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Systematic review on the integration of IOT in sustainable water management in mining

Revisión sistemática acerca de la integración de IOT en la gestión sostenible de agua en la minería

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Abstract

This article presents a systematic review in the context of environmental sustainability and mining 4.0 in the extractive industry, with the aim of analyzing the effectiveness of the Internet of Things (IoT) in sustainable water management. Based on a review of 63 scientific articles, 20 relevant studies were selected for a more exhaustive analysis. Key technologies such as smart sensors, microcontrollers, and cloud platforms were identified as fundamental for real-time monitoring and efficient control of water resources. The results show that the use of IoT significantly increases efficiency in water management and treatment, mainly through early detection of leaks. However, barriers to its implementation were identified, especially in rural contexts and small-scale mining operations, such as limited connectivity and a lack of technical capabilities in communities. The conclusion highlights the value of integrating emerging technologies, such as artificial intelligence and blockchain, to strengthen environmental decision-making, considering not only water but also air quality. It is recommended to promote field studies in real mines and advance the adoption of technological solutions adapted to diverse environments, especially in Latin America. This analysis provides a solid foundation for future research on the use of IoT in water management in the mining sector.

Keywords: Internet of Things, water management, mining 4.0.

Resumen

El presente artículo desarrolla una revisión sistemática en el contexto de la sostenibilidad ambiental y la minería 4.0 en la industria extractiva, con el objetivo de analizar la efectividad del uso del Internet de las Cosas (IoT) en la gestión sostenible del agua. A partir de la revisión de 63 artículos científicos, se seleccionaron 20 investigaciones relevantes para un análisis más exhaustivo. Se identificaron tecnologías clave como sensores

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inteligentes, microcontroladores y plataformas en la nube, las cuales resultan fundamentales para el monitoreo en tiempo real y el control eficiente del recurso hídrico. Los resultados evidencian que el uso del IoT incrementa significativamente la eficiencia en la gestión y el tratamiento del agua, principalmente mediante la detección temprana de fugas. No obstante, se identificaron barreras para su implementación, especialmente en contextos rurales y operaciones de pequeña minería, tales como la limitada conectividad y la carencia de capacidades técnicas en las comunidades. La conclusión destaca el valor de integrar tecnologías emergentes, como la inteligencia artificial y blockchain, para fortalecer la toma de decisiones en materia ambiental, considerando no solo el agua, sino también la calidad del aire. Se recomienda promover estudios de campo en minas reales y avanzar en la adopción de soluciones tecnológicas adaptadas a diversos entornos, especialmente en América Latina. Este análisis constituye una base sólida para futuras investigaciones sobre el uso del IoT en la gestión hídrica en el sector minero.

Palabras clave: Internet de las Cosas, gestión del agua, minería 4.0.

Introduction

Mining accounts for more than 10% of Peru's Gross Domestic Product (GDP) and constitutes a key source of foreign exchange for the country. However, this industry demands high volumes of water and poses significant risks of water pollution (Ministerio de Energía y Minas [MINEM], 2023). In this context, the growing relevance of technology to enhance environmental management, planning, and safety in mining operations is evident.

Among emerging technologies, the Internet of Things (IoT) has emerged as an innovative tool to optimize the use of natural resources, particularly water, through solutions that integrate sensors, remote monitoring, and real-time data analysis. In the mining sector, the journal Tecnología Minera (2024) highlights recent studies demonstrating the IoT's capability to monitor critical water parameters—such as flow rate, quality, and distribution—through sensor networks integrated into data analysis platforms. In sectors like smart agriculture, the IoT has already proven effective in significantly reducing water consumption through automated systems (Andrade & Aguilar, 2021).

Despite the growing interest in using IoT for water management in mining, the scientific literature on the topic reveals significant gaps. First, there is a lack of studies evaluating the impact of these technologies on water quality, particularly within the context of Latin American mining. Second, there is a shortage of quantitative evidence that clearly establishes a relationship between the implementation costs of IoT and its economic and environmental benefits (Quispe, 2024). Lastly, although social and cultural factors are crucial for the success of any technological innovation, little attention has been paid to the institutional, social, and technical barriers that hinder its adoption (Basso, 2024). Therefore, it is essential to understand not only the technical capabilities of IoT but also the contextual factors influencing its effective implementation across various types of mining operations.

The central issue this review addresses is determining how the integration of IoT technologies contributes to sustainable water management in the Peruvian mining industry. Specifically, it seeks to answer the following questions: Which IoT technologies are most effective for optimizing water consumption? (Casavilca & Antonio, 2024); What is the economic and environmental return of implementing continuous monitoring systems based on IoT in operations of varying scales?; and What are the main technical, social, and regulatory barriers that impede the adoption of IoT solutions for water management in rural mining contexts? (Yong, 2021).

