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3D Characterization of Mining Waste Piles: Bridging Geophysical and Geochemical Techniques for Improved AMD Prediction

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ABSTRACT
Mining waste piles constitute a substantial environmental liability due to their propensity to generate Acid Mine Drainage (AMD), a severe form of water contamination caused by the oxidation of sulfide minerals. The complexity and heterogeneity of these garbage piles make it difficult to forecast and mitigate AMD accurately. When applied alone, traditional characterization techniques—whether they be based on non-specific geophysical surveys or discrete geochemical sampling—are frequently inadequate. This review article summarizes the most recent developments in mining waste pile classification by promoting an integrated, synergistic strategy that unifies geophysical and geochemical methods. In order to overcome the limitations of both individual approaches, the paper explains the principles, strengths, and limitations of key geophysical methods, such as Electrical Resistivity Tomography (ERT) and Induced Polarization (IP), and geochemical methods, such as Acid-Base Accounting (ABA) and kinetic tests. The paper then shows how the spatial data from geophysical surveys can be used to intelligently guide geochemical sampling to create comprehensive three-dimensional models that turn fragmented information into a continuous, spatially resolved map of AMD risk. Lastly, the review discusses future directions, including the use of machine learning, remote sensing, and advanced sensor technology, while emphasizing the crucial need for standardized protocols and interdisciplinary training to ensure the wider adoption of this potent methodology. The integrated approach is the most reliable foundation for managing AMD proactively as opposed to reactively, producing more long-lasting and beneficial environmental results.

KEYWORDS
Mining waste piles; Acid Mine Drainage (AMD); Integrated geophysical-geochemical methods; 3D AMD risk mapping; AMD proactive management

1 Introduction

Modern society is based on the global mining sector, which supplies the raw resources needed for economic growth, infrastructure, and technology (Radebe & Chipangamate, 2024). However, this activity produces enormous amounts of solid waste, such as tailings and waste rock, which are sometimes kept in big mounds on the surface (Agboola et al., 2020). One of the main issues with these trash piles is the possibility of Acid Mine Drainage (AMD), which is a serious and long-lasting environmental hazard. AMD is a complicated geochemical process that is brought on by the oxidative weathering of sulfide minerals, mostly pyrite (FeS2), in the presence of oxygen and water (Brar et al., 2022). Sulfuric acid, which is produced by this reaction, mobilizes heavy metals and other harmful materials from the surrounding waste matrix, severely contaminating soil, groundwater, and surface water (Jaishankar et al., 2014). Since AMD is a long-term process, these waste heaps may continue to be a concern for centuries, hence proactive and precise AMD prediction is essential to mine-site management and repair.

Traditional techniques of defining mining waste piles have frequently depended on discrete geochemical sampling or the use of a single geophysical tool. Direct and quantitative information on the material's capacity to produce acid is provided by geochemical analysis, which entails gathering and evaluating samples from many places (Miller, 2013). However, these approaches are frequently spatially constrained and only offer a fragmented two-dimensional or one-dimensional picture of a highly complex three-dimensional system because of the intrinsic variability and enormous volume of garbage piles (Chang et al., 2025). On the other hand, geophysical techniques provide a non-invasive way to map the waste pile's subsurface structure and properties, including porosity, moisture content, and the presence of conductive layers. Although effective at giving a spatial overview, these techniques frequently lack the direct chemical specificity needed to identify AMD-generating zones with certainty (Dimech et al., 2022). The problem is that neither approach alone can provide a thorough three-dimensional understanding of the physical and chemical conditions required for reliable AMD prediction.

This review study fills a significant gap by investigating the synergistic potential of an integrated strategy that combines geophysical and geochemical methods. Synthesizing the current understanding of each method's particular strengths and illustrating how their strategic combination might overcome each one's limits are the main goals. A more representative and geographically precise dataset may be produced by using geophysical surveys to guide the targeted collection of geochemical samples. The trash pile's physical structure and the geographical distribution of important geochemical markers for AMD risk may then be mapped using this combined data to produce a comprehensive three-dimensional model (Agboola et al., 2020). In order to enable more effective and targeted mitigation strategies, this approach offers a powerful framework for more accurate AMD prediction as shown in Figure 1. The subsequent sections will offer a thorough review of important geophysical and geochemical techniques, followed by an examination of successful integration methodologies and a discussion of the difficulties and future directions for this field (Figure 1).

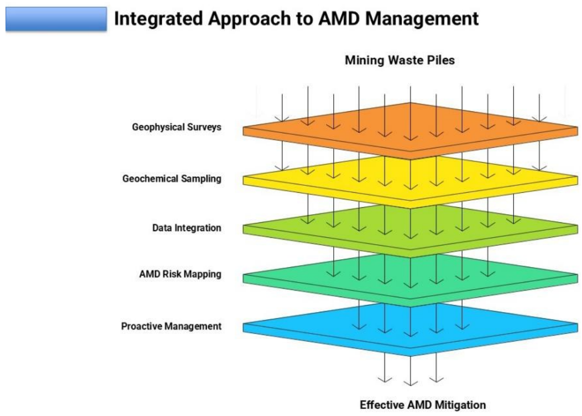

Figure 1 shows the integrated approach to AMD management.

2 Geophysical techniques for characterization

Geophysical techniques are a strong, non-invasive way for studying the subsurface features of mining waste heaps, offering crucial insights into their underlying structure, composition, and hydrogeological characteristics (Dimech et al., 2022). Geophysical surveys produce continuous information that may be used to produce two- and three-dimensional representations of the garbage pile, in contrast to geochemical sampling, which delivers data at discrete sites (Hauck, 2013). Key factors connected to AMD development as shown in Table 1, including porosity, moisture content, the presence of sulfide minerals, and the position of impermeable layers, can be linked to the spatial differences in physical qualities seen in these photos. The main geophysical methods used in this situation are thoroughly described in the parts that follow, with an emphasis on their fundamentals, uses, and inherent drawbacks (Jessell, 2001).

