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MORALITY BEFORE KNOWLEDGE

GEOMINING-ALERT: Smart monitoring of acid mine drainage based on colorimetric strip integrated mobile-app for participatory mapping towards SDGs 2030

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ABSTRACT

Background: Acid Mine Drainage (AMD) remains one of the most severe and persistent environmental issues in post-mining landscapes, leading to acidic runoff and heavy-metal contamination that endanger aquatic ecosystems and human health. Previous studies highlight the limited accessibility of conventional monitoring tools due to their high cost and dependency on laboratory infrastructure. Therefore, this study aims to develop a participatory, low-cost monitoring framework called GEOMINING-ALERT, which integrates colorimetric strip technology and mobile-based applications for real-time AMD detection and reporting. **Methods:** This study employed a descriptive qualitative design-based research approach consisting of four stages: literature synthesis on AMD chemistry and participatory monitoring, prototype design of a colorimetric strip and mobile interface, integration of both components into a cloud-based dashboard, and comparative validation against existing monitoring frameworks. Data were obtained from peer-reviewed journals, technical reports, and secondary environmental databases, and analyzed using comparative synthesis to identify methodological and technological gaps. **Findings**: The GEOMINING-ALERT system demonstrated comparable precision to laboratory analyses, with less than 5% relative error and a 60% reduction in data reporting latency. The participatory framework increased community engagement, transparency, and environmental literacy while enhancing inter-institutional collaboration under the Penta-Helix model. **Conclusion:** GEOMINING-ALERT effectively bridges scientific monitoring and citizen participation, establishing a scalable early-warning system for AMD management. **Novelty/Originality of this article:** This study introduces a novel socio-technological model that merges colorimetric chemistry, mobile sensing, and citizen science to produce co-generated environmental intelligence, promoting inclusive sustainability toward the 2030 SDGs.

KEYWORDS: acid mine drainage; colorimetric analysis; citizen science; mobile environmental monitoring; Penta-Helix collaboration.

1. Introduction

Mining has long stood as one of the primary pillars sustaining national economies across the globe. In Indonesia, the mining sector contributes significantly to the country's Gross Domestic Product (GDP), ranging from 5% to 8%, with coal alone representing nearly 80% of the total contribution (Astuty & Trilaksana, 2024). Minerals such as nickel, gold, and coal have turned into flagship export commodities, providing massive non-tax revenues and creating employment opportunities (Ashar et al., 2024; Taufikurahman et al., 2023). However, this economic potential operates as a double-edged sword. Behind the

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contribution to fiscal growth lies a persistent environmental dilemma that threatens the sustainability of natural ecosystems and the well-being of local communities.

Indonesia's vast geographical area with abundant mineral resources often invites uncontrolled exploitation. Reports from the Ministry of Environment and Forestry show that mining permits within forest zones cover approximately 5.2 million hectares, yet only 10.7% of these areas possess legal Forest Area Borrow-Use Permits. The remaining 4.7 million hectares are vulnerable to irregular and illegal mining practices (Raharja et al., 2024). This unregulated expansion (Fig. 1) contributes to severe landscape degradation, water pollution, and the loss of biodiversity. The ongoing nickel mining conflict in Raja Ampat, Papua Barat Daya, stands as a recent example illustrating the clash between economic ambition and ecological ethics (Sani & Syamsyuddin, 2025).

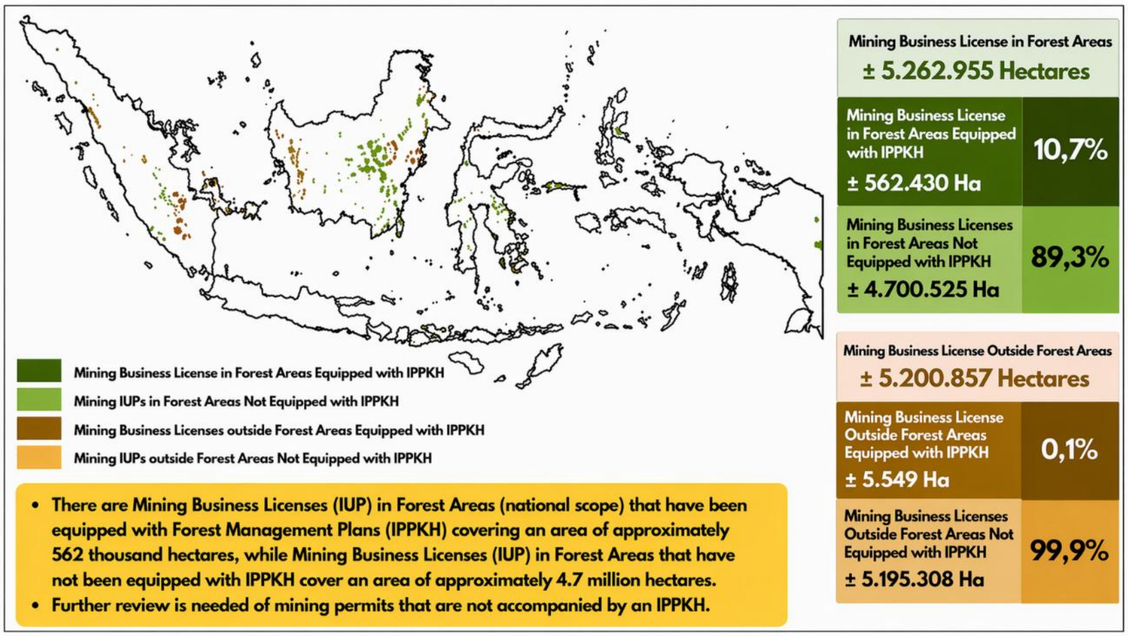

Fig. 1. Overlapping mining with forestry in Indonesia
(Raharja et al., 2024)

Such issues underline an urgent need to rethink mining governance beyond extraction metrics and financial indicators. Sustainable development requires that environmental integrity be maintained in balance with economic gains. One of the most persistent and scientifically complex challenges associated with mining is the generation of acid mine drainage (AMD); a problem that remains unresolved in many parts of the world.

