BID | Invest

Development Effectiveness and Strategy Briefs N°37 / December 2025

Smart Mining in Latin America and the Caribbean: Accelerating Transformative Investments

- **Technology adoption will define mining competitiveness in LAC:** The accelerated deployment of technologies such as AI, automation, digital twins, and blockchain is optimizing extraction and processing, while boosting productivity, sustainability, and transparency. Countries that move more rapidly will capture greater investment and achieve stronger global positioning.

- **Tangible impact on efficiency and costs:** Digitalization can improve a mine's throughput rate by 10–20%, increase productivity in drilling operations by 20–30%, and reduce overall costs by approximately 30%. In addition, it makes it possible to exploit deposits that were previously considered unviable.

- **Safety, sustainability, and governance as priorities:** Automation and real-time monitoring reduce labor and environmental risks, while robust digital governance frameworks are critical for managing ethical, operational, and cybersecurity risks.

- **Collaboration and the local ecosystem as key drivers:** Startups, regional suppliers, and research centers complement the global supply. Scaling technology adoption requires effective public-private coordination and financing.

1. INTRODUCTION

In a recent IDB Invest publication, we analyzed the strategic role of the mining sector in the region's energy and technological transition.[1] Latin America and the Caribbean (LAC) hold a significant share of the global reserves needed for decarbonization and technological innovation, positioning the region as a strategic player in the race for critical minerals. This publication builds on that analysis, focusing on how digital transformation and emerging technologies are redefining the mining of critical minerals, and highlights the need to accelerate their adoption to maximize economic, social, and environmental benefits.

WHAT ARE CRITICAL MINERALS? DEFINITION AND GLOBAL CONTEXT

In this document, the term "critical minerals" refers to both minerals and metals that are essential for the energy and technology transition. Minerals are natural materials extracted from the earth, some of which are used to obtain metals like copper, lithium, or silver, later applied across multiple industries.

The global energy transition and technological advancement increasingly depend on these minerals, which are vital for manufacturing batteries, electric vehicles, solar panels, and digital technologies.[2] Demand for critical minerals is projected to more than double by 2030 and quadruple by 2050.[3]

The definition of critical minerals varies by country and strategic priorities. Generally, it refers to resources vital to the economy or national security, with supply chains exposed to vulnerabilities. For example, in the United States, the U.S. Geological Survey (USGS) defines as critical those minerals indispensable for industry and defense, and whose supply may be at risk. In 2025, the USGS includes 60 critical minerals,[4] including copper, lithium, silver, and zinc, as well as 15 rare earths.

In LAC, the definition of critical minerals responds to the local geological and economic context. The region prioritizes resources such as copper, lithium, nickel, and silver not only for their global strategic importance but also for their potential to generate productive linkages, added value, and sustainable regional development.

As demand for critical minerals rises, new technologies are key for mining companies facing growing pressure to increase production, meet higher sustainability and safety standards, and strengthen community engagement and local development. The adoption of Industry 4.0 technologies—including artificial intelligence (AI), automation, advanced sensors, digital governance, and data analytics, as well as new processing-optimization technologies such as biotechnology and direct lithium extraction (DLE)—has gained momentum in recent years, transforming how strategic minerals are explored, extracted, processed, and commercialized. Technological progress has accelerated operational transformations, reshaping manual tasks and increasing the sector's capacity to operate remotely, autonomously, and more sustainably[5].

[1] *The mining sector as a driver of energy and technological progress: Challenges and enabling factors for private investment and sustainability* *Development Effectiveness and Strategy Briefs N°34 / April 2025.*
[2] *Ibid.*
[3] *WRI, 2025*
[4] *USGS, 2025.*
[5] *Chatterjee et al., 2025.*

Historically, the global mining sector has been slow to adopt digital innovations—by 2021, it was 30%-40% less digitally mature than other industries.[6] However, Latin America has made sustained progress in recent years. Countries such as Chile, Peru, Mexico, Argentina, and Brazil are leading projects that integrate technologies to improve efficiency, reduce environmental impacts, and strengthen operational resilience. Digital transformation offers the mining sector a decisive opportunity to innovate and enhance competitiveness in the region.