Table 1 Correlation with acid mine drainage indicators

Geophysical Parameter	Acid Mine Drainage Indicator	Relationship Strength	Limitations	References
Low resistivity / high conductivity	Acid mine drainage-affected water, high total dissolved solids, leachate zones	Strong; consistently observed across studies	May be confounded by naturally conductive materials (clays, saline groundwater)	(Lu et al., 2025)
High chargeability (Induced Polarization/ TimeDomain Induced Polarization)	Sulfide mineral content, acid mine drainage generation potential	Strong; high chargeability zones align with acid mine drainage risk	Requires calibration with borehole or chemical data; may be affected by non-sulfide conductive minerals	(Duz et al., 2025)
Conductivity anomalies (Electromagnetic methods)	Acid mine drainage plumes, groundwater contamination	Strong for reconnaissance; effective for mapping large-scale anomalies	Limited depth resolution; follow-up with Electrical Resistivity Tomography/Induced Polarization needed for detail	(Manrique, 2023)
Magnetic susceptibility	Aeolian transport of contaminated dust	Moderate; useful for surface/near-surface contamination	Not directly related to acid mine drainage in groundwater; site-specific utility	(Wheelock, 2024)

2.1 Electrical Resistivity Tomography (ERT)

ERT is one of the most popular geophysical techniques for describing piles of mining waste. The electrical resistivity of the subsurface, a basic characteristic that determines how strongly a material resists the passage of electric current, is measured using the ERT concept (Sun et al., 2025). In actuality, two electrodes pump an electric current into the ground, while a second pair measures the potential difference that results. A complete dataset of apparent resistivity values is gathered by methodically shifting the locations of these electrodes (García-Nieto et al., 2024). A cross-sectional or volumetric model of actual resistivity is then produced by inverting these values; this is usually shown as a faux section or a three-dimensional volume. In particular, water-saturated zones and those containing conductive fluids, like the low-pH, sulfate-rich waters associated with AMD, tend to have very low resistivity, while dry, compacted material or bedrock has high resistivity (Zeng et al., 2025). As a result, ERT is very effective at determining the preferential flow paths of water, mapping the depth of the water table, and delineating zones of high fluid content, which are frequently precursors to AMD. The resistivity of mining waste materials varies greatly and is driven by a number of factors, including mineralogy, moisture content, porosity, and the concentration of dissolved ions in the pore water (Kukemilks & Wagner, 2021). The capacity of ERT to create continuous, high-resolution photographs of the subsurface without requiring destructive excavation is its main advantage. The results' ambiguity, however, is a major drawback; without supporting data, it would be challenging to distinguish between a low resistivity anomaly that would suggest conductive clay or a high moisture content.

2.2 Induced Polarization (IP)

In IP surveys, a current is applied to the ground for a brief period of time and then turned off; the subsurface material continues to discharge a small voltage because of its chargeability, which is measured over time and quantified as chargeability ("Chapter 1 - Introduction, " 1976). IP is frequently used in conjunction with ERT and provides complementary information by measuring the sub surface ' s chargeability, which is the ability of a material to store an electrical charge when a current is applied and is primarily related to the presence of metallic minerals, such as sulfide minerals, and to a lesser extent, clay. A zone with disseminated sulfide minerals in a wet environment—a prime location for AMD generation—is strongly indicated by a low-resistivity, high-chargeability anomaly (Ali et al., 2023). The primary benefit of IP is its high sensitivity to sulfide mineralization, a property that is largely undetected by other geophysical methods. Like ERT, IP data can be ambiguous because some clay minerals can also produce a strong IP response, necessitating careful interpretation and integration with other datasets (Ali et al., 2023).

2.3 Ground Penetrating Radar (GPR)

GPR is an electromagnetic technology that produces pictures of the shallow subsurface with great resolution. The process entails sending high-frequency radio waves into the earth and timing the return of reflected waves (Zhang et al., 2023). The reflections are brought on by variations in the materials' electromagnetic characteristics, such as electrical conductivity and dielectric constant, which alter depending on the kind of material, porosity, and moisture content. Internal layers, stratigraphy, and the placement of distinct items inside the trash pile are all areas in which GPR excels (Liu et al., 2023). It is capable of accurately locating the water table, identifying buried infrastructure, and drawing borders between various waste rock kinds. GPR's high-resolution capacity makes it perfect for locating shallow, near-surface structures that could be directing water into the interior of the pile. However, the electrical characteristics of the material have a significant impact on how successful GPR is. It functions best in areas with poor conductivity, such as dry, sandy materials, where the radar signal may travel farther. In contrast, in highly conductive materials like water-saturated clays or waste piles with high concentrations of dissolved salts, the radar signal is rapidly attenuated, severely limiting its depth of penetration (Song et al., 2021).

2.4 Seismic refraction and reflection

Seismic techniques, such as seismic refraction and reflection, map underlying structures using acoustic energy and the varying velocities at which sound waves pass through different materials (Carrera et al., 2024). Seismic waves are produced by an energy source (such as a hammer or a tiny explosive) and travel into the subsurface during a seismic survey. An array of geophones then picks up these waves. The travel duration of waves that have been refracted along layers with higher seismic velocity—which is directly correlated with material density and compaction—is measured by seismic refraction (Schwardt et al., 2022). The main advantage of seismic methods is their ability to provide information on the physical properties of the waste pile, such as density and stiffness, which are difficult to obtain with other techniques. Seismic reflection, on the other hand, measures waves that are reflected back to the surface at interfaces between layers of different acoustic impedance (Schwardt et al., 2022). Although more complex and expensive, seismic reflection can provide a more detailed image of deeper stratigraphy and complex fault structures. This makes it an excellent method for determining the depth to bedrock, identifying the thickness of various waste layers, and evaluating the degree of compaction within the waste pile (Maleki et al., 2025). However, they are often less suitable for fine-scale, high-resolution mapping of heterogeneous materials and are commonly used for large-scale structural investigations.