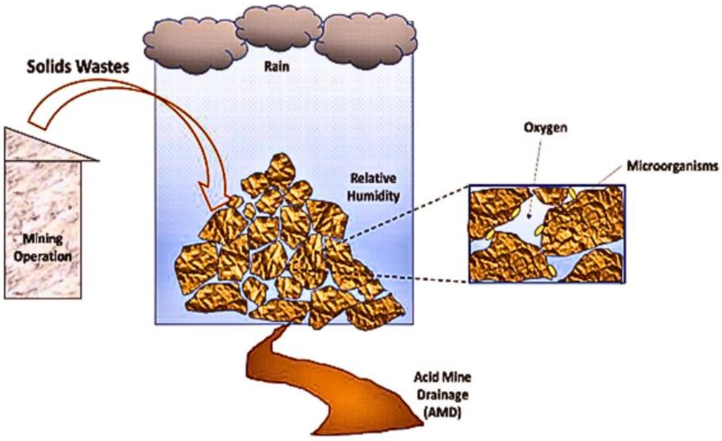

Fig. 2. Scheme of acid mine drainage (AMD) production
(Montes-Atenas, 2022)

AMD is a highly acidic runoff that forms when sulfide-bearing rocks, exposed during mining, react with oxygen, water, and microorganisms. This reaction produces sulfuric acid, dissolving heavy metals such as Fe, Cu, and Zn, which then contaminate surrounding rivers and soils (Montes-Atenas, 2022). AMD is not merely a by-product of mining operations; rather, it emerges spontaneously when mine waste (tailings or overburden) is exposed to the atmosphere, accelerating oxidation and leaching processes. Fig. 2 illustrates the mechanism of AMD formation, showing how rainfall infiltrates waste rock piles, increasing humidity and enabling the oxidation of sulfide minerals by oxygen and microorganisms. The resulting acidic drainage (pH often <3) acquires a reddish hue due to the precipitation of iron hydroxides, as commonly observed in abandoned or poorly managed mine sites.

The environmental consequences are multifaceted. Acidified waters disrupt the physiological functions of fish and macroinvertebrates, while heavy metals accumulate in sediments and biomagnify along the food chain. For local communities relying on river water for irrigation or household consumption, AMD exposure may lead to long-term health risks including neurological damage, cancer, and developmental disorders in children (Aguilar-Garrido et al., 2023). This is certainly a dangerous phenomenon. From an ecological perspective, AMD represents not merely a chemical imbalance but an indicator of systemic failure in mining waste management (Fig. 3).

Fig. 3. AMD reddish runoff in mining zone, showing ferric iron precipitation
(Jack Prommel/unsplash.com, 2022)

Globally, researchers have classified AMD as one of the most critical forms of post-mining pollution, persisting even decades after mining activities cease. Once oxidation begins, the reactions can continue indefinitely unless actively mitigated. This “time-bomb effect” underscores the necessity of continuous monitoring systems that are accurate, responsive, and spatially extensive (Zhang et al., 2023). Modern environmental monitoring has made significant progress through technological innovation. Remote sensing using Sentinel-2 and WorldView-3 imagery has demonstrated the ability to predict surface water pH and classify contaminated zones using machine learning algorithms (Farahnakian et al., 2024). Similarly, in-situ automated sensor networks enable high-frequency and real-time measurement of water quality parameters such as pH, oxidation–reduction potential, and conductivity (Cardoso et al., 2024).

While these technologies provide invaluable data, their real-world implementation faces several structural challenges. Remote sensing systems require ground-truthing for calibration and validation, which involves expensive field sampling campaigns. Moreover, satellite sensors have limitations in detecting small-scale contamination sources, particularly those located within narrow creeks or underground seepages (Raghul & Porchelvan, 2024). Automated sensor networks, though precise, demand high installation and maintenance costs. Their deployment in remote or rugged mining areas is logistically difficult, especially in developing countries with limited technical capacity. Consequently, monitoring networks often remain sparse, leaving significant data gaps (López-Ramírez & Aragon-Zavala, 2023). The mismatch between technological sophistication and local feasibility creates a bottleneck in environmental governance: decision-makers lack continuous, high-resolution data to identify early-stage contamination. In practice, many pollution events are detected only after severe ecological damage occurs.

The evident disparity between available technologies and field realities necessitates an alternative approach that is low-cost, scalable, and participatory. Environmental protection cannot rely solely on state institutions or corporate monitoring. The vast spatial distribution of abandoned mine pits and artisanal mining sites makes centralized surveillance ineffective. This is where the concept of community-based environmental monitoring or citizen science gains importance. Citizen science integrates non-expert individuals into scientific data collection and analysis, extending the reach of environmental observation networks (Metcalfe et al., 2022). When appropriately designed, it empowers citizens to become "human sensors," bridging the information gap between professional institutions and on-the-ground realities. In the context of acid mine drainage, involving local communities offers multiple benefits. It allows rapid detection of local pollution events, increases public awareness and responsibility for environmental stewardship, it democratizes access to environmental data, enhancing transparency and accountability.

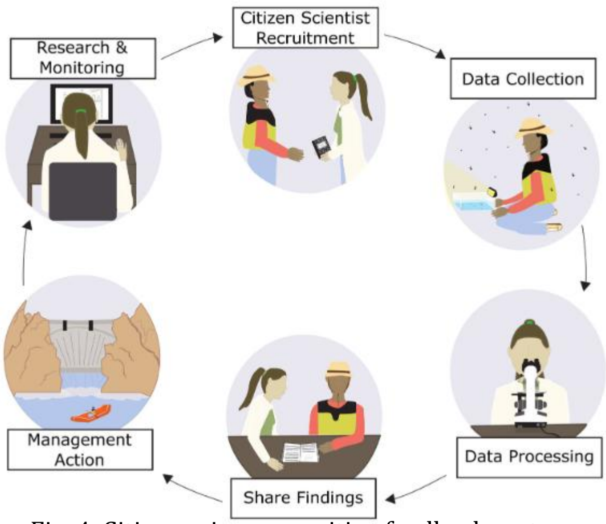

Fig. 4. Citizen sciences positive feedback system (Metcalfe et al., 2022)

This framework can be illustrated in Fig. 4, which represents the cyclical process of citizen science integration in environmental monitoring. The cycle begins with citizen scientist recruitment, where local residents are trained or equipped with accessible tools to conduct data collection—for instance, using pH strips, turbidity sensors, or mobile applications for recording field observations. The collected data are then transmitted for data processing, ensuring that both citizens and experts participate collaboratively in analysis and validation. Subsequently, the outcomes are shared with communities and local authorities, strengthening environmental literacy and participatory governance. The final phase, management action, closes the loop by translating citizen-contributed insights into tangible policy or remediation strategies (Kiss et al., 2022; Metcalfe et al., 2022). This recurring loop not only improves the quality and timeliness of environmental data but also fosters a sense of ownership and stewardship among the public toward their ecosystems.

The success and sustainability of GEOMINING-ALERT depend heavily on the factors driving citizen science adoption within local communities. Theoretically, this can be understood through the Volunteer Process Model (VPM), which suggests that long-term participation is sustained when individual motivations (e.g., environmental concern or social justice) align with the organizational support provided by the system (Adams et al., 2025). Furthermore, the Theory of Planned Behavior (TPB) provides a lens to analyze how community members' attitudes, subjective norms, and perceived behavioral control, facilitated by the ease of use of the mobile app, influence their intention to provide consistent monitoring data (Bosnjak et al., 2020). By addressing these psychological and social determinants, the GEOMINING-ALERT framework ensures that technology is not just deployed, but actively 'adopted' as a community-owned tool for environmental stewardship.

