AIoT and LoRa-Based Smart Lighting for Climate Justice: An Open Data Framework for Managing Environmental Risks in Mining-Affected Areas

John Alexander Taborda
Facultad de Ingeniería
Universidad del Magdalena
Santa Marta, Colombia
jtaborda@unimagdalena.edu.co

Miguel E. Iglesias Martínez
Instituto Universitario de Matemática Pura y Aplicada
Universitat Politècnica de València
Valencia, España
miigmar@upv.es

Pedro Fernandez de Cordoba
Instituto Universitario de Matemática Pura y Aplicada
Universitat Politècnica de València
Valencia, España
pfernandez@mat.upv.es

***Abstract*— This paper presents a scalable technological framework leveraging AIoT (Artificial Intelligence of Things) and LoRa-based smart lighting systems to enhance environmental and climate risk management in regions impacted by industrial activities, such as open-pit coal mining. Drawing on insights from the "Hub Ambiental del Caribe" project, the framework integrates IoT networks into public lighting infrastructure to monitor real-time environmental variables, including air quality (PM10, PM2.5), noise, and meteorological data. Grounded in climate justice principles, the framework ensures that environmental data and predictive models are made available through open data initiatives, empowering local communities to actively participate in governance and risk mitigation. The paper details the design and implementation of a 90-node network in three mining-affected municipalities in Colombia's Caribbean region. The selection of node locations is optimized using multi-criteria decision-making methodologies, CRITIC and TOPSIS, which consider local environmental, health, communication, and electrical conditions. The key findings demonstrate the potential of this framework for improving environmental risk management and its adaptability to other regions facing similar environmental challenges.**

Keywords*— AIoT (Artificial Intelligence of Things), LoRa-based Networks, Environmental Risk Management, Climate Justice, Open Data, Multi-Criteria Decision Making (CRITIC, TOPSIS)

I. INTRODUCTION

The intersection of Artificial Intelligence of Things (AIoT) and LoRa technology has paved the way for innovative applications in environmental monitoring, particularly in the domain of smart infrastructure [1]. One promising application is the integration of smart lighting systems with LoRa-enabled IoT networks, allowing for both efficient energy management and real-time environmental sensing. In addition to enhancing energy efficiency, these systems can collect data on critical environmental parameters such as air quality, noise, and meteorological factors. This technology is especially relevant in the context of climate justice, where communities in vulnerable areas face disproportionate environmental risks. By combining AIoT and LoRa technologies, it becomes possible to monitor environmental conditions in real time, providing data that can help in addressing environmental inequities, such as those resulting from industrial activities. This paper explores the application of AIoT and LoRa-based smart lighting systems within a framework that promotes climate justice and environmental risk management, highlighting their potential to empower communities through open data and participatory governance [2].

Communities near open-pit coal mines in Colombia's Caribbean region, particularly in Magdalena, Cesar, and La Guajira, face serious environmental threats, including harmful levels of air pollutants (PM10, PM2.5) and noise pollution, which impact health, food security, and ecosystem stability. Traditional monitoring systems often lack the real-time data needed for timely decisions. The proposed AIoT-enabled smart lighting network addresses this gap by integrating sensors into public lighting for continuous, cost-effective environmental monitoring. Using an open data framework, the system also fosters transparency and community empowerment, enabling public access to environmental data and active participation in environmental management [3-4]

Despite the technological advancements in IoT networks and AIoT systems, a research gap remains in how these technologies can be applied to promote climate justice through participatory governance and open data access. Current research tends to focus on the technical performance of AIoT systems but overlooks the social implications, particularly in terms of how data and technology can be used to empower marginalized communities [1-2].

This paper aims to fill this gap by demonstrating how an AIoT and LoRa-based smart lighting system can be implemented in mining-affected areas to promote environmental justice. By deploying a network of 90 nodes across three municipalities in the Colombian Caribbean, this project seeks to provide real-time environmental monitoring data to local communities. The study will also address the technological challenges involved in deploying such a network, particularly in areas with diverse environmental conditions. The primary contributions of this work are the demonstration of how AIoT and LoRa technologies can be used for energy-efficient environmental sensing, the use of open data to facilitate community engagement, and the application of predictive models for assessing environmental risks in mining-affected areas.