In light of this, the general objective of this article is to analyze the role of the Internet of Things in sustainable water management within the mining sector, considering its impact on water consumption efficiency, quality control, and the mitigation of environmental impacts. Specifically, three objectives are proposed: (1) to identify and compare IoT technologies used to optimize water consumption at different levels of mining operations; (2) to evaluate the economic and environmental benefits derived from their implementation; and (3) to recognize the main technical, social, and regulatory barriers that condition their adoption in rural mining communities.

Based on the above, the following general hypothesis is proposed: the implementation of IoT technologies in water management in mining significantly improves resource use efficiency and contributes to the reduction of environmental impacts. Specifically, the following hypotheses are posited: (a) the use of IoT smart sensors significantly enhances real-time monitoring capacity; (b) IoT systems applied in mining operations can reduce water waste through process automation (Basso, 2024); and (c) regulatory and training barriers account for more than 50% of the obstacles to IoT adoption in rural mining communities (Andrade & Aguilar, 2024).

This systematic review will be conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which guide the stages of identification, selection, eligibility, and inclusion of scientific studies published between January 2020 and April 2025. To achieve this, databases such as PubMed, Scopus, ProQuest, Google Scholar, and ScienceDirect will be consulted, using the terms “IoT” AND “water

management" AND "mining" in titles and abstracts. Inclusion criteria will encompass empirical studies with quantitative data on water consumption or quality in mining contexts in Peru or comparable countries (Chile, Mexico), published in Spanish or English. Studies lacking a clear methodology, those without a DOI, those without quantitative data, or those published prior to 2020 will be excluded. After removing duplicates and reviewing titles and abstracts, full readings of eligible articles will be conducted to extract key variables.

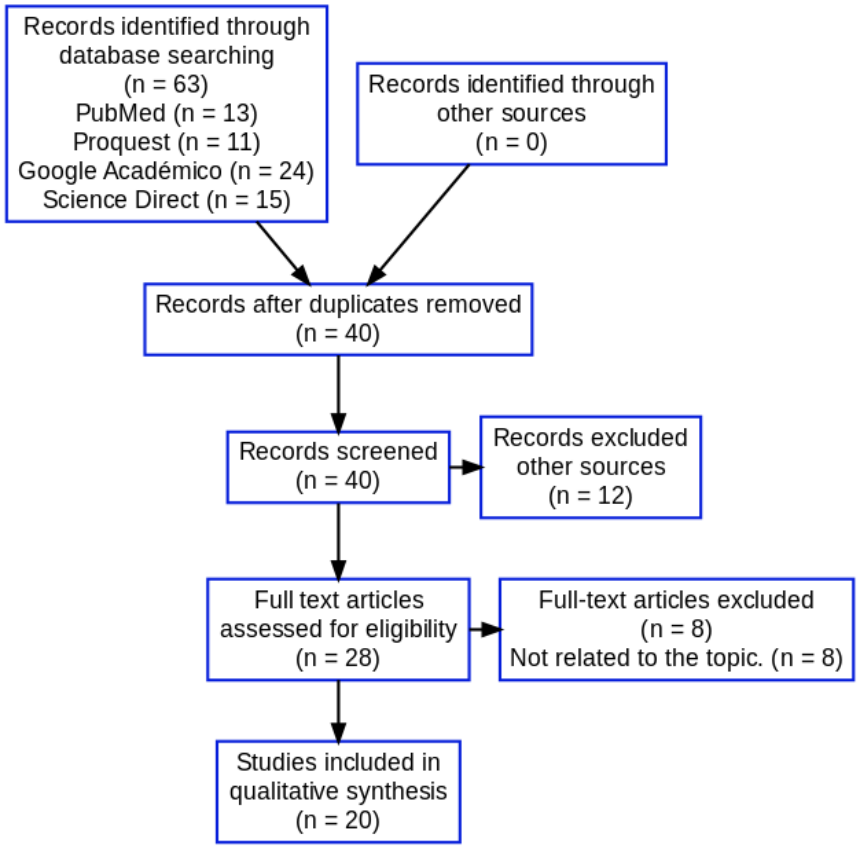
Methodology

To carry out this systematic review, the PRISMA method was applied to ensure transparency and appropriate selection of related studies.

The review process was developed following PRISMA guidelines, beginning with the preparation of a detailed protocol that encompassed the identification of the research question, search strategy, inclusion and exclusion criteria, data extraction, and synthesis of results. This systematic approach ensured accuracy and coherence at each stage of the process.

