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Enhancing Environmental Monitoring in Gold Mining: A Systematic Review of IoT Sensors and Technologies for Effective Hazardous Waste Detection

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ABSTRACT

Gold mining contributes significantly to the economy but generates hazardous waste and toxic waste such as mercury and cyanide, posing serious environmental threats. Conventioal monitoring methods are outdated and lack real-time detection. This study aims to review recent applications of Internet of Things (IoT) technology for hazardous waste and toxic waste monitoring in gold mining. Using a systematic review of 35 publications (2015–2025), the study examines system architecture, sensor types, communication protocols, and implementation challenges. Results show that effective systems integrate multi-parameter sensors (pH, heavy metals, hazardous gases), low-power communication (LoRa, ZigBee), and real-time monitoring platforms. Key challenges include harsh environments, network limitations, and sensor maintenance, with solutions involving robust design and advanced analytics. The incorporation of artificial intelligence, including Edge AI and machine learning, enhances predictive and anomaly detection capabilities. IoT-based monitoring improves accuracy, efficiency, and sustainability, supporting more proactive environmental risk management in gold mining.

1. Introduction

The gold mining sector has long been a key pillar in the economic development of many countries, including Indonesia, due to its significant contribution to Gross Domestic Product (GDP) and job creation [1,2]. Gold is not only an economic commodity, but also a symbol of monetary stability and foreign exchange reserves. However, along with the increase in mining activities to meet global demand, there are serious environmental consequences that, if not appropriately managed, can threaten the sustainability of the ecosystem and public health. One of the most crucial environmental impacts in gold mining is the production of hazardous and toxic waste. This waste is produced from

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the use of various chemicals, such as mercury and cyanide, in the gold extraction process, which aims to separate the precious metal from its impurities [3,4]. These compounds are toxic and persistent, polluting soil, surface water, groundwater, and air long-term. In addition, this pollution is difficult to restore, requires huge remediation costs, and often permanently damages natural habitats [5,6].

The impact of hazardous and toxic waste pollution in the gold mining sector can be seen clearly in the case of Pesanggaran, Banyuwangi. Pollution in this area reduces the quality of water and soil, causes vegetation death, disrupts land fertility, and increases the risk of health problems ranging from skin diseases to cancer for the surrounding community [7,8]. This shows that environmental challenges in gold mining are complex and multidimensional. Incidents like this underscore the urgency of mitigation and prevention [9,10]. Although environmental regulations have been established by the government, such as the Environmental Protection and Management Law in Indonesia, implementation and supervision in the field, especially in remote mining areas, still face various obstacles [11,12]. Hazardous and Toxic Waste monitoring methods in mining areas are generally still reactive and conventional, relying on manual sampling and laboratory analysis [3,13]. This approach has several significant limitations: it is time-consuming, has high operational costs, has a limited coverage area, and most crucially, is periodic, thus not providing real-time early detection [4]. As a result, pollution is often only detected after the waste has spread widely, causing damage that isn't easy to repair and requires huge remediation costs, as happened in Banyuwangi [1,3]. This gap highlights the need for more proactive, efficient, and automated monitoring systems to prevent unintended impacts.

In the last decade, the Internet of Things (IoT) has emerged as a transformative technology that offers innovative solutions to various environmental problems, including monitoring. Internet of Things (IoT) enables automated data collection, real-time transmission, and in-depth analysis by integrating intelligent sensor networks, wireless communication devices, and cloud computing platforms [14,15]. In the context of monitoring Hazardous and Toxic Waste in mining areas, IoT-based systems enable sensors to continuously monitor key parameters such as pH, conductivity, heavy metal concentrations, or specific chemicals in soil or water [16,17]. The collected data can then be accessed and analyzed in real-time, triggering early alerts if anomalies are detected or thresholds are exceeded, allowing for rapid response and effective mitigation [18,19]. The advantages of IoT lie in its ability to provide continuous monitoring, broad spatial coverage, and better data accuracy than traditional methods [20,21].

