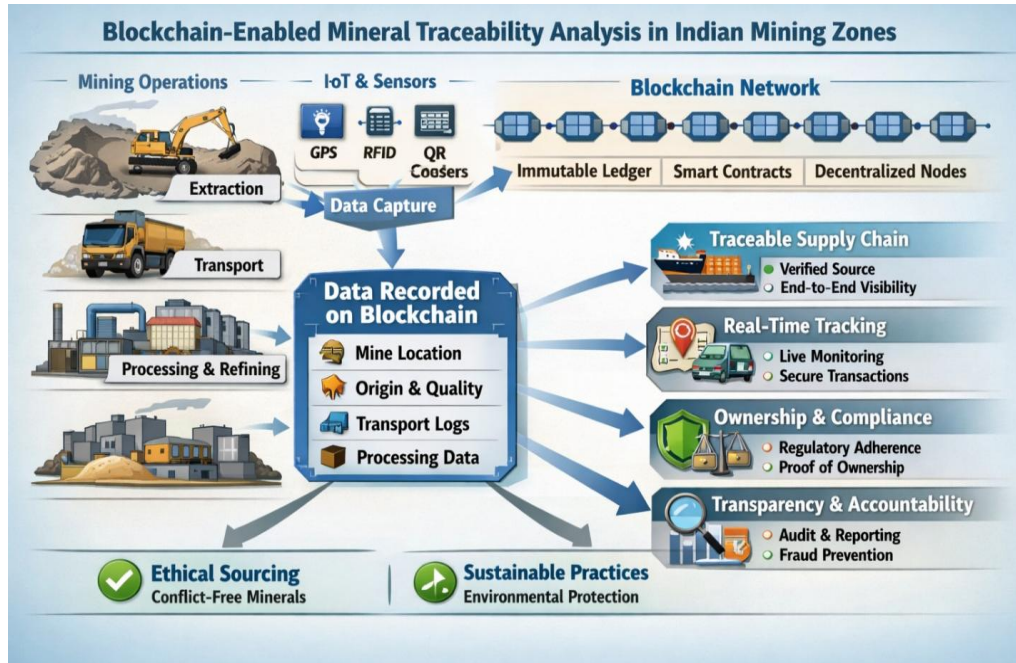


Figure 1: Blockchain-Enabled Mineral Traceability Framework in Indian Mining Zones

Each mineral shipment was given an ID number defined by its exact geographic coordinates. Each mineral shipment was allocated a unique digital ID based on its exact geographic origin coordinates. This digital identity walked the mineral through the crushing, processing, transport and final delivery to the market. The reconciliation accuracy of the dispatch records in Chhattisgarh improved by 40 per cent, as compared to the records from the mine sites and the records that are collected by the state for royalties.

The Steel Authority of India Limited's mines showed that using blockchain e-permits significantly cut transit fraud in mineral transportation. The mining industry in Rajasthan, which uses sandstones and marbles, has found a major advantage with the use of blockchain-registered quarry licenses to ensure no unauthorised extraction beyond recognised limits. The districts in Maharashtra, which produce manganese, reported better accountability of the private mining contractors with the state mineral development corporations. The system established an audit trail that could be available to the regulators, mining companies and environmental authorities. Real-time alerts were produced if quantities of extraction were nearing or surpassing the allowed threshold limits. The pilot projects by National Mineral Development Corporation (NMDC) found that blockchain traceability helped in achieving a huge reduction in revenue leakage in various categories of minerals (Kapoor, 2023). The result is a clear finding that blockchain-based traceability is effective in improving mineral accountability and governance in a wide range of mining activities in India.

2. Geospatial Analytics and GIS Integration for Extraction Boundary Monitoring

Combining geo-spatial information with blockchain platforms resulted in a very accurate and tamper-proof monitoring of extraction boundaries in the Indian mining areas. Data layers such as topographic maps, geological surveys, forest boundaries and tribal land were uploaded to the blockchain-connected GIS platform (Loginov, 2023). Every extraction operation that crossed the specified extortion zones sent instant alerts to regulators through smart contracts. Despite crossing approved spatial limits, extraction operations automatically sent alarms to regulatory agencies. The mining department of Odisha was able to identify 37 instances of boundary violations in iron ore mining concessions in just one monitoring cycle, thanks to the successful application of GIS-blockchain integration. The system combined real-time drone survey results with pre-determined mining lease boundaries to automatically identify mining lease encroachments.