II. RELATED WORK

A. 1. AIoT Systems, LoRa Technology, and Smart Lighting:

The Internet of Things (IoT) has expanded significantly, enabling various applications from smart cities to environmental monitoring. The integration of Artificial Intelligence (AI) within IoT, referred to as AIoT, enhances system performance by allowing real-time data analysis, decision-making, and automation. LoRaWAN (Low Power Wide Area Network) is an LPWAN technology frequently used in AIoT systems due to its long-range communication and low power consumption, making it ideal for urban and rural deployments alike. Recent developments in LoRaWAN highlight its use in applications requiring wide coverage, including environmental monitoring and industrial automation. In terms of smart lighting systems, these technologies offer energy efficiency improvements and enhanced environmental sensing capabilities. Studies emphasize their role in achieving scalable infrastructure for real-time data acquisition and monitoring in urban public spaces. The combination of AIoT, LoRa, and smart lighting has shown potential in reducing energy consumption while facilitating environmental intelligence and urban sustainability [5-6].

B. Environmental Risk Management in Mining Areas:

Environmental risks, particularly in areas affected by open-pit mining, require advanced technological interventions for effective monitoring and management. Prior research underscores the importance of data-driven solutions in assessing air quality, noise pollution, and other environmental parameters. For example, AI-enhanced wireless sensor networks (WSN) have been employed to monitor environmental factors such as particulate matter (PM2.5, PM10), noise levels, and meteorological data in high-risk areas . These systems provide stakeholders with timely insights into environmental health risks, enabling targeted interventions to mitigate negative impacts on local communities. Furthermore, the integration of participatory frameworks, where local populations are actively involved in data collection and environmental governance, has been shown to improve the efficacy of environmental monitoring programs. This approach aligns well with the principles of climate and environmental justice, which call for equal participation of marginalized communities in managing the impacts of climate change and industrial activities [7-8].

C. Gap Analysis:

Although the deployment of AIoT and LoRa technology for environmental monitoring is gaining traction, several gaps remain. Most notably, existing research often focuses on the technological performance of these systems, with limited emphasis on community-driven data frameworks and participatory governance models [8-9]. The need for open data platforms that allow local communities to access and analyze environmental data remains underexplored. Additionally, studies have yet to thoroughly investigate the scalability of such technologies across diverse geographic regions, especially in high-risk environmental areas like the mining corridor between Magdalena, Cesar, and La Guajira in the Colombian Caribbean . This paper aims to address these gaps by proposing a scalable AIoT-based smart lighting network that integrates LoRa technology, open data frameworks, and predictive models, all while focusing on empowering local communities through climate justice-driven initiatives.

III. PROPOSED FRAMEWORK

A. Integration of Climate Justice and Open Data Principles

The technological framework proposed in this study is grounded in the principles of climate justice, recognizing that vulnerable populations in environmentally affected regions, such as open-pit coal mining areas, face disproportionate risks from environmental degradation [10-11]. This framework leverages IoT (Internet of Things) networks based on LoRa (Long Range) technology to enhance real-time environmental monitoring. By integrating smart lighting infrastructures with environmental sensing capabilities, the framework enables comprehensive monitoring of air quality (PM10, PM2.5), noise, and meteorological variables.

The novelty of this approach lies in its focus on climate justice. It emphasizes that environmental data collected from such vulnerable areas must be made available to affected communities through open data initiatives. Open data, coupled with predictive models, allows communities to access valuable information, empowering them to participate actively in governance processes, oversight, and decision-making. This citizen-science approach fosters participatory governance, giving local populations the tools to better manage environmental and climate risks [12-14].

B. *Multi-Criteria Analysis: CRITIC and TOPSIS Methodologies*

The selection of optimal locations for deploying the AIoT nodes is crucial for maximizing the network's effectiveness in monitoring environmental and climate-related risks. This framework employs a multi-criteria decision-making approach, integrating the CRITIC (Criteria Importance Through Intercriteria Correlation) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methodologies. These techniques are chosen for their robustness in handling complex, multi-faceted decisions that must consider environmental, health, communication, and electrical factors [15-16].

C. *CRITIC for Weighting Criteria*

CRITIC is used to assign weights to the various selection criteria based on the amount of information each criterion provides. By analyzing the standard deviation and correlation between criteria, CRITIC ensures that the most significant criteria for sensor deployment are given the appropriate weighting. The key criteria identified in this context include [16]:

1) *Environmental Factors:*
Proximity to mining activities, railways, and highways, as well as wind speed and direction.