Although the potential of IoT in environmental monitoring has been widely studied, systematic reviews that specifically discuss the design of IoT-based hazardous and toxic waste monitoring systems for early detection of pollution in gold mining areas are still relatively limited. Existing research tends to be fragmented or focuses on only one aspect, such as a particular type of sensor or a general IoT platform, without comprehensively integrating all the elements needed in the complex context of gold mining [22,23]. Therefore, this systematic literature review is critical for synthesizing existing knowledge, identifying effective system architectures, analyzing the most relevant sensor technologies, and examining the challenges and opportunities for implementation in mining environments.

Previous studies have examined mentoring systems that generally use only a single sensor and a limited scale. However, there has been no research on multi-parameter integration and field testing. Therefore, a systematic review of the use of IoT in detecting hazardous waste in gold mining environments is needed. Through this systematic review, we aim to answer key questions such as: “How can an IoT-based B3 waste monitoring system architecture be designed for early detection in gold mining areas?”, “What sensor technologies are most effective and relevant for detecting specific hazardous waste contaminants in mining environments?", and "What are the technical and non-technical challenges faced in implementing IoT monitoring systems in gold mining areas, and how can they be addressed?". It is hoped that the results of this review will not only enrich the scientific literature but also provide practical guidance and concrete recommendations for academics, researchers, the mining industry, and policymakers in developing and implementing more proactive and sustainable environmental monitoring systems in the future.

2. Methodology

2.1 Research Method

For manuscript publication, all provided Figures must follow the standard of quality for publication. Authors must provide a high quality with high resolution Figure. Content in the Figure should be clear and readable as shown in Figure 1(b) (Especially, the font size of contour legend). For example, as in Figure 1:

This study uses a Systematic Literature Review (SLR) approach to collect, analyze, and synthesize current knowledge of IoT-based hazardous and toxic waste monitoring systems for early pollution detection in gold mining areas. The SLR approach was chosen because it can provide a comprehensive picture systematically and objectively, and can be replicated while identifying research gaps and recommendations for future development.

2.2 Research Questions

As the primary foundation in this systematic literature review approach, the study was designed to answer three research questions (Research questions/RQ). It was formulated systematically to align with the study's objectives. These questions aim to explore the technical, functional, and implementative aspects of the hazardous and toxic waste monitoring system based on the Internet of Things (IoT) in the gold mining environment. The following are the details of each question:

- RQ1: How can the architecture of an IoT-based hazardous and toxic waste monitoring system be designed for early detection in gold mining areas?
- RQ2: What sensor technology is most effective and relevant for detecting specific hazardous and toxic waste contaminants in gold mining environments?
- RQ3: What are the technical and non-technical challenges faced in implementing an IoT monitoring system in a gold mining area, and how can they be solved?

2.3 Search Strategy

Literature search strategy is a crucial step in a Systematic Literature Review to ensure that all relevant studies are identified systematically and transparently. This study's search strategy was designed to answer three main research questions with a broad scope, but still relevant.The search was conducted on five major electronic databases, namely **Institute of Electrical and Electronics Engineers (**IEEE Xplore), ScienceDirect, SpringerLink, Scopus, and Google Scholar, which were selected for their credibility and coverage in technology and environment. Here are the details of each search strategy:

a. Database
Literature search was conducted on major electronic databases:

- IEEE Xplore
- ScienceDirect
- SpringerLink
- Scopus
- Google Scholar

b. Keyword

The combination of keywords used includes:

- “IoT” or “Internet of Things” or “hazardous waste” or “toxic waste”
- “gold mining” OR “mining area”
- “Environmental monitoring”
- “early detection” OR “real-time monitoring”

c. Inclusion Criteria

- Articles in Indonesian or English
- Year of publication: 2015-2025.
- Focus on IoT-based environmental monitoring systems, especially those relevant to hazardous and toxic waste or mining environments.
- Contains implementation studies, system architecture, or sensor technology.

d. Exclusion Criteria

- Does not discuss IoT in an environmental context.
- Focus on mining other than gold (unless discussion of sensor technology is generally relevant).
- Full access to documents is not available.

e. Screening & Selection Process

The selection process follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) stages, starting from initial identification, screening of titles and abstracts, to full-text review.