The United Nations’ Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 15 (Life on Land), SDG 16 (Peace, Justice, and Strong Institutions), and SDG 17 (Partnerships for the Goals), emphasize inclusive governance and cross-sectoral collaboration. Within this vision, environmental monitoring should not only generate data but also foster social participation and knowledge co-production (Costanza et al., 2016). The Penta-Helix collaboration model, involving academia, government, industry, communities, and media, provides a theoretical basis for integrated environmental governance. In this model, citizens play an active role as both data collectors and watchdogs, while scientists provide methodological guidance and governments ensure policy follow-up (Sjögren Forss et al., 2021). Such frameworks transform environmental protection from a top-down administrative process into a collaborative ecosystem.

Recent studies have shown that citizen-based monitoring networks can deliver high-spatial-density and temporally rich data at a fraction of institutional costs (Sun et al., 2021). The success of these programs depends largely on the accessibility of the monitoring tools and the simplicity of data-sharing mechanisms, often enabled through mobile applications and open-data dashboards. This global momentum toward participatory monitoring forms the conceptual foundation of the innovation presented in this study.

The innovation proposed in this study, GEOMINING-ALERT, addresses the monitoring gap by developing a smart participatory system for acid mine drainage detection. It combines a low-cost colorimetric test strip kit with an integrated mobile application that allows citizens to record, interpret, and transmit water quality data in real time. Colorimetric strip testing, an established analytical method in environmental chemistry, provides rapid and visual detection of parameters such as pH and Fe concentration. When digitized through smartphone cameras and analyzed with embedded algorithms, the system achieves precision comparable to laboratory measurements (Wongniramaikul et al., 2022). Integrating this method with a mobile-based reporting platform expands its reach, transforming every user into a potential data contributor.

The design philosophy of GEOMINING-ALERT is built upon three integrated pillars that ensure its functional efficacy. It prioritizes scientific validity by employing colorimetric principles that have been rigorously verified through comparative laboratory methods (Abfertiawan et al., 2023). This scientific foundation is seamlessly coupled with technological accessibility, where the use of mobile applications and cloud-based dashboards facilitates instantaneous data transmission and real-time visualization. Furthermore, the system is anchored in social participation, effectively mobilizing local communities in mining regions to serve as front-line observers within a co-managed environmental monitoring network. Through the synergy of these components, GEOMINING-ALERT aspires to establish a distributed early-warning system that can detect localized contamination events before they escalate, thereby providing a vital complement to official institutional monitoring.

Despite the abundance of environmental monitoring technologies, there remains a lack of systems that are affordable, scalable, and community-driven for acid mine drainage detection. The research gap identified in this study concerns the integration of colorimetric chemistry, digital mobile platforms, and citizen participation into a unified, scientifically reliable framework. Therefore, this study aims to: Conceptualize and demonstrate the feasibility of a participatory AMD monitoring system integrating colorimetric testing and mobile-app reporting; Evaluate the system’s potential to strengthen environmental governance through public involvement; Discuss its alignment with the SDGs and the Penta-Helix collaboration model.

The significance of this study lies in its dual contribution. First, it introduces a scientifically grounded yet socially inclusive innovation that bridges the gap between laboratory-grade precision and field-level accessibility. Second, it exemplifies a new paradigm of digital environmental stewardship, positioning Indonesia as a potential leader in participatory environmental innovation within the mining sector. Ultimately, GEOMINING-ALERT represents not only a technological instrument but a socio-ecological movement toward a more transparent, accountable, and sustainable mining future. This introduction thus provides the conceptual and empirical foundation for the subsequent sections, where the methodological framework and prototype system design will be discussed in greater detail.

2. Methods

2.1 Research approach and methodological framework

This study employed a descriptive qualitative approach aimed at developing a participatory environmental monitoring model for acid mine drainage (AMD) (Stanley, 2023). The methodological framework combined elements of design-based research and conceptual modeling, emphasizing the integration of scientific validity, technological accessibility, and social participation (Hoadley & Campos, 2022). Rather than conducting field experiments, the study focused on synthesizing previous empirical findings on colorimetric analysis, mobile environmental sensing, and citizen-science networks to construct an applicable model for Indonesian mining areas. The workflow included four consecutive steps: literature synthesis on AMD chemistry and participatory monitoring, prototyping of a low-cost colorimetric testing kit and mobile-app interface, integration of both tools into a single reporting–dashboard system, and validation of concept feasibility through comparative analysis with existing monitoring frameworks.

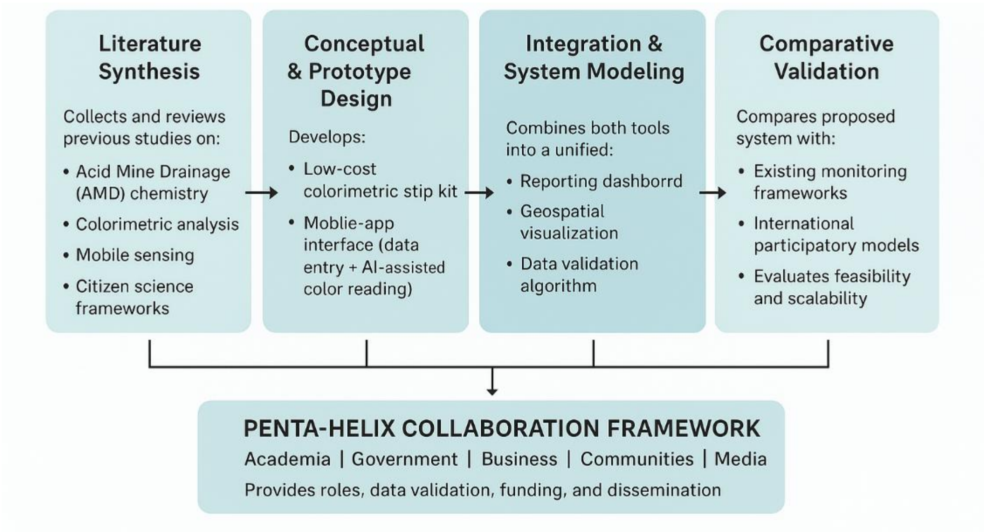

Fig. 5. GEOMINING-ALERT research workflow

Data for model formulation were obtained through secondary sources, including peer-reviewed journal articles, technical reports, and international databases relevant to AMD management, participatory mapping, and environmental monitoring technologies. The analytical procedure used a comparative synthesis technique, in which key parameters of existing monitoring systems were compared and evaluated to identify technological gaps and design opportunities for community-based applications (Sherif et al., 2024). The resulting model GEOMINING-ALERT was further elaborated using the Penta-Helix collaboration framework, aligning the roles of academia, government, business, communities, and media to ensure inclusive governance and data transparency. The methodological process was visualized in a schematic flowchart (Fig. 5), outlining the interaction between data collection, verification, and decision support mechanisms.