Although many mining innovations originate outside the region, Latin America has become a strategic space for piloting advanced technologies and transferring knowledge. In recent years, a dynamic ecosystem of startups, local suppliers, and research centers has emerged to develop technological solutions tailored to regional challenges and complementary to global supply chains. Over time, these providers evolve, export, achieve world-class standards, and generate greater added value by strengthening productive linkages and creating new economic and social opportunities.

For Latin America to strengthen its position as a key player in the race for critical minerals, it is essential to accelerate the adoption of these advanced technologies. This requires coordinated public and private sector action to address challenges such as insufficient infrastructure, capital-intensive legacy operations, institutional resistance to change, digital skills gaps, data governance shortcomings, and connectivity limitations. Overcoming these barriers is essential for the region to fully capture the economic, social, and environmental value associated with the mining of the future.

2. WHY IS ACCELERATING TECHNOLOGICAL INNOVATION IN MINING SO IMPORTANT?

The early incorporation of innovations such as AI, automation, digital twins, and blockchain not only enhances economic performance and reduces environmental and social impacts but can also strengthen investor, community, and stakeholder confidence. These technologies boost productivity, lower costs, anticipate operational and environmental risks, improve traceability, and raise transparency standards in a sector historically associated with significant impacts. Today, accelerating the adoption of cutting-edge technologies is essential to transform mining and meet growing demands for sustainability, efficiency, transparency, and accountability.

Electrification, automation, and digitalization are revolutionizing mining operations by replacing analog equipment with integrated autonomous systems that minimize emissions and reduce environmental footprints. This shift enables safer, more efficient, and predictive models, improving productivity and environmental performance. Digital advances make it possible to increase a mine's throughput rate by 10–20%, improve productivity in key operations (such as drilling) by 20–30%, and reduce overall operating costs by around 30%.[7] Additionally, they enable the development of complex or low-grade deposits previously considered economically unviable[8], significantly expanding regional development opportunities.

Technological innovation also plays a critical role in occupational safety. Automation, remote operation, and autonomous tools remove workers from high-risk zones, aligning with global zero-fatality goals.[9] Similarly, drones, sensors, and computer vision systems strengthen structural monitoring, explosives management, and contaminant detection[10] while generating continuous environmental information that allows precise management of critical indicators such as water, air, tailings, and emissions[11]. This real-time measurement capacity enables more informed decision-making and significantly reduces operational and environmental risks.

The local ecosystem in LAC has been expanding in recent years, with more mining-focused startups and local suppliers and stronger research and pilot-testing centers. These players provide flexibility, local knowledge, and rapid response to operational and environmental challenges, complementing international suppliers. Their integration into the mining value chain not only fosters innovation and efficiency but also supports regional development, job creation, and productive diversification, strengthening sustainability and the social license to operate. In Chile, more than 1,500 providers[12] offer innovative solutions for Mining 4.0 and support for tech startups[13] to contribute to more sustainable mining.

Finally, ensuring responsible and sustainable adoption of these technologies requires strong corporate governance frameworks. These frameworks enable clear policies, proactive risk management, and improved oversight, while guaranteeing transparency and accountability throughout the value chain.

[6] BCG, 2021.
[7] Ibid.
[8] Cucuzza, J. 2021.
[9] BHP, 2024.
[10] MCH, 2022.
[11] Cacciuttolo et al., 2024.
[12] Olave, R. 2025.

3. WHAT ARE THE MAIN TECHNOLOGY TRENDS TRANSFORMING MINING IN LAC?

Below are six categories of technology trends—both digital and physical—that seek to optimize resource use and reduce environmental impact in mining. Each section includes concrete examples of how these technologies are being incorporated into mining projects in LAC.

i) Artificial intelligence (AI) and advanced analytics

Artificial intelligence (AI) and digitalization enable the processing of large volumes of operational, environmental, and labor data, enabling more informed and agile decision-making. In Chile, BHP and Microsoft integrated AI and machine learning in the Azure cloud[14] to optimize copper recovery at the Escondida mine. This has reduced water and energy consumption and improved operational efficiency. In Mexico, the company XControl Technologies has implemented generative AI (genAI) solutions for explosives control in underground mines,[15] operational safety, and regulatory compliance.