2.4 PRISMA Flow Diagram

In this study, the literature selection process followed the PRISMA 2020 guidelines to ensure transparency, replication, and accountability in reporting Systematic Literature Reviews (SLRs) as in Figure 1.

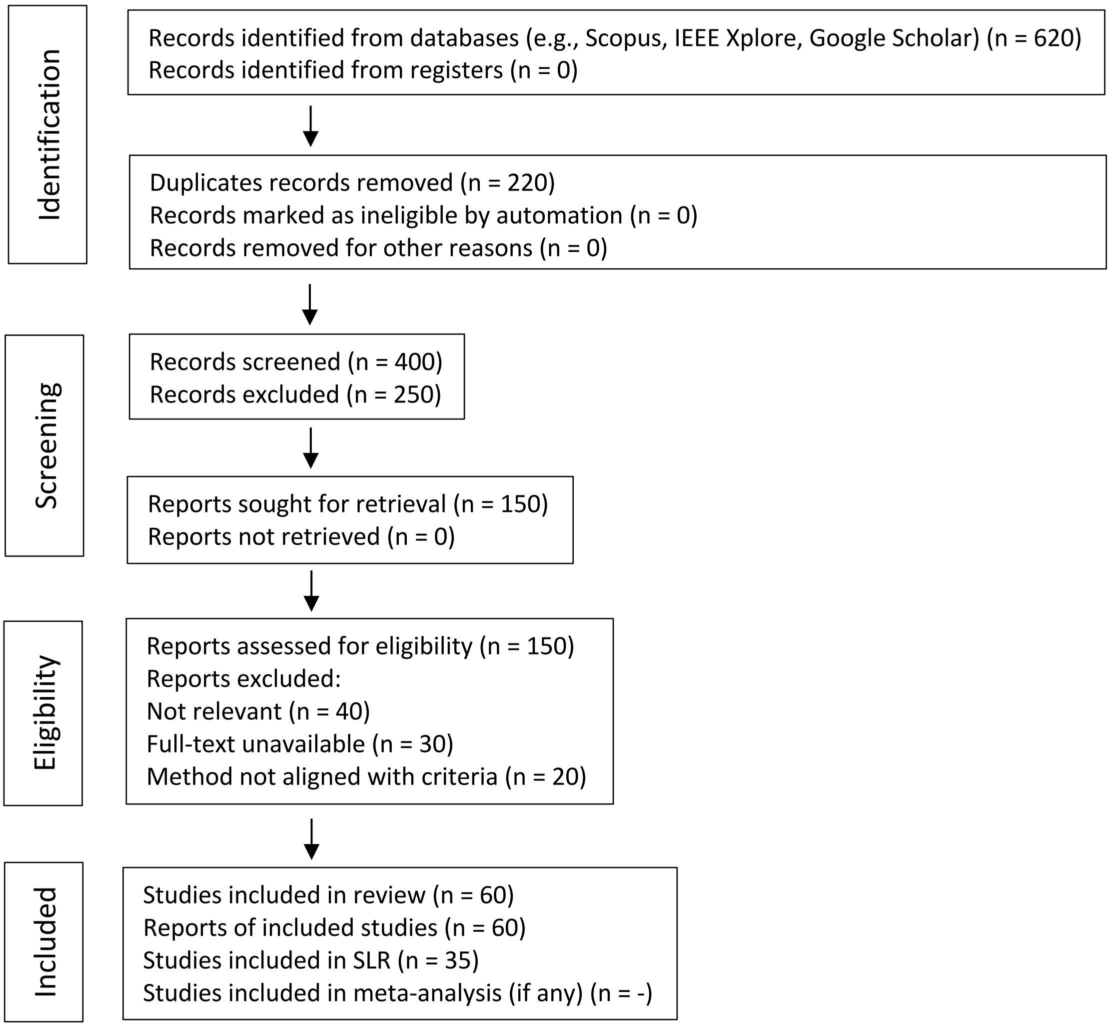

Fig. 1. PRISMA flow diagram for systemathic literature review methodology

3. Results

3.1 Overview of Selected Studies

After reviewing the literature search and selection process using the PRISMA approach, 35 articles met the inclusion criteria and were relevant to IoT-based hazardous and toxic waste monitoring systems in gold mining areas. These articles come from various sources such as reputable international journals and national proceedings, and cover the period 2015 to 2025. Most publications come from Indonesia, China, and countries with active mining industries.From the initial total of 620 articles, a selection process based on title, abstract, and full content eliminated articles that were irrelevant or did not have complete access. The selection process is visualized in a PRISMA diagram.