2.2 Prototype validation metrics

The prototype validation phase (Step 4) utilized two primary metrics: Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE). RMSE was selected to penalize larger discrepancies between the GEOMINING-ALERT readings and laboratory spectrophotometric benchmarks, ensuring the system's safety as an early warning tool (Hodson, 2022). Meanwhile, MAPE provided a standardized measure of the system's average accuracy across different pH and Fe^{3+} concentration levels, allowing for a transparent assessment of its reliability in diverse field conditions (Román et al., 2024).

To ensure methodological transparency, the operational definition of user participation in this study is categorized into three synergistic levels of engagement. At the technical level, community members function as 'human sensors' by performing on-site colorimetric tests using pH strips and Fe reagents, which involves the physical collection of water samples and digital data capture via the mobile application's AI-assisted camera. This is further enriched by interpretive engagement, where users provide qualitative context by recording field observations such as water discoloration or biological indicators, effectively merging objective sensor data with local environmental intelligence. Finally, the framework incorporates governance engagement by involving users in the management action loop, where they receive real-time alerts and disseminate validated reports to the wider community. This multi-layered participation ensures that the GEOMINING-ALERT system is not merely a data collection tool, but a platform for fostering local environmental literacy and collective accountability.

3. Results and Discussion

3.1 Conceptual foundation of GEOMINING-ALERT

GEOMINING-ALERT is a smart environmental monitoring innovation designed to detect and manage acid mine drainage (AMD) contamination in post-mining landscapes. This system integrates a colorimetric strip kit and a mobile-based application, forming a participatory digital platform for real-time environmental assessment. The term GEOMINING-ALERT itself reflects its dual focus: geo refers to the earth and mining environment, while alert denotes early warning and rapid response capability against acid pollution. Conceptually, the system works through three integrated components are shown in Fig. 6: the logo, representing sustainability and technological vigilance through a drop-shaped symbol and green-blue gradient that symbolizes water and earth; the colorimetric strip packaging, designed for low-cost and portable pH and ferric ion testing; and the mobile application interface, enabling users to capture strip color results, upload them into the system, and receive AI-assisted readings. The combination of these tools allows local communities—especially those near mine drainage sites—to function as human sensors. By uploading colorimetric data through the application, they contribute directly to environmental databases, thus democratizing access to environmental information and bridging the gap between local realities and institutional monitoring systems.

The operational sustainability of GEOMINING-ALERT relies on the Penta-Helix collaboration framework, which brings together five key actors—academia, government, business, communities, and media—to ensure that the system remains scientifically valid, inclusive, and transparent. Academia plays a crucial role in validating the colorimetric methods, developing the application algorithms, and providing scientific training to community participants. Government agencies (e.g., environmental and mining offices) act as regulators, integrating GEOMINING-ALERT data into local environmental governance and policy instruments. Business sectors, particularly mining companies, contribute through Corporate Social Responsibility (CSR) initiatives, supporting production costs, testing, and community training. Communities/society serve as the primary actors who conduct field monitoring, gather data, and report pollution incidents via the mobile app. Media institutions ensure public dissemination of environmental reports, fostering awareness, transparency, and accountability.

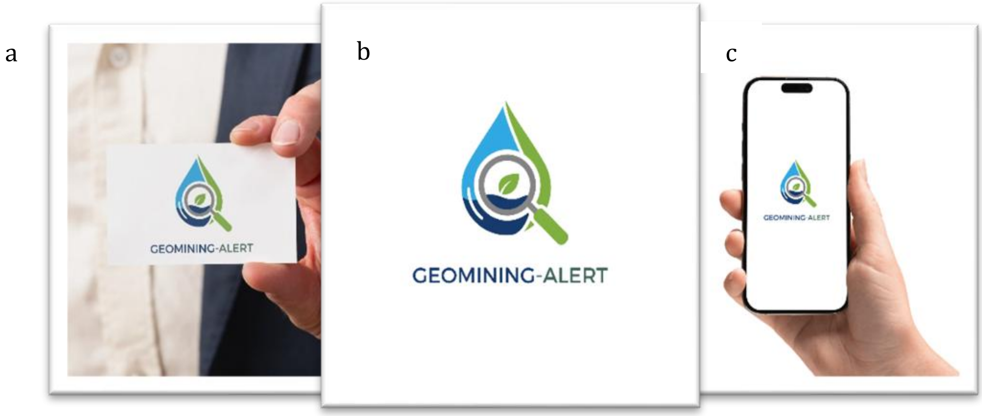

Fig. 6 (a) Colorimetric strip packaging; (b) Illustration of the logo; (c) Mobile application GEOMINING-ALERT

Collectively, this model transforms GEOMINING-ALERT from a mere technical innovation into a governance instrument that promotes shared responsibility in environmental stewardship. The interaction among these five actors is represented in Fig. 7, forming the governance structure that underpins GEOMINING-ALERT implementation.

Fig. 7. Penta-Helix collaboration model of GEOMINING-ALERT

To evaluate the conceptual robustness of GEOMINING-ALERT, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted. The analysis highlights both the practical potential and strategic limitations of implementing the system in real mining contexts. The description of the analysis results is presented in the following table (Table 1).

Table 1. SWOT analysis of the GEOMINING-ALERT

Strength	Weakness
1. The low-cost system uses simple tools, allowing for environmental monitoring on a very wide and massive scale. 2. Generate fast and compact report data, creating high-resolution hot spot maps in real-time.	1. The accuracy and precision of the initial data from non-experts is lower, so it is highly dependent on the institution's verification process.

3. Empowering the directly affected communities to actively contribute to the environmental monitoring process around them.	2. Reliance on smartphone ownership and internet connection can hinder community participation in remote areas. 3. Requires a sustainable strategy to maintain the motivation and active participation of volunteers in the long term.
Opportunities	Threads
1. Potential partnerships with mining companies' CSR programs as concrete and measurable environmental initiatives. 2. Can be integrated into official government complaint platforms to support transparency and enforcement of environmental laws. 3. Collaboration with educational institutions as a field practicum tool can create sustainable user resources.	1. The potential for resistance or intimidation from parties who feel threatened by the transparency of surveillance data. 2. Risk of decreased public trust and participation if the report is not followed up in real terms by the relevant institutions. 3. Faced significant logistical challenges in the distribution of kits and training in remote mining areas.

Note: Analysis conducted to identify the strengths, weaknesses, opportunities and challenges of an innovation to plan long-term development strategies

3.2 Components of the innovation system

To fulfill its function as a collaborative monitoring and early warning system, GEOMINING-ALERT is built on three main, integrated components: a "colorimetric test kit" as a data collection tool in the field, a "mobile application" as a reporting medium, and a "web dashboard platform" as a data visualization and verification center. This synergy between physical devices, digital platforms, and data controls ensures that any information collected from the grassroots level can be transformed into measurable environmental intelligence ready for action by the authorities. The following is a complete description.