Figure 1

PRISMA flow diagram for article selection process



***Note*:** Authors' own elaboration.

The search for relevant studies was conducted in academic databases such as PubMed, Scopus, ProQuest, Google Scholar, and ScienceDirect, using a strategy that combined keywords such as: "IoT," "Internet of Things," "Water management" OR "Gestión del agua," "Mining" OR "Minería," and "Sustainability" OR "Sostenibilidad." Studies published in the last eight years that addressed the integration of IoT and its impact on sustainable water management were included.

The inclusion criteria considered studies published in the last eight years that investigated the application of IoT in sustainable water management within the mining industry. Furthermore, only those studies that presented clear results regarding the impact of this technology in the sector were selected.

Regarding the exclusion criteria, studies that were not directly related to the integration of IoT in the mining context were discarded, as well as those that did not present concrete results or did not meet appropriate methodological standards for a systematic review.

The review was structured in four stages according to the PRISMA protocol:

- **Identification**: A systematic search was conducted in the mentioned databases, identifying 63 documents using the key terms in titles, abstracts, and keywords.
- **Screening**: Sixteen duplicate articles were removed, along with another seven that fell outside the established time frame (last five years), leaving 40 relevant studies.
- **Eligibility**: Titles, abstracts, and results were reviewed, excluding 12 articles that did not align with the research objectives, reducing the set to 28 documents.
- **Final Inclusion**: An additional eight articles were discarded for not being directly related to the topic, problem, or study objectives, or for lacking a valid DOI, resulting in a total of 20 articles included in the final analysis.

Table 1
Articles related to thematic axes

Thematic axis	Description	Related studies
1. IoT Technologies and Methodologies	Applications of sensors, microcontrollers, cloud platforms, and monitoring systems for water control.	Alshami (2024), Bo (2022, 2023), Choubey (2022), Fang (2022), Puneeth (2024), Vallejo (2024), Nguyen (2022), Shaikh (2023)
2. Impact on Sustainable Water Management	Assessment of the environmental and operational benefits of IoT: water consumption efficiency, leak detection, and water recycling.	Monteiro (2022), Shafaei (2021), Bothe (2023), Huang (2023), Leuenberger (2021), Kagiso (2020), Zhenguo (2020)
3. Integration with Emerging Technologies	Combined use of IoT with AI, blockchain, big data, and predictive systems to optimize environmental decision-making.	Miller (2025), Humnabadkar (2024), Alshami (2024), Monteiro (2022), Molaei (2020), Kagiso (2020)
4. Barriers and Challenges to Adoption	Technical (connectivity), economic (costs), and social (lack of technical capabilities, resistance to change) limitations.	Leuenberger (2021), Maseeh (2021), Nguyen (2022), Vallejo (2024), Miller (2025), Humnabadkar (2024), Shaikh (2023)
5. Experiences and Cases of Application	Real-world cases of IoT implementation in mining globally, highlighting lessons learned and replicability.	Fang (2022), Bo (2022, 2023), Huang (2023), Choubey (2022), Puneeth (2024), Zhenguo (2020), Nguyen (2022)

Results and discussion

This chapter presents the results obtained from the critical evaluation of the twenty studies selected in the systematic review, covering the period 2020–2025. The sample includes various methodological approaches, including systematic and bibliometric reviews, experimental studies, IoT-based prototype developments, simulation models, case studies, and mixed methodologies.

Table 2
Results of the quality assessment of the studies

Author (year)	Study design	Internal validity	External validity	Risk of bias
Miller (2025)	Systematic Review IoT-AI for Environment	Yes	No	Moderate
Alshami (2024)	Systematic Review + Bibliometrics	Yes	Yes	Moderate

Puneeth (2024)	IoT Prototype with Sensors and Cloud	Yes	No	Moderate
Vallejo (2024)	Open Source IoT Prototype	Yes	No	Moderate
Humnabadkar (2024)	Review of Advanced Technologies	Yes	No	Moderate
Bothe (2023)	Qualitative Review (Water Life Cycle)	Yes	No	Moderate
Huang (2023)	Geophysical Case Study	Yes	No	Moderate
Shaikh (2023)	Review of IoT-Based WMS	Yes	No	Moderate
Bo (2023)	Cloud IoT Model with Sensors	Yes	No	Moderate
Monteiro (2022)	Water Simulation Model	Yes	No	Moderate
Fang (2022)	Anaerobic Fermentation Experiment	Yes	No	Low
Choubey (2022)	IoT System Development (Prototype)	Yes	No	Moderate
Bo (2022)	Multisensor IoT System	Yes	No	Moderate
Nguyen (2022)	IoT System for Dust and Water	Yes	No	Moderate
Leuenberger (2021)	Geospatial Mixed Methods	Yes	No	Moderate
Maseeh (2021)	Review of IoT and ICT in Water	Yes	No	Moderate
Shafaei (2021)	Experimental Trial (EDW Tailings)	Yes	No	Low
Kagiso (2020)	Review of IoT/WSN Technologies	Yes	No	Moderate
Molaei (2020)	Bibliographic Review of IoT in Mining	Yes	No	Moderate
Zhenguo (2020)	IoT + Multiple Regression	Yes	No	Moderate