3.2 Classification of Existing Studies

The division of articles into five main groups serves as an effort for thematic categorization and as a critical analysis strategy to describe the complexity of the approach, the relevance of the context, and the diversity of scientific contributions presented by each study in Table 1. Through this classification, the conceptual and methodological patterns underlying these studies can be identified in more depth, providing a foundation for mapping the development direction and determining research gaps that still require further exploration.

Table 1
Articles are grouped into five main categories based on their focus of discussion

CATEGORY	FOCUS OF DISCUSSION	EXAMPLE ARTICLE
IoT System Architecture	IoT-based B3 waste monitoring system building design	[24]
Sensor Technology	Types of sensors for detecting heavy metals, pH, conductivity, etc.	[25,26]
Data Communication	Communication protocols (LoRa, WSN, Zigbee, etc.)	[27]
Implementation in Mines	Case study of monitoring system implementation in a mining area	[28]
IMPLEMENTATION CHALLENGES	TECHNICAL AND NON-TECHNICAL CONSTRAINTS IN IMPLEMENTATION	[2]

3.3 Synthesis of Key Findings
3.3.1 IoT system architecture

Most studies recommend an IoT system architecture for hazardous and toxic waste monitoring in gold mines with three main layers, which work in an integrated manner as follows:

a. Sensor Layer

This layer is the primary foundation for collecting environmental data directly and in real-time. The data collected includes important environmental quality parameters such as mine water pH, heavy metal concentrations (Hg, Pb, As), temperature, humidity, cyanide levels, and hazardous gases (H_2S, CO_2, CH_4). The sensors used in this layer include pH meters, ISE (Ion Selective Electrode), conductivity sensors, gas sensors (MQ-series), and cyanide sensors.

b. Network Layer

This layer acts as a liaison between sensors and central applications. Measurement data is sent via various wireless communication protocols. LoRa/LoRaWAN is often used for open-pit mines because it supports long-distance transmission with low power consumption. Mesh WSN or ZigBee is more suitable for underground mines because it can overcome geographical barriers. This layer must resist environmental disturbances and support redundancy to ensure data continuity.

c. Application Layer

This layer processes the received data into meaningful information. Its functions include data visualization in the monitoring dashboard, data analysis to detect anomalies, and activation of early warning systems in the event of pollution. Several studies have integrated AI technology, such as Edge AI or Long Short-Term Memory (LSTM), into this layer to improve prediction accuracy and detect anomalies automatically.