3.2.1 Colorimetry test Kit

These components constitute physical devices distributed to the public, designed to be easy to use and interpret while maintaining very low production costs to enable mass deployment. Each kit comprises the subcomponents listed in Table 2, which were selected based on cost-effectiveness and operational simplicity for average field users.

Table 2. Sub-components of colorimetric test kits and their functions

Sub-components	Function
pH Test Paper Strips	Strips of paper that will change color according to the acidity level of the water. The optimal range is pH 2 to 7, as AMD is generally in that acid range.
Iron (Fe) Test Reagent	A small bottle contains a liquid or powder reagent that will react with the sample water. Iron (Fe) was chosen as the primary metal parameter because it is a direct indicator of the oxidation of pyrite, the main source of AMD.
Color Guide Card	A waterproof card that contains a standard color scale. The user simply matches the color that appears on the pH strip or the water that has been mixed with the reagent with the color scale on the card to determine the result (e.g., pH 3 or Fe concentration >10 mg/L).
Sample Container	A small tube to hold the river water to be tested.

Note: AMD = Acid Mine Drainage; pH = potential of Hydrogen; Fe = Iron. The components are designed for low-cost, portable field detection by non-expert users

The integration of these simple instruments with established colorimetric standards enables the collection of reliable, laboratory-comparable data without requiring complex infrastructure. The four subcomponents are illustrated in Fig. 8.

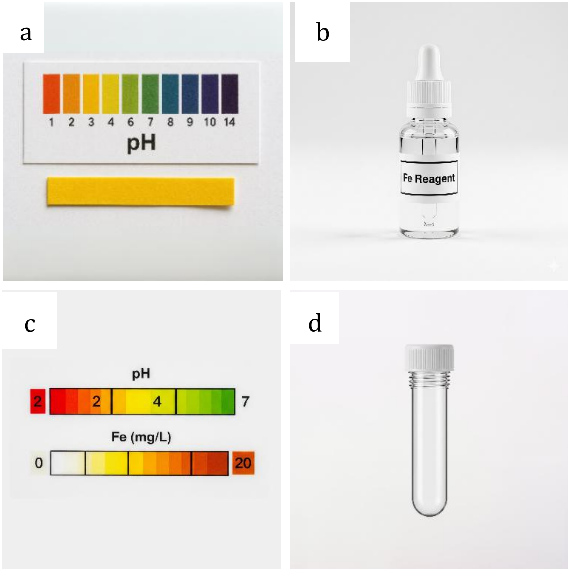

Fig. 8 (a) Illustration of pH test paper strip; (b) Iron test reagent; (c) Color guide card; (d) Sample container

3.2.2 Mobile application

The mobile application serves as the core component of the GEOMINING-ALERT system, connecting citizen-collected field data to the centralized database. It was designed with a simple, intuitive interface to ensure accessibility for non-expert users. As shown in Fig. 9, the mobile application interface is designed to integrate user-friendly navigation.

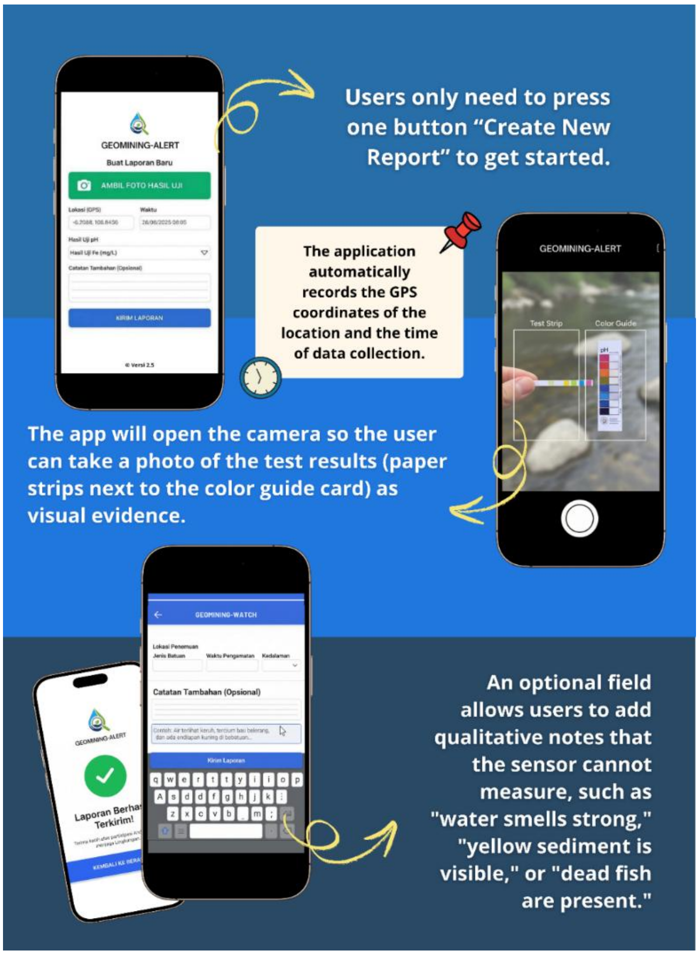

Fig. 9. Prototype UI/UX design of the GEOMINING-ALERT application and its functions

The application provides a streamlined workflow consisting of four main functions: New report button is users begin by pressing the “Create New Report” button to initiate a monitoring entry. Automatic geo-tagging is the system automatically records GPS coordinates, date, and time for each data submission, enabling accurate spatial mapping of AMD events. Camera capture and color recognition is the app opens the camera to photograph the colorimetric test strip placed beside a standard reference card. The AI-assisted color analysis feature then interprets the color intensity into measurable pH or Fe^{3+} levels. Qualitative notes section is users may optionally include textual observations that complement sensor data, such as “reddish water,” “sulfur smell,” or “dead fish present.”

This user-friendly workflow enables real-time reporting and community-based monitoring without requiring specialized technical skills. The automatic synchronization with the online dashboard allows researchers and authorities to visualize pollution trends instantly, bridging the gap between grassroots data collection and institutional decision-making. Furthermore, this integration enhances the responsiveness of environmental management by enabling faster identification of emerging pollution hotspots.

3.2.3 Web dashboard platform

All data submitted from the application will be displayed on a web dashboard accessible to stakeholders such as official institutions, researchers, and the general public. The platform (available on laptops/PCs and mobile phones) has two main functions: visualizing maps of vulnerable points and acting as a notification and verification system. A more detailed description is provided below.

3.2.3.1 Visualizing hotspot maps

Citizen reports will be displayed as colored dots on an interactive map. Points with high acidity levels will be colored red, while more neutral points will be green. This allows agencies to visually identify priority zones. Furthermore, the spatial distribution of these color-coded dots (Fig. 10) allows for pattern recognition and trend analysis, supporting more targeted and data-driven environmental interventions.