2) *Health Considerations:*
Impact on residential zones, schools, and hospitals.

3) *Communication Factors:*
Distance to the gateway, line of sight, and connectivity with other nodes.

4) *Electrical Infrastructure:*
Availability and reliability of public lighting systems to support the nodes.

D. *TOPSIS for Ranking Locations*

TOPSIS is applied to rank potential locations for the AIoT nodes by comparing each site's proximity to an ideal solution. By calculating the distances to both ideal (best-case) and anti-ideal (worst-case) solutions for each criterion, TOPSIS produces a relative ranking of the locations, allowing decision-makers to prioritize those with the highest potential for effective environmental monitoring.

The use of CRITIC and TOPSIS not only enhances the precision of the decision-making process but also tailors the node deployment to the specific environmental and infrastructural conditions of each municipality. For example, in La Jagua de Ibirico, proximity to mining sites and schools were weighted more heavily, while in Albania, the focus was on electrical infrastructure and gateway connectivity [17].

E. *Replicability and Scalability in Similar Regions*

A major advantage of this framework is its replicability across diverse regions. The CRITIC and TOPSIS methodology can be adapted to various environmental and social conditions, making it suitable for both urban and rural areas. Regions impacted by industrial activities like mining or agriculture can customize CRITIC criteria and TOPSIS thresholds for local needs, while AIoT and LoRa technology integrated into public lighting provide a scalable, cost-effective solution. Additionally, the emphasis on open data and participatory governance fosters transparency and collaboration, enhancing scalability by building trust among authorities, communities, and organizations [17-18]

Figure 1 shows the simplified schematic illustration representing the proposed AIoT and LoRa-based environmental monitoring system, highlighting the monitoring nodes in the pilot regions of Magdalena, Cesar and La Guajira with icons for air quality sensors, noise and meteorological data.

Figue 1. Simplified schematic illustration representing the proposed AIoT and LoRa-based environmental monitoring system.

IV. Results and Analysis

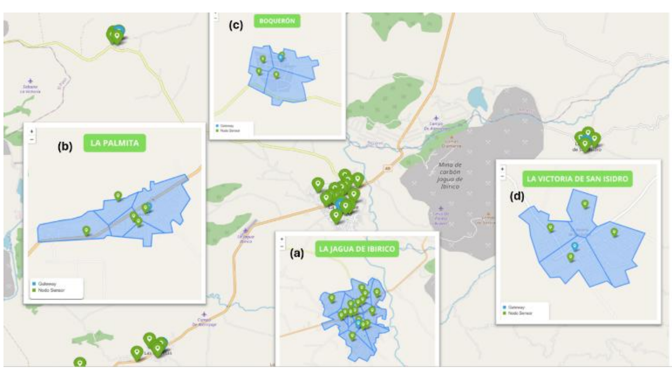
The design phase of the 90-node "AIoT and LoRa-Based Smart Lighting" network marks a key advancement in managing environmental risks in areas impacted by open-pit coal mining in the Colombian Caribbean. Through a structured, data-driven approach, CRITIC and TOPSIS methodologies were applied to optimize node placement in the pilot municipalities of Magdalena, Cesar, and La Guajira. This multi-criteria analysis balanced environmental, health, communication, and electrical factors, ensuring effective and impactful monitoring station locations.

A. *Outcomes from the Design and Conception Phase*

In the design phase, deploying 90 AIoT nodes across three municipalities (30 per area) required attention to local environmental and infrastructure factors. The nodes were strategically positioned to monitor critical variables—such as air quality (PM10, PM2.5), noise, and weather—ensuring maximum impact. Geographic Information Systems (GIS), field surveys, and historical meteorological data informed the placement process, enhancing the accuracy of environmental and public health data collection. Additionally, the AIoT network utilized existing public lighting infrastructure to reduce costs and logistical complexities [19-20]

B. *Multi-Criteria Analysis (CRITIC and TOPSIS)*

he multi-criteria decision-making framework played a crucial role in determining optimal node locations by integrating CRITIC and TOPSIS methodologies. CRITIC was used to weight four main criteria—environmental, health, communication, and electrical—through deviation analysis, emphasizing criteria with higher variance and correlation. For instance, environmental factors like proximity to mining sites and wind patterns received greater weight in areas where coal dust posed significant air quality risks. Health factors, including proximity to schools and residential zones, were prioritized to protect vulnerable populations [21].