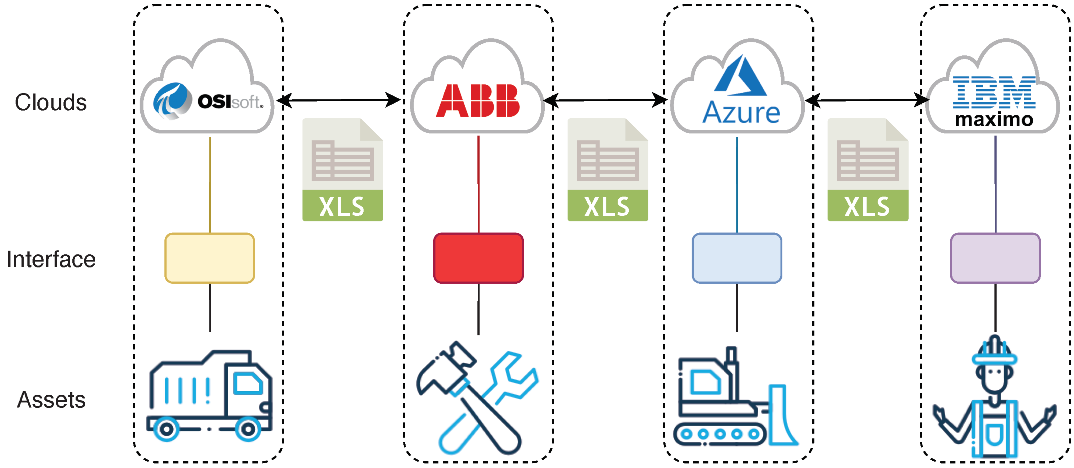

Fig.2. The IoT system architecture is based on three layers (sensor, network, application layer) for monitoring hazardous and toxic gold mine waste [24]. Vertical silos in each domain of mining.

The IoT architecture image, adapted from [24], not only strengthens the narrative explanation but also substantially illustrates the 3-layer system structure (sensor, network, application) widely used in IoT implementations for mining environmental monitoring. Figure 2 illustrates the schematic representation of this layer within the three-tier IoT architecture, highlighting how data flows from sensors through the network to the application level for real-time analysis and decision support. This visualization shows the functional relationships between layers, data flow paths, and examples of the application of this architecture in the mining industry sector that are relevant to the context of this study. The functions of these three system layers will be mentioned in Table 2.

Table 2
Function table of each layer

LAYER	MAIN FUNCTIONS	EXAMPLE ARTICLE
Sensor Layer	Collecting environmental data (pH, heavy metals, gases, cyanide)	[24]
Network Layer	Data transmission (LoRa, ZigBee, mesh WSN)	[29]
APPLICATION LAYER	DATA ANALYSIS, VISUALIZATION, AND EARLY WARNING)	[9]

3.3.2 Sensor Technology

Table 3 presents the types of sensors commonly used in IoT-based B3 waste monitoring systems, complete with main functions and relevant supporting references for each monitored environmental parameter.

Table 3
The sensors used vary greatly, depending on the parameters being monitored

SENSOR TYPE	MAIN FUNCTION	REFERENCE
pH Sensor	Measuring the acidity of mine water	[25]
Conductivity Sensor	Indicators of ion concentration and metal pollution	[25]
ISE (Ion Selective Electrode)	Specific heavy metal detection (Hg, Pb, As)	[30]
Gas Sensor (MQ-series)	Detection of hazardous gases such as H_2S, CO_2, CH_4	[31]
CYANIDE SENSOR	MEASURING RESIDUAL GOLD EXTRACTION CHEMICALS	[17]

3.3.3 Communication protocol

In the IoT system architecture for monitoring B3 waste in gold mines, communication protocols play an important role as a link between sensors in the field and the monitoring application center. This protocol must accommodate the characteristics of extreme mining environments, such as remote locations, geographic barriers, and power and network limitations. Some of the most widely used communication protocols in studies related to IoT-based mine monitoring include:

a. LoRa/LoRaWAN Edge AI

LoRa (Long Range) and LoRaWAN (LoRa Wide Area Network) are widely used in open-pit mines and wide-area areas because they support long-distance data transmission (up to 15 km) with very low power consumption. This protocol is ideal for mines far from the network center or areas with minimal communication infrastructure.

b. ZigBee / Mesh WSN (Wireless Sensor Network)

ZigBee and mesh WSNs are commonly used in underground mines or environments with complex physical obstacles. The mesh topology allows each node to act as a repeater, effectively extending the signal coverage in areas with many obstacles.

c. MQTT (Message Queuing Telemetry Transport)

MQTT works at the application layer to integrate cloud systems or IoT platforms. This lightweight protocol is designed for publish-subscribe-based communication, supporting efficient data delivery in systems with limited bandwidth. Several studies, such as [32], [33], also emphasize the importance of selecting a communication protocol that supports network redundancy to ensure continuity of monitoring in the event of a disruption or failure of a particular node. A comparison of each protocol is described in Table 4. Figure 3 shows a mesh network-based IoT communication architecture used in an underground mine. Each sensor node functions as a data collector and forwarder to a central gateway, supporting layered communication and path redundancy. This topology is designed to overcome physical barriers and ensure data continuity in complex environmental conditions [10].