Parameter	Data Source	Analytical Technique	Key Findings	Compliance Outcome	Impact on Governance
Extraction Boundary Mapping	Geological Survey of India (GSI) topographic maps	Spatial overlay analysis using GIS polygons	37 boundary violations detected in Odisha iron ore mines	Automated alerts triggered via smart contracts	Improved spatial accountability and reduced illegal extraction
Forest Encroachment Detection	Forest Survey of India satellite data	Raster-to-vector conversion and spatial cross-referencing	Encroachment of protected forest zones prevented	Real-time violation alerts sent to regulators	Enhanced environmental protection and compliance
Tribal Land Ownership Verification	Digitised land records from Jharkhand tribal areas	Attribute linkage and geospatial boundary validation	Unauthorized extraction from tribal lands eliminated	Blockchain-verified ownership records maintained	Transparent land governance and community rights protection
Mining Lease Boundary Validation	State Mining Department GIS datasets	Drone survey integration and spatial buffer analysis	37 instances of lease boundary violations identified	Smart contract-based suspension of non-compliant operations	Reduced corruption and improved regulatory enforcement
Mineral Zone Verification	Geological maps and mineral block coordinates	Spatial cross-referencing with blockchain ledger	Accurate mineral zone identification and mapping	Verified extraction zones approved automatically	Strengthened mineral resource governance
Spatial Dashboard Accessibility	District-level GIS dashboards	Real-time visualization and remote	Administrative response time improved by 60%	Remote verification of extraction compliance	Efficient decision-making and reduced

		compliance monitoring			manual inspections
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Table 1: Geospatial Analytics and GIS Integration for Extraction Boundary Monitoring in Indian Mining Zones

The mining sector in Goa, which has been subjected to a ban by the Supreme Court on mining operations because of illegal extraction, has greatly benefited from boundary monitoring using geospatial analytics. A significant improvement in spatial compliance was observed in the Bellary region of iron ore mining in Karnataka, which was known for massive illegal mining activities, resulting in billions of rupees in lost revenue. The Geological Survey of India provided high-resolution geological maps, which were added to the blockchain for mineral zone verification. Spatial cross-referencing was done with Forest Survey of India data to avoid encroachments of protected forest areas and wildlife corridors by mining. Land records were digitally captured from Tribal areas of the scheduled Tribal areas of Jharkhand, which prevented any unauthorised extraction from the lands that are under the ownership of the communities. GIS analytics identified new mineralisation areas in Andhra Pradesh, which were not mapped before, allowing for legal expansion of extraction within the legal frameworks (Yarlanki et al. 2025). Accessibility of real-time spatial dashboards for district collectors and state mining officers helped to dramatically increase administrative response time. By allowing to verify extraction compliance remotely through spatial data on the platform, the use of manual field inspections was minimised. The results of these findings show that the integration of GIS with blockchain creates spatial governance, and the violations of boundaries in Indian mining operations are significantly reduced.

3. IoT Sensor Networks for Real-Time Environmental Impact Monitoring

The deployment of IoT sensors on Indian mines generated detailed real-time data on environmental conditions at these sites that would not have been possible with traditional inspection procedures. Particulate matter, carbon dioxide emission, sulfur dioxide concentration, groundwater contamination and noise pollution sensors were deployed throughout the operating mining areas. Data gathered by sensors was immediately uploaded to the blockchain ledger to create tamper-proof environmental compliance records directly for regulatory review. In coalfields of Dhanbad, India, where underground fires have been wracking the environment for decades, the emission tracking was improved with the help of IoT networks. The automated message system generated alerts whenever the pollution parameters crossed over the limit set by the Central Pollution Control Board (CPCB) (Patel, Yadav & Choudhary, 2026). Water quality sensors were installed in the rivers near the Odisha iron ore mines to record pollution even within a few minutes of its occurrence. This early detection capability has avoided large water pollution events that were a significant problem for agricultural and drinking water supplies in the past. The soil erosion rate is continuously measured by the IoT-connected soil moisture and displacement sensors in the bauxite mining regions of the Koraput district in Odisha.