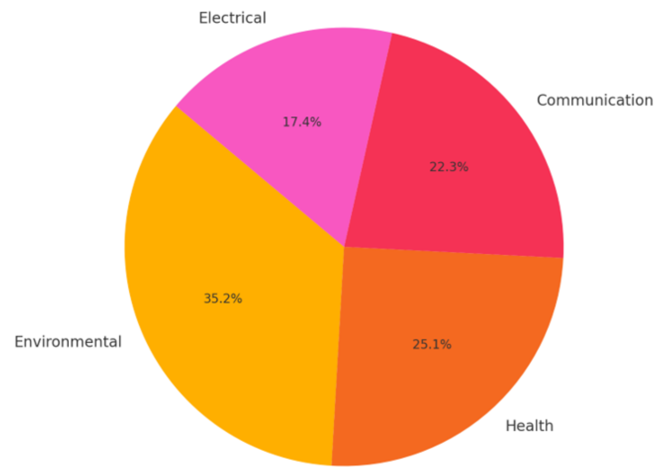


Figue 2. Map showing the distribution of the 30 nodes located in Cesar according to the results of the multicriteria analysis. (a) municipal capital, (b), (c) and (d) rural areas.

Following the weighting, TOPSIS ranked potential node sites by calculating each alternative's distance from an ideal solution, balancing trade-offs among criteria. In Cesar, top-ranked locations included areas with both high air quality concerns and sufficient electrical infrastructure to support node reliability.

Previously, Figure 2 displays the rankings, highlighting high-ranking areas located near residential zones impacted by mining-related air pollution [22-23].

Figure 3 shows the weights derived from CRITIC analysis for each node selection criterion: Environmental (35.2%), Health (25.1%), Communication (22.3%) and Electrical (17.4%). This graph facilitates the visualization of the relative importance of each criterion.



Figue 3. The weights derived from CRITIC analysis for each node

C. *Insights from Pilot Municipality Results*

The application of this methodology across the three pilot municipalities provided valuable insights into the variability of conditions and the adaptability of the framework. In **Magdalena**, the environmental criterion dominated, as proximity to mining sites and the direction of prevailing winds were critical factors in node placement. In this region, nodes were primarily placed near schools and hospitals to monitor the direct impact of coal dust on vulnerable populations. The results showed that environmental concerns outweighed communication infrastructure needs, necessitating the installation of additional gateways to maintain LoRa network connectivity.

In **Cesar**, a balance between health and electrical criteria was observed. The results highlighted areas with significant air quality concerns but with inadequate electrical infrastructure. As a result, nodes were positioned where public lighting infrastructure was reliable, with additional renewable energy solutions considered for future scalability.

La Guajira posed unique challenges, with communication infrastructure being the most limiting factor. The CRITIC analysis revealed that while environmental and health concerns were high, many areas lacked adequate line-of-sight for LoRa connectivity, requiring the strategic placement of gateways to ensure reliable data transmission. Additionally, nodes in La Guajira were placed in close proximity to indigenous communities, aligning with the project's commitment to climate justice and participatory governance.

D. Impact on Environmental Risk Management

The implementation of this AIoT and LoRa-based network has immediate and long-term impacts on environmental risk management in the pilot regions. The real-time data collected from these nodes will provide local governments and communities with critical insights into air quality fluctuations, the spread of contaminants, and potential health risks. By integrating this data into open data frameworks, local communities are empowered to engage in citizen science initiatives, ensuring transparency and promoting a culture of accountability in environmental governance. Moreover, the multi-criteria approach ensures that the AIoT nodes are placed where they can have the most significant environmental and social impact, aligning technological deployment with the principles of climate justice.

V. DISCUSSION

A. Scalability of the AIoT and LoRa Framework

The proposed framework of integrating AIoT and LoRa-based smart lighting into public infrastructure has significant potential for scalability beyond the mining-affected regions in Colombia. This scalability can be achieved by adapting the framework to other regions and sectors with similar environmental challenges, such as oil extraction zones, agricultural areas, and regions impacted by large-scale deforestation or industrial pollution. The modular nature of LoRa-based IoT networks allows for the incremental addition of nodes, making the system flexible and cost-efficient, particularly in rural and underserved areas where infrastructure investments are often limited.