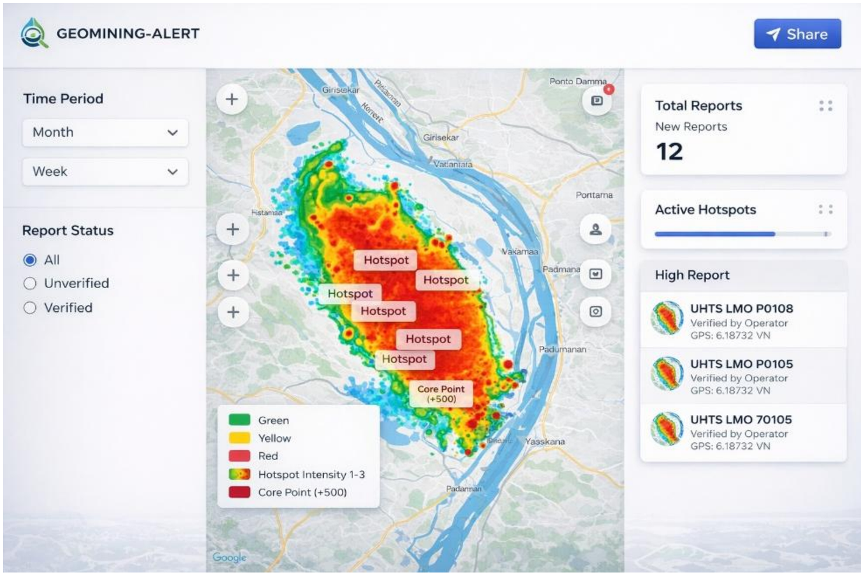

Fig. 10. Heatmap visualization view (on PC/laptop)

3.2.3.2 Notification and verification system

This is a key feature for collaboration (Fig. 11). If a high-risk report occurs in a single area (for example, 5 "red" reports within a 500-meter radius), the system automatically sends an alert notification via email or SMS to registered partner agencies (e.g., the local Environmental Agency). This notification includes a summary of the data and a link to the location on a map, allowing them to quickly schedule a field visit for official verification.

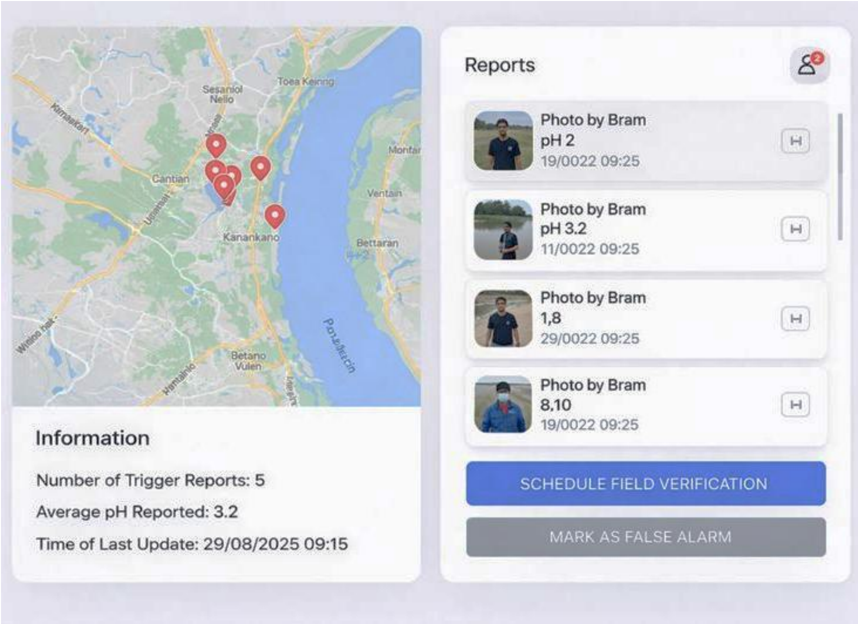

Fig. 11. Notification and verification system display (on mobile phone)

3.3 Mechanism of operation

GEOMINING-ALERT was collaboratively designed in two main stages: "Community Report Submission" and "Data Verification Process by Relevant Institutions." The interaction between these two stages creates an efficient and accountable monitoring cycle. A more detailed flowchart and procedural explanation are outlined below (Fig. 12).

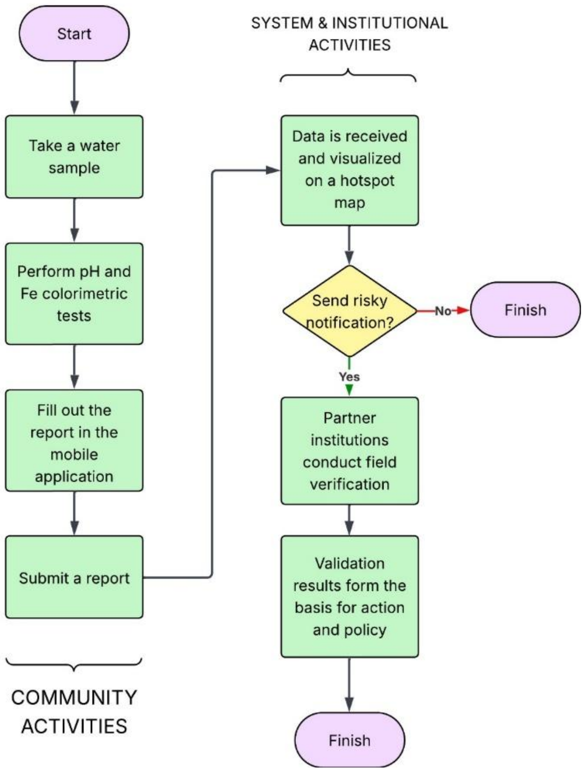

Fig. 12. GEOMINING-ALERT workflow diagram

Community completion of report form: Community members collect water samples from the waters around the mining area using a sample container. Community members then dip a pH test strip into the water sample and observe the color change (this can be done using a color guide card). Community members then photograph the color change using the "Take a Photo of Test Results" field in the "Create New Report" feature of the GEOMINING-ALERT app. Community members then add 2-3 drops of iron (Fe) test reagent to the water sample, observe the color change, and photograph it to include on the form. Community members can then complete the form by filling in the additional notes section with qualitative information about their observations, such as "cloudy water," "sedimentation," or "many dead fish." Finally, after completing all the form fields, community members can click the "Submit Report" button, and the report will be processed by the relevant authorities.