2.5 Gravity and magnetic surveys

Passive geophysical techniques such as gravity and magnetic surveys are used to quantify the gravitational and magnetic field fluctuations that occur naturally on Earth. Variations in the density of underlying materials generate small changes in the gravitational field, which are measured by a gravity survey (Peng et al., 2025). When it comes to mining waste, this may be used to define the overall mass and volume of the waste pile as well as to pinpoint areas of notable density difference, such compacted vs loose material. The existence of magnetic minerals causes fluctuations in the Earth's magnetic field, which are measured using magnetic surveys (Mashaan & Yogi, 2025). Although they are not directly related to AMD, magnetic anomalies can occasionally be connected to certain mineralized zones or geological units within the waste pile, such pyrrhotite or magnetite, which can serve as a stand-in for the original ore body's location. Instead of being utilized for in-depth, high-resolution characterization, these techniques are usually employed for large-scale, reconnaissance-level assessments that identify the garbage pile's general extent and broad structure (Jia & Ye, 2023). Their primary benefit is that, in comparison to more comprehensive surveys, they may cover huge regions more rapidly and for less money. However, the resolution is generally low, and the results are often highly ambiguous, requiring extensive a priori knowledge or corroboration from other methods (Wright, 2005).

3 Geochemical techniques for characterization

Geochemical characterization is a critical component of assessing the environmental risk posed by mining waste piles, particularly their ability to produce AMD (García & Rosique, 2025). Geochemical techniques give precise, quantitative information on the chemical and mineralogical characteristics of the waste material itself, whilst geophysical approaches give a geographical framework of the subsurface (Aallaoui et al., 2025). By assessing a material's inherent ability to produce and neutralize acids, these techniques are intended to give a clear picture of how likely it is to cause AMD. The two primary types of geochemical characterization are usually static and kinetic tests, which provide a quick and inexpensive way to evaluate a material's acid-base balance and a more detailed, time-dependent simulation of weathering processes, respectively (Aallaoui et al., 2025; García & Rosique, 2025). The success of these methods depends heavily on a careful and representative sampling strategy, which is a crucial component of the larger 3D characterization endeavor (Figure 2).

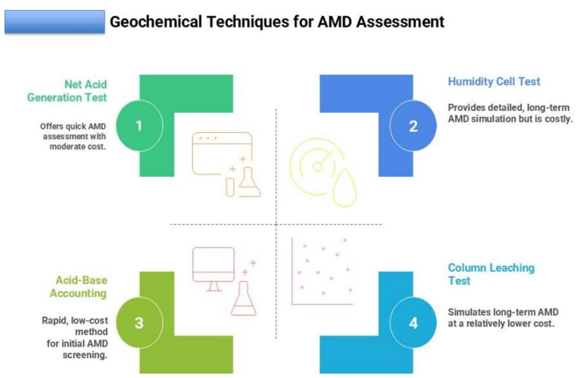

Figure 2 Shows the geochemical techniques for AMD assessment.

3.1 Static tests

Static tests are a speedy and cost-effective technique of screening large numbers of samples to establish their overall acid-generating capacity (Moyo et al., 2025). They give a basic, first-order evaluation of the balance between the acid-producing minerals and the acid-neutralizing minerals inside a sample. The most used static test is Acid-Base Accounting (ABA) (Hageman et al., 2015). Quantifying a sample's highest acid-producing potential (APP) and maximum acid-neutralizing potential (ANP) is its main objective. Since all sulfur is assumed to be present as reactive sulfide minerals, most frequently pyrite ($FeS2$), the APP is mostly determined from the overall sulfur content (Cruz et al., 2001). Usually, the APP is stated in kilos of calcium carbonate ($CaCO3$) equivalent per waste ton. To calculate the amount of acid eaten, a crushed sample is reacted with a predetermined amount of acid, and the surplus acid is titrated with a base. This yields the ANP (Hageman et al., 2015). Additionally, kilos of $CaCO3$ equivalent per ton are used to indicate this number. The Net Neutralizing Potential (NNP = ANP - APP) is the primary measure that is obtained from ABA. While a negative NNP raises the possibility of AMD, a positive NNP shows the sample is not acid-generating (Aphane & Vermeulen, 2015). The Net Acid

Generation (NAG) test is frequently used as a supplement to or alternative to ABA. It is a more empirical test that directly measures the net acidity or alkalinity produced under controlled, accelerated oxidation conditions (Karlsson et al., 2021). In a NAG test, a sample is oxidized with hydrogen peroxide (H2O2) to promote the rapid oxidation of sulfide minerals. The final pH of the resulting solution (the NAG pH) provides a quick indicator of the sample's potential. One of the main limitations of ABA is that it only gives a snapshot of the maximum potential and does not account for the kinetics of the reactions or distinguish between different forms of sulfur (e.g., sulfide, sulfate) (Atherton et al., 2025). A NAG pH below 4.5 is typically regarded a sign of acid-generating potential. The NAG test has an advantage over ABA in that it accounts for both the acid-producing and neutralizing processes as they occur under rapid oxidation, offering a more realistic evaluation of the net consequence. The gradual, long-term dynamics of natural weathering, however, cannot yet be replicated by it (Ochoa-Guerrero et al., 2025).