Table 3 synthesizes the main methodological characteristics, the most relevant findings, and the conclusions of the twenty studies included in the systematic review. The works encompass a wide variety of approaches, ranging from bibliographic and systematic reviews to experimental studies, IoT prototype developments, case studies, and simulation models. The results show a general consensus regarding the positive impact of the Internet of Things on optimizing water resource use, highlighting improvements in real-time monitoring, process automation, and early detection of leaks or failures. Most conclusions emphasize the need to expand the validation of these technologies in real-world scenarios, strengthen connectivity in remote mining environments, and promote integration with other emerging technologies such as artificial intelligence and blockchain to enhance the sustainability of water management in the mining sector.

Table 3

Characteristics of the selected studies

Author (Year)	Methodology	Results	Conclusions
Miller (2025)	Systematic literature review on IoT-AI in environmental monitoring	Identified that AI enhances IoT in predictive modeling and real-time analysis	Integration of AI, blockchain, and cloud is essential for sustainable monitoring systems
Alshami (2024)	Systematic review and bibliometrics on IoT in water management	Identified the most used sensors and communication technologies (Zigbee, Sigfox)	Requires optimization in energy efficiency, interoperability, and standard protocols
Puneeth (2024)	Development of IoT prototype with sensors and cloud	Enables remote monitoring of water quality and early contamination detection	Improves environmental management but requires validation in real scenarios
Vallejo (2024)	Open-source IoT prototype with Arduino/ESP32	Real-time monitoring of temperature and humidity in mining environments	Scalable for small and medium mining operations at low cost

Humnabadkar (2024)	Review of IoT, AI, and blockchain technologies in water management	Demonstrated prediction capabilities and data traceability	Requires regulatory frameworks and cost reduction for mass adoption
Bothe (2023)	Qualitative review of the water life cycle in mining	Highlights the need for continuous monitoring in all phases	Management must be integral and circular, prioritizing recycling and treatment
Huang (2023)	Geophysical case study with IoT and 3D electrical resistivity	Detected risk zones for water ingress in underground mines	Allows for the design of safer and more economical protective pillars
Shaikh (2023)	Review of IoT-based water monitoring systems (WMS)	Systems reduce manual intervention and improve monitoring efficiency	Promote intelligent and cost-effective WMS in resource-limited contexts
Bo (2023)	Cloud IoT model with sensors for water optimization	Increased water reuse rate through real-time analysis	Facilitates decision-making in comprehensive water management in mines
Monteiro (2022)	Dynamic simulation model for water planning	Predictions of water demand with error <5%	Improves comprehensive water management in deep mines over the long term
Fang (2022)	Anaerobic fermentation experiment with waste	Increased microorganisms and efficiency of volatile fatty acid production	Sustainable proposal for treatment and recovery in wastewater
Choubey (2022)	IoT prototype with ultrasonic sensors and automatic control	Real-time monitoring and activation of water pumps	Reduces water waste, requires large-scale validation
Bo (2022)	Development of a multisensor IoT network for water in mines	Continuous monitoring and detection of outlier data	Reliable for operational decisions in underground water management
Nguyen (2022)	IoT system for dust monitoring and water suppression	Detected dust and automatically activated spraying systems	Reduced water use and improved safety in coal plants
Leuenberger (2021)	Geospatial mixed methods on water and health in mining	Improved water infrastructure, but quality issues persisted	Strengthening health and water quality policies in mining areas is necessary
Maseeh (2021)	Review of IoT and ICT in smart water management	IoT allows automatic control and waste reduction	Need for more integrated systems tailored to various contexts
Shafaei (2021)	Experimental trial of tailings dehydration (EDW)	Increased water recovery by raising applied voltage	Promising technique for circular economy in mining
Kagiso (2020)	Review of digital technologies (IoT, AI, WSN, drones)	Highlighted wireless sensor networks for monitoring	Adoption of emerging technologies will

			improve safety and efficiency
Molaei (2020)	Review of IoT applications in mining processes	Improved monitoring of machinery and safety	Need for more integrated and flexible IoT models
Zhenguo (2020)	IoT + multiple regression to predict water zones	Improved accuracy in estimating heights of water conduction zones	Useful tool for preventing water ingress in coal mines