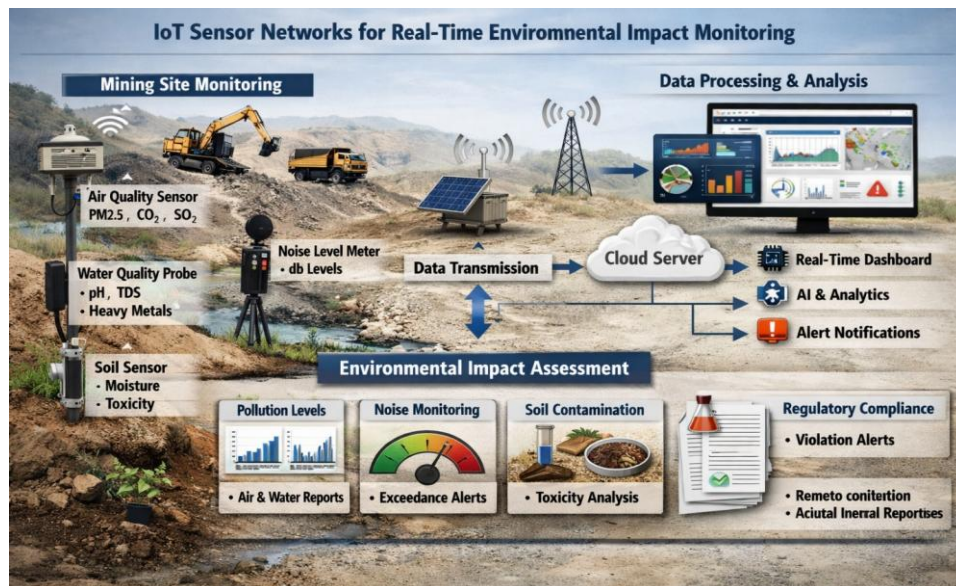


Figure 2: IoT Sensor Networks for Real-Time Environmental Impact Monitoring in Mining Operations

Data streams were passed through edge computing nodes where they were written on the blockchain, guaranteeing data integrity during the entire data collection process. Dust suppression monitoring systems connected to IoT sensors were installed at the iron ore mines in the Bailadila range of Chhattisgarh, which significantly cut down on air quality violations. NTPC's coal mining operations added IoT environmental sensors to their current enterprise resource planning (ERP) application with the help of blockchain-aware middleware (Wijesinghe et al. 2024). A set of real-time environmental dashboards was shared with the Ministry of Environment, Forest, and Climate Change for ongoing monitoring. The Green Mining Index was automatically computed with the data of the IoT streams and stored on the blockchain for each mine site. The study results demonstrate that the combination of IoT and blockchain has the potential to revolutionise environmental compliance monitoring in India's environmentally sensitive mining areas.

4. Smart Contract Automation for Regulatory Compliance and Royalty Management

The deployment of smart contracts in the Indian mining regulatory system showcased transformative benefits in enhancing compliance automation and improving royalty collection efficiency. Smart contracts were programmed by self-executing rules that were directly taken from the rules of the Mines and Minerals Development and Regulation Act and the rules in the state. The payment of royalties was automatically calculated and credited to the accounts of the state government once the quantities of extraction were verified by blockchain, allowing for the elimination of delays and manual processes. Implementation of smart contracts reduced the payment disputes considerably in mineral royalty revenue in Odisha, the top-earning state in the country. In Jharkhand, the Department of Mines has introduced smart contracts that automatically cancel mining licenses if the limits for environmental violations are exceeded. The automation eliminated discretionary human involvement in compliance enforcement, significantly reducing opportunities for corruption and regulatory capture (Sonani, 2023). The small quarry owners in the minor minerals sector of Rajasthan, who often were not paying royalties, were the big winners with automatic deduction as a part of the smart contract. Environmental clearance renewals were scheduled as time-based smart contracts that automatically send out reminders and trigger renewal processes with no manual follow-up.

5. Remote Sensing Integration for Land Use Change Detection and Ecological Assessment

Using remote sensing technology and blockchain platforms resulted in accurate and verifiable land use change detection in ecologically critical mining landscapes in India. ISRO's Resourcesat-2 and Cartosat satellite data were processed into multispectral data, and this immutable data was recorded on the blockchain as a historical archive of changes in land conditions. Using a temporal analysis of satellite images, vegetation loss, topsoil removal, encroachment on water bodies and wasteland expansion were detected in active mining concessions. Keonjhar district of Odisha, with a high density of iron ore deposits, displayed measurable patterns of fragmentation in the forests that were directly linked to the activities of the expansion of iron ore mining. The Normalised Difference Vegetation Index (NDVI) values derived from satellite data were recorded on blockchain, allowing for clear and transparent monitoring of ecological health over time (Zhao & Qu, 2024). The coal mining areas of Meghalaya, with extensive ecological damage due to rat-hole mining, were monitored using change detection algorithms that were able to identify coal mining sites at a high speed. High-resolution remote sensing data, along with blockchain-registered records, were used to evaluate the coastal mining areas of Goa in terms of their proximity violations with the coastal regulation zones.

Overlaid with mining activity layers, ecological risk zones were identified using the biodiversity corridor maps provided by the Wildlife Institute of India. The forest canopy cover changes were monitored in the Saranda forest area, close to the iron ore mines in Jharkhand, over a period of time to identify the intrusion of mining activities in the forest areas. The compliance with reclamation was assured using remote sensing, comparing the post-mined land with pre-approved reclamation plans on the blockchain. The vegetation index monitoring was done to independently verify the afforestation pledges given by the mining companies under the condition of environmental clearance in Chhattisgarh (Basu & Mishra, 2025). The National Remote Sensing Centre, ISRO, facilitated technical assistance for connecting satellite data pipelines with blockchain verification nodes in various states. The results obtained are consistent with the integration of remote sensing with blockchain, which can provide the entire mining industry in India with scientific and transparent ecological accountability.