3.2 Kinetic tests

Kinetic testing is intended to replicate the long-term, organic weathering processes that take place over months to years in a mining waste pile. They offer vital information that static tests are unable to provide, such as the rates at which AMD is generated and the changes in leachate chemistry over time (Koucham et al., 2025). The gold standard for kinetic testing is the humidity cell test. It entails putting a sample of crushed waste rock in a cell and letting it become wet (leaching), flushed with humid air (oxidation), and then allowed to dry. Weekly or biweekly, leachate is gathered and examined for a variety of factors, such as pH, sulfate, and metal concentrations (Karlsson et al., 2021). The HCT offers a time-series dataset that shows the rate of acid generation, the depletion of neutralizing minerals, and the lag period until AMD development. This information is essential for forecasting a garbage pile's long-term behavior and assessing how well possible mitigation techniques work (Li et al., 2024). Column leaching tests are similar to HCTs but are frequently conducted on a bigger scale and are meant to more nearly replicate the vertical flow of water through a garbage pile. A column is filled with the waste material, and deionized water is regularly poured through it to imitate rainfall. At the bottom of the column, the leachate is collected, and its chemical changes over time are examined. Column leaching experiments can offer valuable information on how various moisture conditions and particle sizes affect AMD production, even though they are less standardized than HCTs (Li et al., 2024).

Kinetic tests' main benefit is their capacity to reveal details on the duration and pace of AMD production, which is crucial for long-term environmental management (Kalyoncu Erguler et al., 2014). Their primary drawback is the expense and time involved in carrying them out, which renders them inappropriate for screening a large number of samples.

3.3 Sample collection and analysis

Essentially, the quality of the samples gathered determines how reliable the static and kinetic geochemical tests are. A well-thought-out sampling method is necessary to guarantee that samples are representative of the general features of mining waste piles because of their great variety (GRISHIN & YERMAK, 2019). In order to gather samples from various depths and locations, borehole drilling and grid-based surface sampling are frequently used (GRISHIN & YERMAK, 2019). Since geophysical data may be used to intelligently direct the placement of these boreholes to target zones of interest, integration with geophysical approaches is essential in this case.

After collection, samples are usually put through a series of laboratory tests. X-ray diffraction (XRD) is used to determine which mineral phases—including the acid-neutralizing carbonate minerals and the acid-producing sulfide minerals—are present in the trash. Compared to the total sulfur content alone, this gives a more comprehensive view. To ascertain the sample's overall elemental composition, methods such as Optical Emission Spectrometry (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and X-ray Fluorescence (XRF) are employed (Jamieson, 2011). This data is essential for determining the levels of heavy metals and other hazardous substances that AMD may mobilize. A range of analytical methods are employed to quantify characteristics including pH, alkalinity, and the quantity of sulfate, iron, and other dissolved metals in leachate samples from kinetic testing or pore water samples collected in the field (Matthies et al., 2011).

In conclusion, the direct chemical evidence needed to evaluate AMD possibility is provided by geochemical characterization. A thorough chemical profile may be created by carefully choosing and integrating static and kinetic testing techniques with a solid sampling plan guided by knowledge of the pile's structure.

4 Integration of geophysical and geochemical methods

Geophysical and geochemical techniques are each powerful tools for characterizing mining waste piles, their true value is realized when they are integrated into a single, cohesive framework. This synergistic approach overcomes the fundamental limitations of each method when used in isolation. Geochemical tests provide specific, direct information about the acid-generating potential of the waste material but are often spatially limited and costly to perform on a large scale (Bevandić et al., 2021). On the other hand, whereas geophysical surveys provide a continuous geographical map of subsurface characteristics, their findings are frequently ambiguous and need to be interpreted. By combining these two approaches, a thorough three-dimensional description of the garbage pile is created, converting isolated data points into a spatially resolved AMD risk model. This section examines the strategic approaches for this integration, the advantages it offers, and the obstacles that need to be overcome for it to be implemented successfully (Maleki et al., 2025) (Figure 3).

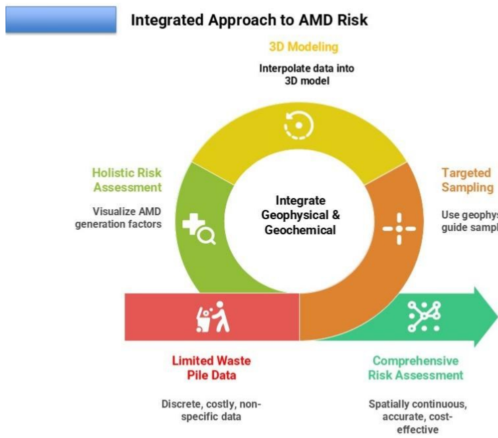

Figure 3 Shows AMD risks management and their protocols.

4.1 A synergistic framework for targeted sampling

The most important part of combining these methods is using geophysical data strategically to direct geochemical sampling. Instead of using a random or grid-based sampling strategy, which might overlook important zones of interest, a preliminary geophysical survey can be carried out to identify areas that are likely to contain problematic materials (El-Raouf et al., 2023). For example, an Electrical Resistivity Tomography (ERT) survey may reveal low-resistivity anomalies that suggest conductive pore fluids or zones of high moisture content, both of which are common in AMD environments. A "geophysical risk map" of the waste pile can be created by overlaying the results of IP surveys, which can identify areas with high chargeability, a strong indicator of disseminated sulfide mineralization, the main source of acid production (El-Raouf et al., 2023). This map then acts as a precise guide for placing targeted boreholes or pits for the collection of geochemical samples, ensuring that samples are collected from the most significant and environmentally relevant zones, maximizing the information obtained from each costly geochemical test, and guaranteeing that the final characterization is representative of the most problematic areas.