Table 4
Communication protocol comparison table

PROTOCOL	RANGE	POWER CONSUMPTION	SUITABLE FOR
LoRa/LoRaWAN	Up to 15 Km	Low	Open pit mining, a large area
ZigBee	< 100 m per hop	Low-medium	Underground mining, WSN mesh
Mesh WSN	Varies (node dependent)	Fepends on mode	Underground mining, WSN mesh
MQTT	(application control)	Depends on the media	IoT cloud integration

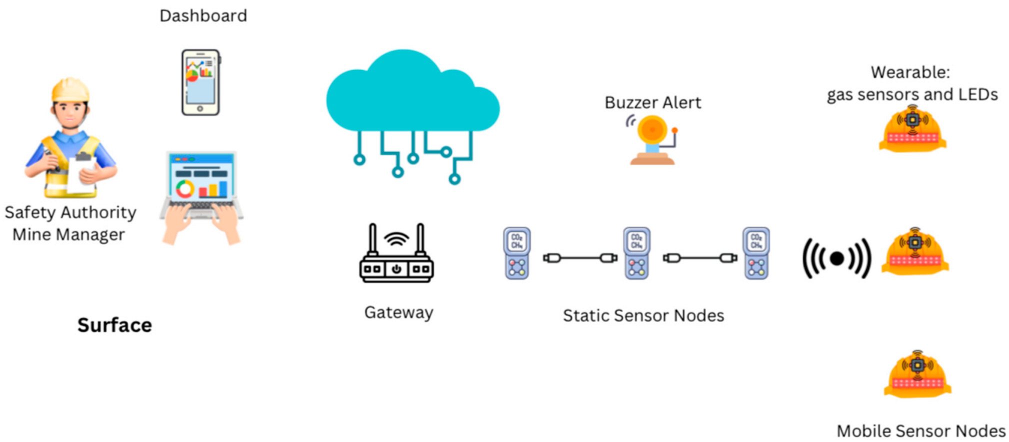

Fig. 3. IoT proposed solution for gas monitoring in underground coal mines

3.3.4 Challenges and obstacles

Figure 3 shows a mesh network-based IoT communication architecture used in an underground mine. Each sensor node functions as a data collector and forwarder to a central gateway, supporting layered communication and path redundancy. This topology is designed to overcome physical barriers and ensure data continuity in complex environmental conditions [34] Several solutions have been proposed to address environmental monitoring systems' challenges, such as using corrosion-resistant materials and special housing for extreme conditions [16]. In network limitations, redundant communication topologies such as mesh WSN or multi-hop LoRaWAN are recommended to maintain data continuity [8]. System maintenance can be optimized through modular sensor design and integration of automatic calibration technology [9]. In addition, cost efficiencies are achieved by utilizing open-source systems and modular design, and operator capacity is increased through training and collaboration with research institutions [35]. Table 5 will provide an overview of the challenges in implementing IoT systems in mining areas. Some solutions include corrosion-resistant materials, technical training, and easy-to-configure modular system designs.

Table 5
The main challenges encountered in the implementation of IoT systems in mining areas include

CHALLENGE	DESCRIPTION	SAMPLE ARTICLE
Extreme Environment	High temperature, high humidity, risk of corrosion, and vibration	[29]
Limited network access	Remote mine, minimal signal	[8]
Sensor Maintenance	Fouling problem, regular calibration is required	[9]
Initial Implementation Costs	IoT devices, networks, and servers	[24]
HR READINESS	**LACK OF OPERATORS TRAINED IN DIGITAL TECHNOLOGY**	[36]

3.3.5 Research gaps

A systematic review of the literature has identified several key research gaps that need to be addressed in the development of an IoT-based monitoring system for hazardous and toxic waste in gold mines. These research gaps are detailed in Table 6.