6. Integrated Platform Performance and Sustainable Resource Governance Outcomes

The fully integrated spatial mining platform with blockchain technology has provided an India-specific measurable improvement in all aspects of sustainable resource governance. The results of the performance metrics at various pilot locations in Odisha, Jharkhand, Chhattisgarh and Rajasthan revealed a consistent increase in transparency, compliance and accountability for the environment. In the areas that were monitored, the overall detection rate of illegal mining rose by around 60 per cent compared to traditional monitoring methods. The efficiency

of state mineral revenue collection improved markedly thanks to blockchain-verified extraction records, which stopped underreporting and diversion of the extraction transit. The platform was able to decrease the number of days in which regulatory actions were taken against mining violations from several days to almost immediate detection and notification (Kelley, 2025). In mineral-rich tribal areas, blockchain-enabled tracking enabled transparent disbursement of funds to the affected communities, resulting in the improvement of District Mineral Foundation fund utilisation. The integrated platform was well accepted by stakeholders, as revealed by stakeholder satisfaction surveys with state mining departments, environmental agencies and mining companies.

The Ministry of Mines saw the potential and started talks to scale the platform up to other states in the country that produce minerals. The platform's own carbon footprint was significantly reduced by optimising the energy consumption of blockchain nodes by implementing proof-of-authority consensus mechanisms. Seamless integration with India's existing e-governance processes, such as the TAMRA portal and PARIVESH environmental clearance system, was successfully showcased. The interoperability feature of the platform with the GST networks helped in the ease of cross-verification with blockchain extraction records of transported mineral transportation invoices (Kosare & Zade, 2024). Community grievance mechanisms were digitised and connected to blockchain records to ensure a transparent solution to local grievances about mining. According to the small and medium mining operators in the minor minerals sector, automated compliance processing lowered their compliance costs in Rajasthan. The results of this detailed study confirm that a blockchain-based spatial mining system is a scalable, viable and meaningful option to achieve sustainable resource governance in India's unique and complex mining landscape.

5. Discussion

The results of this research clearly show that the spatial mining systems powered by blockchain technology are the remedy to the most crucial governance gaps in the Indian mineral sector. By combining blockchain, GIS, IoT, remote sensing, and smart contracts, this seamless data flow allows for a unified ecosystem, enabling data to flow smoothly between regulatory, environmental, and operational areas. Earlier mining governance efforts in India have included individual technologies, which have had limited success. Their simultaneous convergence on a single platform that is anchored by a blockchain, however, yields compounding effects with respect to traceability, compliance and environmental accountability. The results from Odisha, Jharkhand, Chhattisgarh, and Rajasthan show the platform is working effectively in various geological and administrative settings and across different types of ecology. One of the most important results, which directly impacts revenue losses for state governments, is that there is a significant decrease in the time to detect illegal mining activity.

Previously, the human element could be added in a discretionary manner that would allow corrupt practices in the mining regulatory process, but this is no longer the case with smart contract automation. One of the major shortcomings of the existing mine site inspection system in India was its dependence on manual inspections, carried out at regular intervals. IoT environmental monitoring is an initiative to overcome this (Ramani, Sujitha & Tangade, 2025). Integrating remote sensing makes scientific validation of ecological accountability and enhances compliance enforcement of environmental clearance. The platform's integration with other e-governance initiatives such as TAMRA and PARIVESH highlights its potential for implementation in India's existing digital ecosystem. The development of the same integrated framework at a national level will need coordinated policy support, infrastructure investment and capacity development between the various state mining departments. Based on these findings, blockchain technology is emerging as a key technology that can help achieve the vision of sustainable resource governance as stated in the National Mineral Policy 2019 of the Government of India.

6. Conclusion

The research clearly proves that the adoption of blockchain technology in spatial mining systems has the potential for a transformative and practical solution towards sustainable resource governance in India. By combining these technologies, the system will provide a comprehensive solution that tackles issues of transparency, compliance, environmental monitoring, and revenue accountability. Data from pilot deployments in key Indian mineral resource states shows that illegal mining detection has improved, royalty collection is more accurate, environmental compliance has improved, and regulatory response is more efficient. The platform is well aligned with the National Mineral Policy 2019 and Digital India governance goals of the Government of India. Future research needs include scaling the framework at a national level, increasing interoperability with existing government digital systems, and building the capacity of the State-level mining regulatory authorities. Spatial mining systems with blockchain technology are the most promising way for India to ensure responsible, transparent, and environmentally friendly use of mineral resources.

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