4.2 3D modeling and visualization

A single three-dimensional model is created by combining the geophysical and geochemical datasets once they have been gathered. Usually, specialist geological and environmental modeling software is used to do this. The model's structural underpinning is provided by the geophysical data, which has an intrinsic spatial continuity (Qi et al., 2023). For instance, an ERT survey identifies the water table and fluid saturation zones, but a GPR survey may identify the trash pile's stratigraphy. Then, using geostatistical methods like kriging or inverse distance weighting, the discrete geochemical data points—such as NNP values, metal concentrations, and mineralogical data from XRD—are interpolated across this 3D structure (Qi et al., 2023). By converting the geochemical point data into a continuous three-dimensional volume, this procedure makes it possible to see and analyze the geographical distribution of important chemical characteristics. The resultant 3D model is an effective instrument for a comprehensive risk analysis (Wei et al., 2025). In addition to showing the distribution of sulfide minerals, it also shows the possible water flow channels through the pile and the areas where these two crucial elements meet, which are the exact places where AMD is most likely to form.

4.3 Case studies: proof of concept

Several studies have shown that this integrated strategy is effective. For instance, ERT and IP surveys were effectively integrated with focused geochemical sampling in a case study conducted at a copper mining waste rock pile in Canada (Ali et al., 2025). A sizable, high-chargeability anomaly in a low-resistivity zone near the pile's base was discovered by the geophysical surveys; this signature strongly suggests the presence of a subsurface, sulfide-rich layer that is saturated with conductive fluids (Ali et al., 2025). A number of boreholes were dug in response to these findings. A high concentration of reactive pyrite and a highly negative Net Neutralizing Potential (NNP) were verified by further geochemical investigation of the core samples from this anomaly, suggesting a large potential for AMD formation (Power & Almpanis, 2022). This result, which would have been difficult to acquire using a random sample technique, enabled the creation of a highly focused and cost-effective remedial strategy. In another case, geochemical testing verified the clay's poor permeability, and GPR was utilized to map the internal stratigraphy and the identification of a clay-rich layer within a garbage pile (Servos & Power, 2024). Although the entire pile seemed to be rather dry, this combined data showed that the clay layer was functioning as a restricting layer, resulting in a "perched" water table and a confined zone of saturation where AMD was actively developing.

4.4 Benefits and challenges of integration

An integrated geophysical-geochemical method has several important advantages. By offering a spatially continuous picture of the garbage pile, it results in a risk assessment that is more thorough and precise. By limiting the number of samples needed and directing them to the most important sites, it enables more successful and economical sampling operations. As a result, repair techniques that target the precise causes and sites of AMD development become more knowledgeable and efficient (Pierwola et al., 2020). Additionally, the 3D models assist stakeholders grasp and comprehend the complexity of the issue by acting as effective communication tools.

Despite these benefits, difficulties persist. The scale mismatch between the discrete character of geochemical samples and the continuous nature of geophysical data is the main challenge. Additionally, the interpretation of the geophysical data is not unique, necessitating a thorough knowledge of both geophysics and geology to prevent misunderstandings. Moreover, a multidisciplinary team with knowledge of geophysics, geochemistry, and geostatistical modeling is necessary for the effective use of this strategy (Servos & Power, 2024). Some high-resolution geophysical surveys can be expensive, but the savings in sampling and the improved accuracy of the final risk assessment frequently make up for this. For this effective strategy to be widely adopted, these issues must be resolved by standardized procedures, enhanced modeling software, and ongoing multidisciplinary training.

5 Future outlook

A synergistic integration of geophysical and geochemical approaches is the most efficient way to obtain the 3D characterization of mining waste heaps, which is a necessary step for accurate AMD prediction (Hariram et al., 2023). This review has emphasized how geochemical tests, such as Acid-Base Accounting (ABA) and kinetic tests, provide the vital chemical data on acid-generating potential, while geophysical techniques, such as ERT and IP, provide the necessary structural and spatial context. When these techniques are combined, it is possible to create intricate 3D models that convert disparate data points into a continuous, spatially resolved picture of AMD risk (Matsumoto et al., 2018) (Figure 4).

One of the most potential future prospects is the expanded use of sophisticated sensing technology and data science. Insights into surface characteristics, temperature anomalies, and plant stress—all of which can act as stand-ins for

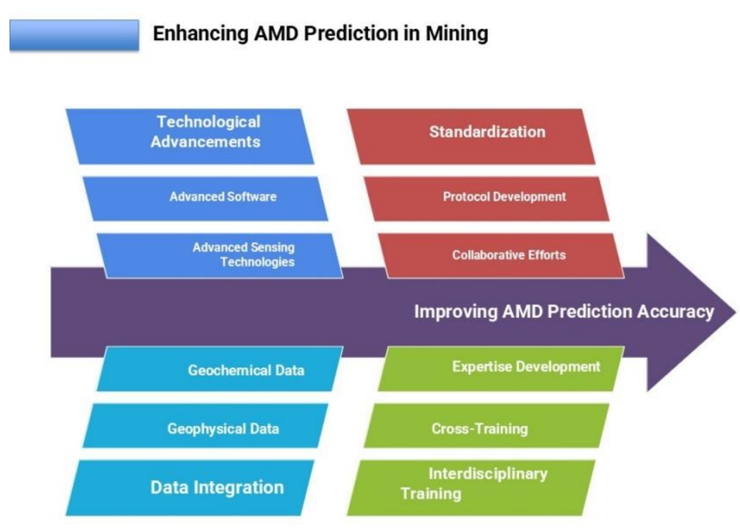

Figure 4 Shows the limitation and future outcomes of AMD.

underlying geochemical processes—could be obtained by combining remote sensing data from drones and satellite pictures (Masina et al., 2020). Furthermore, integrated datasets are perfect for machine learning (ML) and artificial intelligence (AI) research due to their growing number and complexity. When combined with environmental, geophysical, and geochemical data, machine learning algorithms may uncover intricate patterns and connections that are difficult for humans to see. This could lead to a significant leap in predictive accuracy, allowing for the real-time forecasting of AMD onset and the identification of high-risk zones with unprecedented precision (Jooshaki et al., 2021).