ii) Automation and robotics

Automation and robotics are already transforming regional mining. Autonomous fleets, drones, and teleoperation systems are reducing worker exposure to risk zones and improving productivity. In Brazil, Vale operates more than 90 autonomous trucks[16] and has automated over 350 processes, consolidating its position as a regional leader in mining innovation. In Chile, the Spence mine uses autonomous drones[17] for conveyor belt inspections, reducing inspection time by 90% and eliminating worker exposure to hazardous areas. Likewise, Scania[18] launched a pilot of electric and autonomous trucks for material transport aimed at reducing emissions and operating costs. In Colombia, Cerro Matoso has implemented bulldozer teleoperation,[19] increasing productivity and reducing occupational risks.

iii) Digital twins

Digital twins allow the of create virtual representations of a mine, replicating the behavior of its processes, which makes it easier to simulate and predict failures. Their use helps decrease operating costs and downtime, while also strengthening operational resilience[20] In Peru, Anglo American uses digital twins[21] at Quellaveco to simulate production scenarios, anticipate risks, and coordinate predictive maintenance, reducing unplanned shutdowns and improving safety.

Also in Peru, Ferreyros developed a digital twin[22] to optimize truck fleet transportation, saving fuel and reducing costs while lowering environmental impact.

In Chile, digital twins have been incorporated into the Escondida mine[23] to improve operations management, optimize resource use, and reduce environmental impacts.

iv) Sensors and Internet of Things (IoT) Networks

Sensors and IoT networks enable real-time monitoring, improving efficiency and safety. In Mexico, the Peñasquito mine, one of the country's main silver producers—a metal valuable for solar energy, electronics, and electric vehicles—has upgraded its Control Center by integrating Wi-Fi and GPS to coordinate its mining fleet in real time,[24] reducing fuel use, decreasing emissions, and optimizing haul cycles. Digitalization is also progressing rapidly in Mexico, Peru, and Chile through private 4G/5G networks for mining operations. In Mexico, Ericsson and Epiroc[25] implemented a private cellular network that supports autonomous equipment operation, real-time safety monitoring, and improved data traceability. In Peru and Chile, Ericsson[26] is developing 5G networks to enable automation, data analytics, and the IoT connectivity, linking mines with remote control centers and optimizing energy and operational efficiency.

An example from Canada illustrates the potential for replication in LAC. Goldcorp[27] (now Newmont Goldcorp), uses smart ventilation sensors in underground mines through ventilation-on-demand systems, reducing electricity consumption and improving safety by ensuring clean air in critical zones. This technology could be replicated in underground copper mines in Latin America, where safety and efficiency are priorities.

v) Blockchain and digital traceability

Digital governance is emerging as a critical new frontier in mining. Solutions such as blockchain and digital compliance platforms are strengthening traceability and commercial transparency,[28] regulatory compliance, and the social license to operate. These platforms help mining companies comply with environmental, social, and operational regulations through automated reporting, audits, and data traceability. In Chile, the state-owned Codelco uses the Waybridge platform to digitalize and trace every copper transaction, improving commercial transparency. In Colombia, the state platform Zeta[29] digitalizes the submission and evaluation of technical mining documents, improving regulatory efficiency and ensuring greater traceability in supervision processes.

Digital governance not only involves the use of advanced systems but also the establishment of clear structures for decision-making, responsibility assignment, and effective accountability mechanisms. The aim is to not only have solid governance frameworks but also adaptive systems capable of responding agilely to new realities and mining methods. This includes promoting more dynamic decision-making processes based on principles of transparency, responsibility, and accountability. Just as digital technologies and AI are transforming mining operations, governance practices must be updated to effectively address the ethical, operational, and value-creation challenges these tools bring.