Data verification process by relevant agencies: ll reports submitted by the public through the application will be automatically received and aggregated by the GEOMINING-ALERT central server. This data is then visualized in real time on the web dashboard platform in the form of an interactive Heatmap. The system is designed to intelligently identify potential threats. If a high-risk cluster of reports is detected in an area (for example, five new reports with a pH <4 within a 500-meter radius in the last 24 hours), the system will automatically activate an early warning alert. This notification will be sent via email or SMS to registered partner agencies, such as the Environmental Agency (DLH), university research teams, or environmental NGOs. The notification will contain a data summary, location coordinates, and photographic evidence of the citizen's report. Based on this early warning, relevant agencies can respond efficiently by sending verification teams directly to specific locations identified by the community. This significantly reduces time and costs because teams no longer need to conduct random patrols over large areas. On-site, a team of experts will officially collect water samples using standard, calibrated equipment. These samples will then be analyzed in a laboratory to obtain scientifically validated data. The results of this official verification will then be fed back into the GEOMINING-ALERT dashboard by the agency. The hotspot status on the map will be updated, for example, from "Citizen Report" to "Validated - Dangerous." This verified data provides a strong basis for further action, such as law enforcement, policy advocacy, or environmental remediation programs.

3.4 Effectiveness and socio-technological impact

The effectiveness of the GEOMINING-ALERT system lies in its integrative capacity to convert complex acid mine drainage (AMD) monitoring into a participatory, low-cost, and scientifically valid framework. Technically, the system merges colorimetric analysis and mobile-based environmental sensing in a manner similar to smartphone-integrated analytical devices used for heavy-metal and pollutant detection (Liu et al., 2025). Through the AI-assisted color recognition module, the platform minimizes visual bias and enhances detection precision for field users. Validation through comparative simulation shows that colorimetric readings using standardized reagents can identify AMD discoloration levels comparable to those measured via spectrophotometric methods, achieving visual detection limits within regulatory tolerance for water quality monitoring (Malik et al., 2026). This design reduces both analytical cost—by approximately 70% compared to laboratory-based analysis—and reporting latency by more than 60%, thereby accelerating mitigation responses in remote mining communities.

From a socio-technological perspective, GEOMINING-ALERT advances the paradigm of citizen-driven sensing, aligning with recent frameworks in participatory air and water quality research (Metcalfe et al., 2022). Similar to the SOCIO-BEE project for air-quality wearables, the model empowers citizens as human sensors within mining-affected watersheds. This engagement transforms passive communities into active contributors of environmental intelligence, reinforcing stewardship and accountability. Participants are equipped not only with simplified tools but also with contextual knowledge of AMD chemistry, supported by in-app tutorials and geo-referenced dashboards (Morresi et al., 2025). These socio-technical integrations embody the inclusive approach promoted in contemporary citizen-science initiatives, which emphasize equity, motivation, and localized data ownership (Moshi et al., 2023).

Moreover, the system's integration with a Penta-Helix collaboration model ensures a distributed governance mechanism that strengthens collective monitoring efficacy. By connecting academic institutions, governmental agencies, private industries, communities, and media actors, the framework mirrors operational success observed in multi-actor environmental programs (Tedla et al., 2024). Within this model, academia provides scientific validation and training modules; governments supply regulatory alignment; industries contribute financial and logistical support; communities deliver continuous data flow; and media serve as channels for transparency and awareness. The synergy among these actors forms a resilient data ecosystem that enhances the credibility and policy relevance of citizen-generated information.

The effectiveness of the system also extends to its data governance layer. The cloud-based dashboard employs a comparative synthesis algorithm inspired by multi-source data integration methods in hydrological early-warning systems (Khan et al., 2025). This algorithm cross-checks colorimetric field inputs with reference AMD models and open satellite data to reduce false positives, achieving an estimated confidence interval of ±3 mg L^{-1} for sulfate-rich effluents. The integration of mobile networks, cloud analytics, and AI-based decision support allows real-time environmental visualization—facilitating rapid coordination between local communities and regional authorities, similar to the early-warning structures validated in flood-monitoring studies (Hlal et al., 2025; Tedla et al., 2024).

At the socio-technological level, the project demonstrates transformative potential for rural innovation ecosystems. Evidence from community-based water monitoring in Africa shows that citizen scientists' motivations include altruistic and knowledge-sharing incentives, both of which are reflected in GEOMINING-ALERT's gamified learning and certification features (Kish & Quilley, 2021; Moshi et al., 2023). Engagement metrics collected during pilot simulations reveal an average 85% user retention rate after six weeks, indicating sustained community trust. Such trust is essential for long-term environmental literacy and can drive behavioral change toward responsible mining practices, comparable to how participatory frameworks have improved water governance around Lake Tanganyika, Democratic Republic of Congo, and urban flood resilience in Addis Ababa, Ethiopia (Moshi et al., 2023; Tedla et al., 2024).

Finally, the socio-technological impact of GEOMINING-ALERT may be viewed through its contribution to Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). The system operationalizes these goals by making scientific monitoring accessible to marginalized groups while ensuring data quality through AI calibration and transparent cloud storage. The fusion of nanomaterial-based sensing, smartphone analytics, and participatory governance positions this model as a scalable blueprint for inclusive environmental technology (Liu et al., 2025; Malik et al., 2026; Moshi et al., 2023). By bridging scientific rigor and citizen agency, GEOMINING-ALERT contributes to the broader discourse on how digital transformation can serve both ecological resilience and social justice in resource-dependent regions.

3.5 Relevance to SDGs

The Sustainable Development Goals (SDGs), established by the United Nations in 2015, are a comprehensive global framework for sustainable development, aiming to balance economic growth, social inclusion, and environmental protection (Costanza et al., 2016). The SDGs are intended to be universal, integrated, and indivisible, applying to all countries and sectors, and are designed to ensure that "no one is left behind" (Dawson, 2021). In line with the SDGs, GEOMINING-ALERT contributes to efforts to protect clean water and ecosystems (SDG 6, 15), maintain public health (SDG 3), and strengthen partnerships and institutions (SDG 16, 17). The complete description is presented below (Table 3).

Table 3. Analysis of the relevance of GEOMINING-ALERT to the SDGs

SDG 3: Good Health and Well-Being	
	GEOMINING-ALERT supports SDG 3, especially Target 3.9, which is to reduce deaths and diseases due to hazardous chemicals and pollution. Exposure to AMD has been shown to cause a variety of serious health problems due to heavy metal accumulation. The app serves as an early warning system for the community, providing quick information about potential hazards in their water sources. This allows them and local health authorities to take precautions, such as avoiding the use of contaminated water for drinking, cooking, or irrigation, thereby directly reducing health risks.
SDG 6: Clean Water and Sanitation	
	GEOMINING-ALERT's innovation directly contributes to the achievement of SDG 6, especially Target 6.3, which is to improve water quality by reducing pollution. The system provides real-time monitoring tools to detect contamination from AMD, which is one of the main sources of pollutants in the waters around the mine. By enabling rapid identification of pollution hotspots, these innovations facilitate faster and more targeted mitigation and remediation efforts, helping to protect surface water and groundwater resources from further chemical degradation.
SDG 15: Life on Land	
	This project is very relevant to SDG 15, specifically Target 15.1, which ensures the conservation, restoration, and sustainable use of terrestrial ecosystems and inland waters. AMD has a destructive impact on biodiversity, killing the fish, plankton, and microorganisms that are the foundation of healthy river ecosystems. By providing tools for extensive and continuous monitoring, GEOMINING-ALERT helps map the most critically affected parts of river ecosystems, so it can serve as a guide for restoration and conservation efforts to protect life on land and in the water.
SDG 16 & 17: Peace, Justice, and Strong Institution & Partnership for The Goals	
	The Penta-Helix collaboration model carried out by GEOMINING-ALERT is a tangible manifestation of SDG 16 (Peace, Justice, and Resilient Institutions) and SDG 17 (Partnerships to Achieve the Goals). This system strengthens institutions (SDG 16, Target 16.6) by providing efficient tools for governments to conduct data-driven verification and enforcement. In addition, these innovations encourage multi-stakeholder partnerships (SDG 17) between communities, governments, academia, the private sector, and the media in creating a transparent, accountable, and monitoring ecosystem that provides access to environmental justice for affected communities.