Instrumentation technological developments are also quite promising. The creation of more affordable, portable geophysical sensors with greater resolution may speed up and lower the cost of surveys, allowing for their broader use. Similar to this, developments in automated geochemical sensors and on-site testing kits may lessen the need for laborious laboratory investigations by offering quick feedback that may guide decisions in real time (Dadrass Javan et al., 2025). The capacity to view intricate 3D models and effectively integrate various information will continue to be improved by the growing sophistication of geological and environmental modeling software, making these tools more widely available to practitioners.

Despite these encouraging advances, obstacles persist. The standardization of protocols for data integration, processing, and gathering is urgently needed. The creation of reliable, broadly applicable prediction models may be impeded by the absence of a consistent methodology, which also makes it challenging to compare findings from various research. To create best practices that can guarantee the accuracy and comparability of data, business, academia, and regulatory agencies must work together. Additionally, because this job is intrinsically multidisciplinary, a new generation of specialists with cross-training in data science, geophysics, and geochemistry is needed. It will be crucial to keep funding multidisciplinary education and training in order to develop the knowledge needed to take full advantage of these integrated methods.

6 Conclusion

In conclusion, the integrated geophysical-geochemical approach represents the state-of-the-art methodology for the comprehensive 3D characterization of mining waste piles. It provides the detailed, spatially accurate information necessary to transition from reactive management of AMD to proactive prediction and prevention. By embracing future innovations in remote sensing, machine learning, and sensor technology, while simultaneously addressing the challenges of standardization and professional training, the mining industry can move towards a more sustainable and environmentally sound future where the legacy of mining waste is managed with both precision and foresight.

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References

[1] Aallaoui A. E., Elghali A., Hakkou R., Taha Y., Benzaazoua M., & Ghorfi M. E. (2025). 3D geometallurgical characterization of coal mine waste rock piles for their reprocessing purpose. International Journal of Coal Science & Technology, 12(1), 16.

[2] Agboola O., Babatunde D. E., Isaac Fayomi O. S., Sadiku E. R., Popoola P., Moropeng L., Yahaya A., & Mamudu O. A. (2020). A review on the impact of mining operation: Monitoring, assessment and management. Results in Engineering, 8, 100181.

[3] Ali M. A., Mewafy F. M., Qian W., Alshehri F., Ahmed M. S., & Saleem H. A. (2023). Integration of Electrical Resistivity Tomography and Induced Polarization for Characterization and Mapping of (Pb-Zn-Ag) Sulfide Deposits. Minerals, 13(7).

[4] Ali M. A. H., Qian W., Rabeiy R., Saleem H. A., Mohamed A. S., Muhammad A. U., & Shebl A. (2025). Environmental impact assessment of leachate from mining tailings using electrical resistivity imaging. Scientific Reports, 15(1), 23671.

[5] Aphane V., & Vermeulen P. D. (2015). ACID MINE DRAINAGE AND ITS POTENTIAL IMPACT ON THE WATER RESOURCES IN THE WATERBERG COALFIELD, SOUTH AFRICA. South African Journal of Geology, 118(1), 55-70.

[6] Atherton C., Wilson D., Holland S. P., Raymond K. E., Barsi D. R., Zak J., Smith L., Sego D. C., Amos R. T., Paktunc D., Ptacek C. J., & Blowes D. W. (2025). Diavik Waste Rock Project: Post-emplacement investigation of sulfide weathering from a deconstructed experimental waste-rock pile. Applied Geochemistry, 181, 106293.

[7] Bevandić S., Blannin R., Vander Auwera J., Delmelle N., Caterina D., Nguyen F., & Muchez P. (2021). Geochemical and Mineralogical Characterisation of Historic Zn–Pb Mine Waste, Plombières, East Belgium. Minerals, 11(1).

[8] Brar K. K., Etteieb S., Magdouli S., Calugaru L., & Brar S. K. (2022). Novel approach for the management of acid mine drainage (AMD) for the

recovery of heavy metals along with lipid production by Chlorella vulgaris. J Environ Manage, 308, 114507.

[9] Carrera A., Barone I., Pavoni M., Boaga J., Dal Ferro N., Cassiani G., & Morari F. (2024). Assessment of different agricultural soil compaction levels using shallow seismic geophysical methods. Geoderma, 447, 116914.

[10] Chang C., Maio F. D., Bheemireddy R., Posthoorn P., Gebremariam A. T., & Rem P. (2025). Intelligent optimization of particle size distribution in unscreened recycled coarse aggregates using 3D surface analysis. Journal of Industrial Information Integration, 46, 100864.

[11] Chapter 1 - Introduction. (1976). In J. S. Sumner (Ed.), Developments in Economic Geology (Vol. 5, pp. 1-14). Elsevier.

[12] Cruz R., Bertrand V., Monroy M., & González I. (2001). Effect of sulfide impurities on the reactivity of pyrite and pyritic concentrates: a multi-tool approach. Applied Geochemistry, 16(7), 803-819.