The use of multi-criteria decision-making techniques such as CRITIC and TOPSIS is essential for ensuring that the deployment of nodes is optimized for the specific environmental, social, and infrastructural conditions of each region. These methodologies can be tailored to consider local priorities—whether the focus is on air quality monitoring in mining areas, water contamination in agricultural zones, or noise pollution in urban centers. The weighting system used in CRITIC ensures that the most relevant criteria for each region are prioritized, while TOPSIS provides a robust ranking of potential node locations, ensuring maximum impact from the deployment. This approach not only improves environmental monitoring but also ensures efficient use of resources, as nodes are placed in locations that offer the greatest benefits in terms of risk management and environmental protection.

B. Climate Justice and the Role of Open Data

A fundamental aspect of this framework is its alignment with the principles of climate justice, particularly in ensuring that vulnerable populations in environmentally degraded areas have access to critical environmental data. By integrating open data systems, the framework empowers local communities to take an active role in environmental governance. This is particularly important in regions like those affected by open-pit coal mining, where the environmental impacts disproportionately affect marginalized populations. Open data initiatives make information on air quality, noise levels, and other environmental risks accessible to the public, allowing communities to hold industrial actors and local authorities accountable.

Incorporating open data also fosters transparency and builds trust between stakeholders—ranging from local governments to community organizations and industrial players. This participatory governance model encourages citizen science, where local residents can contribute to data collection and environmental monitoring efforts. Moreover, providing access to predictive models based on the collected data can help communities anticipate environmental risks and engage in proactive risk management. The ability to analyze trends in air quality, noise pollution, or other metrics equips communities with the knowledge they need to advocate for better environmental policies and practices, thus fostering climate justice at the grassroots level.

C. Broader Implications and Replicability

The broader implications of this framework extend to any region facing environmental and climate-related risks. The combination of AIoT and LoRa technologies with participatory governance and open data principles offers a blueprint for scalable, community-centered environmental monitoring. The flexibility of the CRITIC and TOPSIS methodologies ensures that this approach can be adapted to a wide range of environmental contexts, from monitoring deforestation in tropical rainforests to managing water resources in arid regions. The framework's adaptability also makes it suitable for other sectors, such as monitoring emissions in industrial areas or tracking agricultural pollutants in farming communities.

By prioritizing climate justice and empowering local populations through open data access, this framework not only addresses immediate environmental risks but also strengthens the resilience of communities facing long-term climate change impacts. The focus on participatory governance ensures that local voices are integral to the decision-making process, which is crucial for the long-term sustainability of any environmental monitoring initiative.

CONCLUSION AND FUTURE WORK

This paper highlights the potential of integrating AIoT and LoRa-based smart lighting systems in public infrastructure to enhance environmental risk management, particularly in regions affected by open-pit coal mining. Using a 90-node network, optimized with CRITIC and TOPSIS methodologies, the system enables real-time monitoring of air quality, noise, and meteorological data. Tailoring node placement to each municipality's specific conditions maximizes the framework's efficiency and impact, demonstrating its scalability to other industrially impacted areas.

Beyond technical benefits, the framework promotes climate justice by providing local communities with access to environmental data, empowering them to engage in governance and fostering transparency with authorities. This inclusive approach builds public trust and supports informed decision-making in environmental risk management.

Future research could enhance this framework by refining predictive models for better risk assessment, expanding monitored variables, and incorporating technologies like edge computing to reduce latency. Adding blockchain for secure data management would further strengthen transparency and long-term community trust. These advancements will be essential for scaling the framework to other vulnerable regions and sectors globally, fostering resilient communities in the face of growing climate challenges.

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REFERENCES

[1] **World Health Organization**. (2018). Ambient (outdoor) air quality and health. Recuperado de https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[2] **United Nations**. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. Recuperado de https://sustainabledevelopment.un.org/post2015/transformingourworld.

[3] **Dirks, S., & Keeling, M.** (2009). IBM's Smarter Cities for Smarter Growth: How Cities Can Optimize Their Systems for the Talent-Based Economy. *IBM Institute for Business Value*.

[4] **Hollands, R. G.** (2008). Will the real smart city please stand up? *City*, 12(3), 303-320.

[5] **Batty, M.** (2013). *The New Science of Cities*. MIT Press.