13 Revista Nueva Minería y Energía, 2025.
14 BHP, 2023.
15 BNamericas, 2025a.
16 Ibid.
17 BHP, 2022.
18 BNamericas, 2025b.
19 El Universal, 2024.
20 América Minera, 2024.
21 Anglo American, 2025.
22 Ferreyros, 2025.
23 Tecnología Minera, 2025.
24 Rumbo Minero Internacional, 2025.
25 Ericsson, 2025.
26 Idem.
27 BID, 2022.
28 Guía Chile Energía, 2019.
29 Agencia Nacional de Minería Colombia, 2025.
30 Bunel, E. E, CEPAL, 2025.
31 Jovine, R. F., & Paz, M. J. 2025.
32 Bunel, E. E., CEPAL. 2024
33 Mining.com, 2024.
34 Bunel, E. E, CEPAL, 2025.

vi) Process innovations

Technological innovations in extraction, energy, and water systems—including direct lithium extraction (DLE), desalination, fleet electrification, biotechnology, and circular economy approaches—are reducing environmental impact and generating shared value in mining. Innovation in extraction processes[30] is essential to reduce environmental impacts.

One of the most significant advances in Latin America is the growing adoption of direct lithium extraction (DLE),[31] a technology that allows lithium to be recovered from brines with lower water consumption, faster processing speeds, and no generation of solid waste. Argentina leads the way with projects such as Pozuelos-Pastos Grandes, Sal de Oro, Rincón, and the historic Fénix Project in the Salar del Hombre Muerto, where companies such as FMC, Livent, Arcadium, and Rio Tinto have applied DLE since the 1990s, when the technology had efficiency and purity limitations. Today, the most advanced versions incorporate[32] selective adsorption, ion exchange, and membranes, achieving recovery rates above 90%, lower water footprints, and processing times reduced from months to days. The Lilac Solutions pilot plant in Jujuy also stands out. In Chile, the state-owned ENAMI has begun testing high Andean brines in collaboration with international companies to evaluate DLE technologies such as adsorption, ion exchange, and electrodialysis. In Bolivia, the CATL-Brunp consortium is developing advanced electrochemical methods[33] for lithium extraction from natural and geothermal brines. Despite its potential, DLE faces technical[34] (such as material selectivity), energy (electricity consumption), and environmental[35] (liquid waste management) challenges, all of which require rigorous evaluation to ensure scalability and sustainability.

Desalination of seawater and fleet electrification in the copper sector also stand out for their contribution to operational efficiency and environmental sustainability. In Chile, Quebrada Blanca Phase 2 (Teck Resources) has a large-scale desalination plant. It uses desalinated water in 100% of its production processes while advancing toward 100% renewable energy use, avoiding around 1.6 million tons of CO_2 per year. Teck has also implemented an Integrated Operations Center (IOC) with real-time control of the entire mine-to-port chain, supported by 360° video walls, wireless connectivity, and centralized decision-making, which optimizes logistics, reduces transport times, and improves energy efficiency. Another example is the alliance between ABB and Codelco, which seeks to decarbonize operations through electric vehicles and digital control systems.[36] These initiatives optimize resource use and meet ESG requirements by reducing emissions and improving environmental performance.

In the Andean salt flats, a regional project supported by the European Union and led by scientific institutions from Chile, Argentina, and Uruguay[37] uses satellite images, remote sensors, and AI to monitor the impact of lithium extraction on aquifers, ecosystems, and local communities. These initiatives strengthen environmental governance and promote more transparent and sustainable management, requiring clear rules for data and algorithm use throughout the value chain.

Circular economy strategies are generating shared value and reducing environmental liabilities. In Brazil, Vale has developed the company Agera to transform iron tailings into sustainable sand,[38] generating useful by-products for construction. This type of innovation is replicable in critical mineral mining and demonstrates how waste can become a value-creation opportunity.

Biotechnology is also advancing ecosystem restoration in areas affected by mining. The Peruvian company Foreslab[39] uses plant bioengineering techniques—such as temporary immersion, organogenesis, and embryogenesis—to produce native species for the rehabilitation of degraded areas. These solutions contribute to soil and biodiversity recovery and their integration into mine closure planning strengthens sector sustainability.

[35] Jiménez, D., & Saenz, M. 2022.
[36] Mining Digital, 2024.
[37] AGCID Chile, 2024.
[38] Vale, 2023.
[39] Foreslab. 2025.