[13] Dadrass Javan F., Samadzadegan F., Toosi A., & van der Meijde M. (2025). Unmanned Aerial Geophysical Remote Sensing: A Systematic Review. Remote Sensing, 17(1).

[14] Dimech A., Cheng L., Chouteau M., Chambers J., Uhlemann S., Wilkinson P., Meldrum P., Mary B., Fabien-Ouellet G., & Isabelle A. (2022). A Review on Applications of Time-Lapse Electrical Resistivity Tomography Over the Last 30 Years : Perspectives for Mining Waste Monitoring. Surv Geophys, 43(6), 1699-1759.

[15] Duz B. G., Moreira C. A., Hartwig M. E., Miano F. Q., & Furlan L. M. (2025). Electrical resistivity and induced polarization in the investigation of acid drainage in decommissioning a mine. REM - International Engineering Journal, 78.

[16] El-Raouf A. A., Doğru F., Abdelrahman K., Fnais M. S., El Manharawy A., & Amer O. (2023). Using Airborne Geophysical and Geochemical Methods to Map Structures and Their Related Gold Mineralization. Minerals, 13(2).

[17] García-Nieto M. C., Martínez-Segura M. A., Navarro M., Valverde-Palacios I., & Martínez-Pagán P. (2024). A Geophysical Investigation in Which 3D Electrical Resistivity Tomography and Ground-Penetrating Radar Are Used to Determine Singularities in the Foundations of the Protected Historic Tower of Murcia Cathedral (Spain). Remote Sensing, 16(21).

[18] García G., & Rosique G. (2025). Underlying Causes of Long-Term Environmental Pollution by Waste from an Abandoned Metal Mining District: When Legislative and Remediation Measures Are Ineffective. Environments, 12(1).

[19] GRISHIN P. F., & YERMAK A. A. (2019). Perspective directions of complex processing of residual product of the process «Unicracking». The Volume contains works of young researchers-participants of the XV International Forum-Contest of Students and Young Researchers "Topical Issues of Rational Use of Natural Resources", which was held at St. Petersburg Mining University on May 13-17, 2019. The Volume can be of great interest for a wide range of researchers, scientists, lecturersuniversity, specialists and managers of industrial enterprises and organisations as well as for businesspeople involved in exploration, prospecting, development and processing of minerals.,

[20] Hageman P. L., Seal R. R., Diehl S. F., Piatak N. M., & Lowers H. A. (2015). Evaluation of selected static methods used to estimate element mobility, acid-generating and acid-neutralizing potentials associated with geologically diverse mining wastes. Applied Geochemistry, 57, 125-139.

[21] Hariram N. P., Mekha K. B., Suganthan V., & Sudhakar K. (2023). Sustainalism: An Integrated Socio-Economic-Environmental Model to Address Sustainable Development and Sustainability. Sustainability, 15(13).

[22] Hauck C. (2013). New Concepts in Geophysical Surveying and Data Interpretation for Permafrost Terrain. Permafrost and Periglacial Processes, 24(2), 131-137.

[23] Jaishankar M., Tseten T., Anbalagan N., Mathew B. B., & Beeregowda K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. Interdiscip Toxicol, 7(2), 60-72.

[24] Jamieson H. E. (2011). Geochemistry and Mineralogy of Solid Mine Waste: Essential Knowledge for Predicting Environmental Impact. Elements, 7(6), 381-386.

[25] Jessell M. (2001). Three-dimensional geological modelling of potential-field data. Computers & Geosciences, 27(4), 455-465.

[26] Jia J., & Ye W. (2023). Deep Learning for Earthquake Disaster Assessment: Objects, Data, Models, Stages, Challenges, and Opportunities. Remote Sensing, 15(16).

[27] Jooshaki M., Nad A., & Michaux S. (2021). A Systematic Review on the Application of Machine Learning in Exploiting Mineralogical Data in Mining and Mineral Industry. Minerals, 11(8).

[28] Kalyoncu Erguler G., Erguler Z. A., Akcakoca H., & Ucar A. (2014). The effect of column dimensions and particle size on the results of kinetic column test used for acid mine drainage (AMD) prediction. Minerals Engineering, 55, 18-29.

29

Karlsson T., Alakangas L., Kauppila P., & Räisänen M. L. (2021). A Test of Two Methods for Waste Rock Drainage Quality Prediction: Aqua Regia Extraction and Single-addition Net-acid Generation Test Leachate Analysis. Mine Water and the Environment, 40(3), 736-751.

[30] Koucham M. h., Khalil A., Mouhagir L., Zouhri L., & El Adnani M. (2025). Comprehensive Assessment of Environmental Behavior of Mine Tailings for Sustainable Waste Management and Mitigation of Pollution Risks. Water, 17(1).

[31] Kukemilks K., & Wagner J.-F. (2021). Detection of Preferential Water Flow by Electrical Resistivity Tomography and Self-Potential Method. Applied Sciences, 11(9).

[32] Li Z., Sun F., Jiang W., Li X., Jiang J., Jin F., Lu J., & Yang F. (2024). Bibliometric Analysis of Trends and Research Progress in Acid Mine Drainage Remediation from 1990 to 2023. Water, 16(13).

[33] Liu Y., Liu M., Xing J., & Ye Y. (2023). Dual-Parameter Simultaneous Full Waveform Inversion of Ground-Penetrating Radar for Arctic Sea Ice. Remote Sensing, 15(14).

[34] Lu Y., Xie Q., Cao C., Huang J., Wang J., Ren B., & Liu Y. (2025). Determination of leachate leakage around a valley type landfill and its pollution and risk on groundwater. Sci Rep, 15(1), 9465.