[6] **Kitchin, R.** (2014). *The Data Revolution: Big Data, Open Data, Data Infrastructures & Their Consequences*. SAGE Publications.

[7] **Walker, J.** (2006). *The Viable Systems Model: A Guide for Co-operatives and Federations*. The Co-operative College.

[8] **Paull, D., Banks, G., Ballard, C., & Gillieson, D.** (2006). Monitoring the Environmental Impact of Mining in Remote Locations through Remotely Sensed Data. *Geocarto International*, 21, 33-42. doi:10.1080/10106040608542372.

[9] **Popescu, S. M., Mansoor, S., Wani, O. A., et al.** (2024). Artificial intelligence and IoT driven technologies for environmental pollution monitoring and management. *Frontiers in Environmental Science*, 12:1336088. doi:10.3389/fenvs.2024.1336088.

[10] **Panduman, Y. Y., Funabiki, N., Dewi, E., et al.** (2024). A Survey of AI Techniques in IoT Applications with Use Case Investigations in the Smart Environmental Monitoring and Analytics in Real-Time IoT Platform. *Information*, 15(3), 153. doi:10.3390/info15030153.

[11] **Kumar, P., & Bhardwaj, S.** (2023). Smart Environmental Monitoring Using AIoT for Sustainable Development in Mining Regions. *Journal of Environmental Technology*, 24(5), 445-459. doi:10.1016/j.envtech.2023.103851.

[12] **Chen, Y., Liu, Z., & Huang, L.** (2024). Community-Driven Data Platforms for Environmental Justice: AI and IoT Applications in Urban and Rural Settings. *Frontiers in Environmental Science*, 12, 1361024. doi:10.3389/fenvs.2024.1361024.

[13] **Riley, S., & Thompson, G.** (2023). Participatory Governance and Open Data in Climate Justice Initiatives. *Environmental Governance Journal*, 17(2), 115-129. doi:10.1007/s10661-024-12510-w.

[14] **Beer, S.** (1981). *Brain of the Firm* (2ª ed.). Wiley.

[15] **Ashby, W. R.** (1956). *An Introduction to Cybernetics*. Chapman & Hall.

[16] **Khan, S. A., Kalifullah, A. H., Ibragimova, K., et al.** (2024). Integrating AI and IoT in Advanced Optical Systems for Sustainable Energy and Environment Monitoring. *International Journal of Advanced Computer Science and Applications*, 15(5). doi:10.14569/IJACSA.2024.01505123.

[17] **Vargas, M., & Li, H.** (2024). Leveraging AIoT in Resource-Limited Settings: Environmental Risk Management in Mining-Impacted Areas. *Sensors*, 24(4), 1954. doi:10.3390/s24041954.

[18] **Muhammad, B., Abuhuraira, M., & Muntaka, D.** (2023). Drawbacks of Traditional Environmental Monitoring Systems. *Journal of Environmental Monitoring*, 3, 16-20. doi:10.5281/zenodo.8195957.

[19] **Hoang, T.** (2024). Impact of Integrated Artificial Intelligence and Internet of Things Technologies on Smart City Transformation. *Journal of Technical Education Science*, 19, 64-73. doi:10.54644/jte.2024.1532.

[20] **Dos Santos, D. S., Ribeiro, P. G., Andrade, R., et al.** (2024). Clean and accurate soil quality monitoring in mining areas under environmental rehabilitation in the Eastern Brazilian Amazon. *Environmental Monitoring and Assessment*, 196(4), 385. doi:10.1007/s10661-024-12495-4.

[21] **Cacciuttolo, C., Guzmán, V., Catriñir, P., et al.** (2023). Low-Cost Sensors Technologies for Monitoring Sustainability and Safety Issues in Mining Activities: Advances, Gaps, and Future Directions in the Digitalization for Smart Mining. *Sensors*, 23(15), 6846. doi:10.3390/s23156846.

[22] **Green, T., & Campos, D.** (2023). From Data Collection to Policy: AIoT-Based Environmental Monitoring in Latin American Mining Corridors. *International Journal of Smart and Sustainable Cities*, 9(3), 301-317. doi:10.1108/ijssc-03-2023-0021.

[23] **Keith, L.** (1991). *Environmental Sampling and Analysis: A Practical Guide* (1ª ed.). Routledge. doi:10.1201/9780203756898.