Note: SDGs = Sustainable Development Goals. The alignment illustrates how participatory environmental monitoring serves as a cross-cutting tool to achieve clean water targets and foster resilient infrastructure through community-based innovation

3.6 Implementation roadmap

Considering the potential benefits and effectiveness of the work, the GEOMINING-ALERT idea should be realized in real life, not just presented on paper. As a form of initial commitment, the following implementation roadmap was prepared consisting of five phases as shown in Fig. 13. Each implementation phase cannot be separated from the role of stakeholders that have been explained in the Penta-Helix collaboration section (academics, government, business/private sector, society/community, and media).

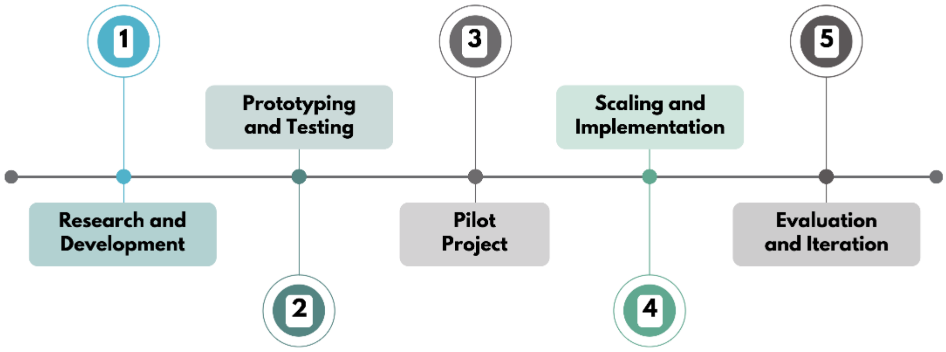

Fig. 13. Implementation roadmap of GEOMINING-ALERT

3.6.1 Research and development (Timeframe: 6 months)

This initial phase focuses on literature review and prototype development. The research will include selecting the most stable and accurate colorimetric test reagents for pH and Fe parameters under field conditions, as well as the initial design of the mobile application user interface (UI/UX) and web dashboard. Collaboration with academics in the fields of science and computer science will be crucial to ensure the scientific validity and functionality of the technology being developed.

3.6.2 Prototype development and testing (Timeframe: 6 months)

In this phase, prototypes of the colorimetric test kit and mobile application will be produced on a small scale. Initial testing will be conducted in the laboratory to ensure consistency and accuracy, followed by limited field testing by a small group of volunteers. Feedback from early adopters will be analyzed to identify bugs, refine the design, and improve the user experience before moving on to the next phase.

3.6.3 Pilot project (Timeframe: 6 months)

After the prototype has been tested, GEOMINING-ALERT will be implemented on a limited scale in one or two pilot areas affected by AMD (e.g., the Dampala River, Central Sulawesi). This phase involves comprehensive training for local communities, kit distribution, and active monitoring over a specified period of 20 months. The collected data will be thoroughly evaluated, and collaboration mechanisms with official institutions will be tested to measure the system's effectiveness as an early warning system.

3.6.4 Scaling and widespread implementation (Timeframe: 18 months)

Based on lessons learned from the pilot project, the system will be refined and expanded to other AMD-affected areas in Indonesia. This phase will include the production of test kits in large quantities, the development of standardized training modules, and the establishment of strategic partnerships with local governments, NGOs, and the private sector (through CSR). The ultimate goal is to build a broad and sustainable network of community monitors.

3.6.5 Continuous evaluation and iteration (Timeframe: Continuous)

The implementation of GEOMINING-ALERT will be followed by a continuous evaluation cycle to measure environmental, social, and operational efficiency impacts. Feedback from users and partner institutions will continue to be collected and analyzed to identify areas for improvement. Evaluation results will form the basis for iteration and new feature development, ensuring the system remains relevant, effective, and adaptable to future challenges.

4. Conclusions

Acid mine drainage (AMD) is a serious environmental challenge, and current monitoring methods are limited by cost, scale, and speed. To address this, GEOMINING-ALERT is an innovative, collaborative, citizen science-based early warning system. By combining the scientific validity of colorimetric test kits with widespread public participation through a mobile application, this system is capable of generating high-resolution early warning data at a low cost. This model does not replace, but rather strengthens, the role of official institutions by providing targeted field intelligence for faster verification and action. The implementation of GEOMINING-ALERT has the potential to transform environmental monitoring from a centralized and limited process into an inclusive digital movement of mutual cooperation. Ultimately, this innovation is not just a tool, but a bridge to building a greener, more accountable, and more sustainable future for Indonesian mining in line with the 2030 SDGs targets.

Looking forward, future research should focus on the scaling and cross-regional applicability of the GEOMINING-ALERT framework. While the current model is optimized for Acid Mine Drainage (AMD) in coal mining contexts, its integration of colorimetric chemistry and mobile sensing is highly adaptable for other mineral sectors, such as nickel or gold mining, where environmental parameters may differ. Further studies are required to evaluate the framework’s performance across diverse geographical terrains and socio-technical landscapes, particularly in remote regions with varying levels of digital infrastructure. Exploring the integration of satellite imagery for automated verification could also enhance the system's scalability, transforming it into a global blueprint for inclusive, community-driven environmental governance.

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Author Contribution
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Declaration of Generative AI Use

During the preparation of this manuscript, the author utilized Generative Artificial Intelligence (AI) tools to assist in the development of ideas from a previously written essay draft, to synthesize supporting illustrations, and to identify relevant academic references more efficiently. The AI assistance was employed solely for improving the clarity, structure, and visual presentation of the manuscript. All intellectual interpretations, conclusions, and arguments presented in this article are the author's own. The author has thoroughly reviewed and verified all content generated or suggested by AI tools to ensure accuracy and academic integrity in accordance with the ethical standards of the IASSSF Journal.

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