[35] Maleki Z. R., Wilkinson P., Chambers J., Donohue S., Holmes J. L., & Stirling R. (2025). Geophysical Survey and Monitoring of Transportation Infrastructure Slopes (TISs): A Review. Geosciences, 15(6).

[36] Manrique I. I. (2023). Quantitative Interpretation of Geophysical Data in Anthropogenic Waste Deposits and Disposal Sites for Resource Recovery and Remediation. Universite de Liege (Belgium).

[37] Mashaan N., & Yogi B. (2025). Mining Waste Materials in Road Construction. Encyclopedia, 5(2).

[38] Masina M., Lambertini A., Daprà I., Mandanici E., & Lamberti A. (2020). Remote Sensing Analysis of Surface Temperature from Heterogeneous Data in a Maize Field and Related Water Stress. Remote Sensing, 12(15).

[39] Matsumoto S., Ishimatsu H., Shimada H., Sasaoka T., & Kusuma G. J. (2018). Characterization of Mine Waste and Acid Mine Drainage Prediction by Simple Testing Methods in Terms of the Effects of Sulfate-Sulfur and Carbonate Minerals. Minerals, 8(9).

[40] Matthies R., Bowell R. J., & Williams K. P. (2011). Geochemical assessment of gold mine tailings proposed for marine tailings disposal. Geochemistry: Exploration, Environment, Analysis, 11(1), 41-50.

[41] Miller J. R. (2013). Forensic Assessment of Metal Contaminated Rivers in the 21st Century Using Geochemical and Isotopic Tracers. Minerals, 3 (2), 192-246.

[42] Moyo A., Parbhakar-Fox A., Meffre S., & Cooke D. R. (2025). An accelerated kinetic leach test for geochemical and environmental characterisation of acid and metalliferous drainage. Environmental Technology & Innovation, 38, 104092.

[43] Ochoa-Guerrero K. M., Rodriguez-Espinosa P. F., Martinez-Tavera E., Sabarathinam C., Sujitha S. B., Hérnandez-Mendoza H., & Alsabti B. (2025). Hydrogeochemical behavior and seasonal fractionation of rare earth elements in a volcanic river system influenced by natural and human factors, central Mexico. Journal of South American Earth Sciences, 164, 105663.

[44] Peng C., Wang C., & Li Z. (2025). Review of geophysical data acquisition methods for underground feature detection and future trends. Tunnelling and Underground Space Technology, 163, 106731.

[45] Pierwola J., Szuszkiewicz M., Cabala J., Jochymczyk K., Zogala B., & Magiera T. (2020). Integrated geophysical and geochemical methods applied for recognition of acid waste drainage (AWD) from Zn-Pb post-flotation tailing pile (Olkusz, southern Poland). Environ Sci Pollut Res Int, 27(14), 16731-16744.

[46] Power C., & Almpanis A. (2022). Improved imaging efficiency of large mine waste rock piles with integrated electrical and electromagnetic geophysical techniques. Journal of Applied Geophysics, 206, 104824.

[47] Qi G., Meng G., Yan J., Tang H., & Xue R. (2023). Three-Dimensional Geological – Geophysical Modeling and Prospecting Indications of the Ashele Ore Concentration Area in Xinjiang Based on Irregular Sections. Minerals, 13(7).

[48] Radebe N., & Chipangamate N. (2024). Mining industry risks, and future critical minerals and metals supply chain resilience in emerging markets. Resources Policy, 91, 104887.

[49] Schwardt M., Pilger C., Gaebler P., Hupe P., & Ceranna L. (2022). Natural and Anthropogenic Sources of Seismic, Hydroacoustic, and Infrasonic Waves: Waveforms and Spectral Characteristics (and Their Applicability for Sensor Calibration). Surveys in Geophysics, 43(5), 1265-1361.

[50] Servos M., & Power C. (2024). Improved ERT imaging with 3-D surface-to-horizontal borehole configurations: relevance to dense non-aqueous phase liquids. Geophysical Journal International, 237(1), 389-401.

[51] Song P., Gogineni S., Galkin I. A., Volakis J., Soderblom J. M., Hayes A. G., Reinisch B. W., Giles R. H., Sood R., Zhang H. L., Braaten D., Melosh H. J., Bruzzone L., Venkatakrishnan S. B., Yan J. B., & O'Neil C. R. (2021). Feasibility Study of a [52]High-Resolution Shallow Surface Penetration Radar for Space Application. Radio Science, 56(2), e2020RS007118.

[53] Sun M., Ou J., Li T., Cao C., & Liu R. (2025). Application of Electrical Resistivity Tomography (ERT) in Detecting Abandoned Mining Tunnels Along Expressway. Applied Sciences, 15(5).

[54] Wei G., Zheng B., Dong J., Yang Y., Yang G., Song S., Guo S., & Qi S. (2025). Research Progress of Three-Dimensional Engineering Geological Evaluation Modeling. Sustainability, 17(8).

[55] Wheelock S. J. (2024). Marsscapes to Terrestrial Moonscapes: A Variety of Water Problems The University of Arizona].

[56] Wright K. B. (2005). Researching Internet-Based Populations: Advantages and Disadvantages of Online Survey Research, Online Questionnaire Authoring Software Packages, and Web Survey Services. Journal of Computer-Mediated Communication, 10(3), JCMC1034.

[57] Zeng H., Zhang Q., Du C., Liu J., & Li Y. (2025). Quantitative Relationship Between Electrical Resistivity and Water Content in Unsaturated Loess: Theoretical Model and ERT Imaging Verification. Geosciences, 15(8).

[58] Zhang D., Wang Z., Qin H., Geng T., & Pan S. (2023). GAN-Based Inversion of Crosshole GPR Data to Characterize Subsurface Structures. Remote Sensing, 15(14).