Highlighted Cases of Technological Innovation in Critical Minerals in LAC

Technology/Innovation Category (Definition)	Technology and Implementation Cases	LAC Countries	Associated Minerals/Metals	Key Functions and Purposes
AI and Advanced Analytics (Techniques to process large data sets using algorithms, statistical models, and machine learning)	• Process optimization platforms • Machine learning for resource modeling • Predictive tools for exploration	Chile, Colombia, Peru	Copper, lithium, and others	• Improve worker safety • Support decision-making • Optimize mining processes
Automation and Robotics (Autonomous and remotely controlled systems)	• Autonomous trucks and drills • Remotely controlled equipment and drones • Robotic sampling systems	Chile, México Peru	Copper, others	• Improve operational safety by minimizing human exposure in high-risk areas • Increase efficiency and productivity
Digital Twins (Digital replicas of physical assets and processes)	• Virtual models of mining operations • Integrated remote monitoring	Chile, Peru	Copper	• Simulate mining processes • Optimize operations and maintenance • Coordinate and monitor assets remotely
Blockchain and Digital Traceability (Distributed ledger technology for secure and transparent transactions)	• Digital platforms for the supply chain • Mineral traceability systems	Chile	Copper	• Enable traceability of minerals and transactions • Ensure secure and transparent supply chains • Digitalize and automate compliance processes
Sensors and Networks (IoT) (Connected sensors and networks)	• Smart wearable devices for health and safety • Conveyor-belt inspection drones • Centralized access-control systems	Argentina, Brazil, Chile, Colombia, Jamaica, Mexico, Peru	Copper, lithium, zinc, and others	• Monitor equipment and operations in real time and collect data • Control access and ensure safety • Detect unauthorized activities and operational anomalies
Process Innovations (Technological improvements in extraction, energy, and water systems)	• Automated process control • Real-time plant monitoring • Direct lithium extraction	Argentina, Bolivia, Chile, Peru	Copper, lithium, silver, and others	• Increase sustainability and efficiency • Supply clean energy and water • Improve resource extraction and recovery

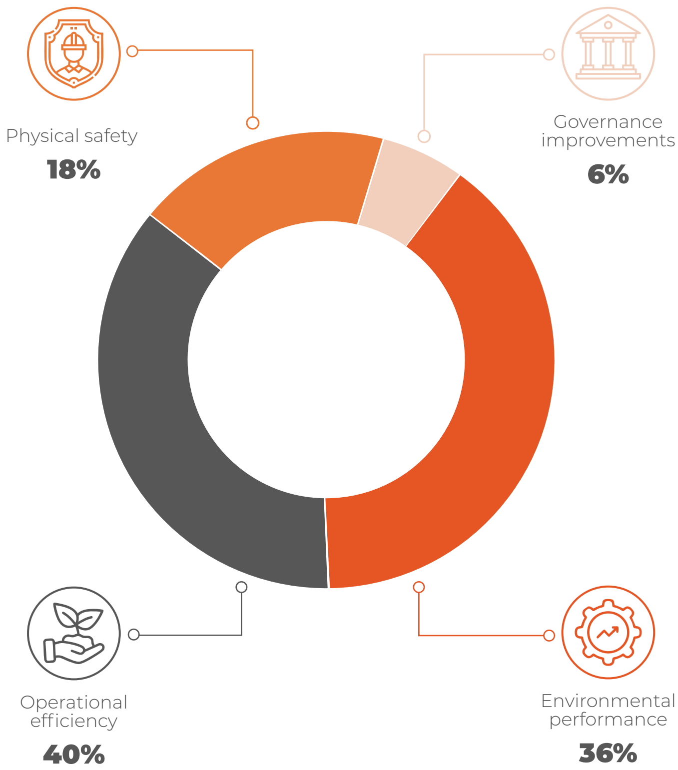
Note: *This table summarizes the analysis of mining projects in critical mineral-producing countries in the region, in which dozens of specific instances of technological innovation with multiple purposes were identified.*

4. WHERE ARE EMERGING TECHNOLOGIES GENERATING THE GREATEST IMPACT IN MINING?

Our analysis of a sample of critical mineral mining projects in the region's main producing countries identified trends in technology adoption and their impact on the industry.[40] The results indicate that most technological initiatives are aimed at improving **operational efficiency (40%),** followed by those focused on **environmental performance (36%)** and **physical safety (18%).** In comparison, only a small share of the identified solutions is explicitly associated with **improvements in governance (6%).**

This distribution indicates that technological adoption in critical mineral mining in LAC has mainly been focused on improving productivity and reducing costs, complemented by growing efforts in environmental management and worker safety. However, the limited presence of initiatives related to governance and traceability reveals a strategic opportunity to promote digital solutions that enhance transparency, ensure data integrity, and strengthen accountability throughout the value chain.