Table 6
Research gaps for this studies

Research Gap	Short Description	Example Article
Multi-parameter sensor integration	Monitoring systems generally only use single sensors, not multi-parameter integration.	[37] [38]
Long-term field system validation	Most studies are based on simulations or lab scale and have not yet been tested for durability in real mines.	[9] [29]
Real-time data-driven AI/ML implementation	AI/ML (LSTM, Edge AI) is discussed chieflyconceptually, but there is not much validation with real data.	[9] [39]
Interoperability with existing monitoring systems	Research related to IoT integration with existing mining environmental management systems is still limited.	[12]

3.4 Future Research

Figure 4 outlines the future research directions for IoT-based environmental monitoring in gold mining, emphasizing the necessity of integrating innovative technologies to enhance efficiency and reliability in harsh conditions. Table 7 provides a detailed overview of various studies that analyze different aspects of this field. Notably, research has revealed that a significant portion of waste monitoring systems in gold mines still relies on single sensors, leading to high operational costs and limited detection capabilities. To address this, one study proposes developing an integrated sensor unit combining multi-channel ion-selective electrodes (ISE) and optochemical biosensors for simultaneous detection of pH, heavy metals, and cyanide, targeting a 40% increase in efficiency and real-time detection accuracy.

Another study highlights the benefits of a hybrid edge-cloud approach, which has reduced latency and energy consumption significantly, making it suitable for remote monitoring applications. By implementing LSTM and CNN algorithms on edge devices like Raspberry Pi, this approach not only enhances anomaly detection in mining data but also mitigates internet dependency, thereby improving the reliability of monitoring systems in hazardous environments. Furthermore, the need for real-world testing is underscored, revealing that a mere 17% of studies have validated IoT systems in active mines. To fill this gap, research is focusing on the resilience of IoT systems against extreme conditions for extended periods, anticipating results that substantiate operational feasibility.

Studies also show that utilizing multi-hop mesh topology can significantly enhance network reliability in underground mining. Research efforts are directed towards comparing various communication architectures to ensure stable and continuous data delivery despite geophysical challenges. In terms of decision support systems, integrating diverse data types has proven to boost decision-making speed and accuracy. An IoT-based system designed to visualize pollution risk maps aims to enable quick, evidence-based responses to hazardous waste management. Lastly, the importance of transdisciplinary collaboration is emphasized, as it can enhance environmental innovation's effectiveness and sustainability, paving the way for better alignment between technical solutions and regulatory frameworks in the gold mining sector. Collectively, these research directions and findings illustrate a comprehensive approach to improving the environmental monitoring landscape in gold mining through advanced IoT applications.

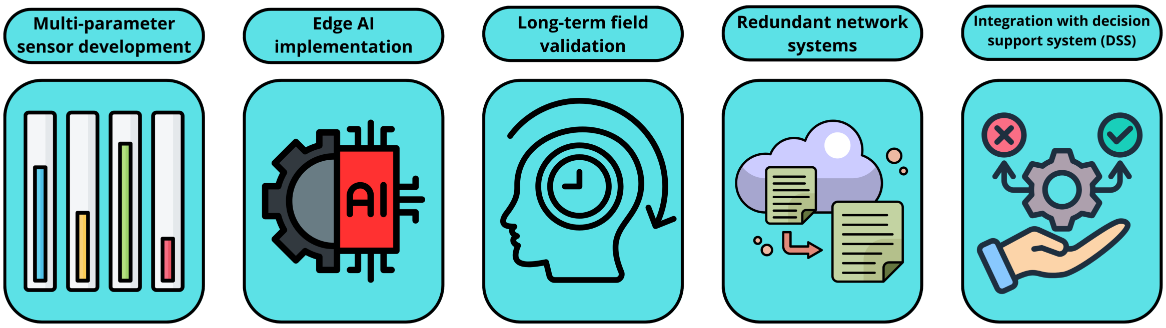

Fig. 4. Future research directions for IoT-based environment monitoring in gold mining