The discussion of results is organized around five thematic axes that structure this research:

1. IoT technologies and methodologies

The analyzed studies demonstrate significant advances in the development of IoT-based technologies and methodologies for water management in the mining sector. Research such as those by Alshami (2024), Bo (2022, 2023), Choubey (2022), Fang (2022), Puneeth (2024), Vallejo (2024), Nguyen (2022), and Shaikh (2023) highlight the design of prototypes and intelligent sensor networks that enable real-time monitoring of critical parameters such as level, pH, turbidity, and conductivity of water. These systems, integrated with microcontrollers like Arduino and ESP32, and LoRa communication modules connected to cloud platforms, have proven effective in data collection and processing. However, most tests have been conducted in controlled environments, limiting their external validity in real mining contexts.

2. Impact on sustainable water management

Regarding the environmental and operational impact of IoT on water resource management, studies by Monteiro (2022), Shafaei (2021), Bothe (2023), Huang (2023), Leuenberger (2021), Kagiso (2020), and Zhenguo (2020) report significant improvements in water consumption efficiency, early leak detection, and optimization of treatment and recycling processes. Monteiro (2022) and Shafaei (2021) demonstrate that integrating sensors with predictive models can significantly reduce water losses and optimize usage throughout mining operations. However, the success of these systems largely depends on proper implementation, constant maintenance, and their adaptability to different environments.

3. Integration with emerging technologies

Various authors highlight the potential of integrating IoT with emerging technologies to enhance environmental decision-making. Research by Miller (2025), Humnabadkar (2024), Alshami (2024), Monteiro (2022), Molaei (2020), and Kagiso (2020) underscores the benefits of combining IoT with artificial intelligence, blockchain, big data, and predictive algorithms. These synergies improve monitoring accuracy and increase information traceability, facilitating the evolution towards intelligent mines. Despite these advances, challenges related to high costs, system interoperability, and the absence of regulatory frameworks that promote large-scale adoption persist.

4. Barriers and challenges to adoption

Barriers to IoT implementation were recurrent in studies by Leuenberger (2021), Maseeh (2021), Nguyen (2022), Vallejo (2024), Miller (2025), Humnabadkar (2024), and Shaikh (2023). The main limitations identified include poor connectivity in remote mining areas, high installation and maintenance costs, and resistance to change from organizations and communities. Additionally, sensors face technical challenges to operate under extreme conditions typical of the mining environment, affecting their durability. Overcoming these barriers will require investments in digital infrastructure, specialized technical training, and the development of more robust technologies adapted to specific geographical contexts.

5. Experiences and cases of application

Finally, the review identified various successful IoT implementation experiences in mining in countries such as China, India, and South Africa. Studies by Fang (2022), Bo (2022, 2023), Huang (2023), Choubey (2022), Puneeth (2024), Zhenguo (2020), and Nguyen (2022) report improvements in water management through the centralization of data in graphical platforms, reduced response times to hydraulic failures, and more efficient compliance with environmental regulations. However, to replicate these cases in Latin America, it will be essential

to adapt technological solutions to local realities, strengthen technical capacities, and promote community participation in technological adoption processes.

General synthesis

The five thematic axes analyzed allow us to conclude that IoT represents a key tool for transforming water management in mining. Significant advances have been identified in the development of technological solutions, improvements in operational efficiency, and concrete examples of successful implementation. However, significant challenges remain related to validation in real scenarios, overcoming technical, social, and economic barriers, as well as the need to integrate IoT with other emerging technologies to achieve sustainable and scalable adoption in diverse mining contexts.

Conclusions

The analysis confirms that the application of the Internet of Things (IoT) in mining has high potential to optimize water resource use and reduce the environmental impact of extractive activities. The evaluated solutions have proven effective in key aspects such as real-time monitoring, process automation, and early detection of failures in water supply and treatment systems. Furthermore, the flexibility of these technologies allows for adaptation to different operational scales, creating opportunities to improve water sustainability in both large and small mining operations.

Nonetheless, the findings also highlight the need to overcome significant limitations to achieve full adoption of these technologies. Among the main challenges are connectivity difficulties in remote areas, high implementation costs, limited technical training in mining communities, and insufficient integration with other emerging technologies.

Therefore, it is recommended to prioritize applied research in real mines, strengthen digital infrastructure, and promote public policies that encourage investment in technological innovation. In this way, IoT can establish itself as a strategic pillar in the sustainable management of water in the mining sector.

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