Impact of Technological Advances in the Critical Minerals Industry



5. WHAT IS NEEDED FOR SAFE, INCLUSIVE, AND LARGE-SCALE TECHNOLOGICAL ADOPTION IN MINING?

Digital and physical innovations are creating new business opportunities and value generation by enabling more efficient, sustainable, and connected operating models. These technologies not only optimize existing processes but also transform decision-making, risk management, and productive linkages within and beyond the sector.

Despite progress, the adoption of emerging technologies is uneven across the region. While some countries demonstrate leadership and technological maturity, others face delays due to gaps in connectivity, financing, regulation, and institutional capacity, as well as a lack of specialized technical skills. This disparity limits the region's ability to fully capture the economic and environmental benefits these innovations offer.

The private sector plays a leading role in driving these technologies. However, achieving impact at scale requires closer collaboration between companies, governments, technology providers, academia, and financial institutions. Cross-sector coordination is key to reducing entry barriers, sharing risks, and accelerating technology transfer. In this context, development banks—such as the IDB Group—can act as catalysts by offering financing, technical assistance, and reference frameworks for the responsible adoption of innovations.

Digital Governance and Risk Management

For the benefits of digital transformation to fully materialize, it is essential to strengthen corporate and sectoral governance frameworks. Digitalization accelerates processes and expands capabilities but also introduces new ethical, operational, and cybersecurity risks that must be managed from the outset.

An accelerated innovation process requires clear decision-making structures, explicit assignment of responsibilities, and strong mechanisms to anticipate and mitigate risks. This includes robust criteria for the responsible use of data and algorithms, privacy and cybersecurity protocols, and monitoring systems that ensure transparency along the value chain. Without these pillars, technological adoption can generate information asymmetries, digital vulnerabilities, or unforeseen impacts on workers, communities, and ecosystems.

Governance must function as both an enabler and guardian of responsible innovation. It is not enough to have infrastructure and specialized talent: it is necessary to build an organizational architecture that connects digital strategy, risk management, and continuous oversight. This integrated approach allows technologies to be scaled safely and reliably, increasing the social legitimacy of mining operations and strengthening trust among companies, communities, and regulators.

[40] *Argentina, Bolivia, Brazil, Chile, Mexico, Peru.*

6. CONCLUSION

Global demand for critical minerals will continue to grow, and the digital and sustainable transformation of critical mineral mining represents a unique opportunity for LAC. It allows for productivity improvements and higher environmental standards, positioning the region as a global reference in responsible mining. However, time is of the essence: the speed of technological adoption will be decisive for attracting investment, reducing negative impacts, and strengthening social trust.

Leveraging this opportunity requires accelerating investment, consolidating public-private collaboration, strengthening technical capacities, and defining clear oversight roles. In this process, it is essential to strengthen the regional innovation ecosystem by more actively integrating startups, local suppliers, and research centers. These actors provide technological solutions tailored to regional challenges, promote economic and social development, and contribute to productive diversification and sustainability. Acting quickly and responsibly, and harnessing local talent and creativity, will be essential for LAC to deploy and scale these innovations and become an international benchmark in responsible mining.

Additional Information

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Acknowledgments: We would like to thank Marta Gutierrez F., Andrés Afanador, Bruno Sbardellini C., Juan Flores, Rodrigo Navas, and Usdin L. Martinez O. for their valuable reviews and contributions, as well as Norah Sullivan and Wendy Barnet for their support in editing this document.

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This publication analyzes how digital transformation is redefining the mining of critical minerals in Latin America and the Caribbean. It presents six key trends: AI and advanced analytics, automation and robotics, digital twins, blockchain and traceability, sensors and IoT networks, and process innovations. These technologies are essential for increasing efficiency, reducing environmental impacts, and strengthening regional competitiveness in the race for critical minerals.

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Design: Greta Design