Table 7
The research for based analysis an explantion of journal

Research Basis	Research Explanation
Such studies, Klein and Julie [3] showed that 62% of B3 waste monitoring systems in gold mines still use a single sensor, resulting in high operational costs and limited detection [24,26].	This study proposes the development of an integrated sensor unit based on multi-channel ISE and optochemical biosensors capable of detecting pH, heavy metals (Hg, Pb, As), and cyanide simultaneously. The system will be tested in a mine simulation with extreme temperatures and high corrosion risks. The main target is to increase efficiency up to 40% and real-time detection accuracy in harsh mining environments.
Based on Sathupadi *et al.*, [10] has reported that the hybrid edge-cloud approach reduced latency by up to 35% and energy consumption by 28%, making it highly efficient for monitoring systems in remote locations.	This study applies LSTM and CNN algorithms on edge devices such as Raspberry Pi to detect anomalies in mining environmental data locally. The model is trained with historical data and evaluated based on accuracy, response, and power efficiency. This approach accelerates early warning and reduces dependence on the internet. The results improve the reliability of the hazardous and toxic waste monitoring system in remote areas.
Based on Duarte *et al.*, [9] has noted that only about 17% of studies tested IoT systems in real-world settings in active mines, although field validation is crucial [9,29].	This study tests the resilience of the IoT system for 6–12 months against fouling, temperatures >40 °C, high humidity (>90%), and mechanical vibrations. The evaluation will focus on data stability, sensor reliability, and calibration needs. The results are expected to be substantial evidence that the system is operationally feasible, not just conceptually.
Studies by Medina *et al.*, [29], Dondo *et al.*, [30] show that multi-hop mesh topology can improve network reliability by up to 60% in underground mining environments [11,12].	This research will test and compare the performance of multi-hop and hybrid LoRaWAN (e.g., LoRa + ZigBee) in overcoming signal interference and geophysical obstacles. Testing is done through simulation and field implementation, focusing on parameters such as RSSI, packet loss, and latency. The goal is to design a redundant, stable, and interference-resistant IoT communication architecture to maintain the continuity of data delivery in remote mines.
Based on Alamanos [13] has showed that integrating spatial, temporal, and environmental data in DSS can increase the speed and accuracy of decisions up to 3 times compared to manual approaches [40].	This study designs an IoT-based DSS that visualizes pollution risk maps by combining real-time sensor data, geology, and weather predictions. This system supports rapid and evidence-based responses, especially for hazardous and toxic waste mitigation in mines. Evaluation is carried out through field case studies and interface trials to ensure the usability and effectiveness of the system in practice.
Based on Klein and Julie [3] has noted that transdisciplinary collaboration can increase the effectiveness and sustainability of environmental innovation by 30–40% because it involves all stakeholders from the design stage.	This research will form and test a cross-sector working model between engineers, environmentalists, AI developers, and regulators through FGDs and case studies in gold mines. The focus is on aligning technical and policy aspects so that the developed IoT system is relevant and can be widely adopted. The results are expected to accelerate technology integration in the policies and operational practices of hazardous and toxic waste management.

4. Conclusions

This study conducts a systematic literature review on developing and implementing an Internet of Things (IoT)-based Hazardous and Toxic Materials waste monitoring system tailored for gold mining environments. By analyzing 35 publications from 2015 to 2025, the research consolidates various methods and findings related to system architecture, sensor technology, communication protocols, and implementation challenges. The results indicate that a three-layer architecture comprising a sensor layer for environmental data collection, a network layer for real-time transmission, and an application layer for data analysis and early warning is the most effective approach. LoRaWAN is identified as the optimal communication protocol for remote mining areas, while key sensors include pH meters, conductivity sensors, ion-selective electrodes for heavy metals, and cyanide sensors. Notably, integrating advanced artificial intelligence technologies enhances the system's ability to detect anomalies and predict potential pollution.

The study's conclusion emphasizes the need for a comprehensive framework that addresses significant challenges in implementing IoT-based waste monitoring systems in the mining sector. It advocates for increased collaboration among disciplines and countries to enhance technological development, particularly through long-term field validation tests and integration with big data-based decision support systems. The novelty of this research lies in its unification of various elements architecture, sensors, communication strategies, and proactive monitoring approaches marking a shift from reactive methods to more predictive, data-driven solutions. By addressing practical challenges and offering innovative recommendations, this study contributes meaningfully to the scientific literature and supports efforts to improve environmental protection in the gold mining industry.

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