AI and Digital Governance for Critical Minerals in the Asia-Pacific

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Abstract

The race for critical minerals is increasingly a race for data—data that can illuminate deposits, monitor impacts and strengthen supply-chain transparency. Artificial intelligence (AI) and digital technologies are reshaping how these minerals—essential for energy transitions, digitalisation, mobility and defence—are governed across the Asia-Pacific. Tools such as machine learning, geospatial analytics, digital twins (DTs) and Internet-of-Things (IoT) sensors are transforming exploration and extraction, while blockchain systems and Digital Product Passports (DPPs) support traceability, circularity and robust measurement–reporting–verification (MRV). Drawing on regional developments, this article argues that policy integration and capacity-building are crucial to align digital innovation with environmental, social and governance (ESG) objectives and to build more transparent and efficient critical-minerals supply chains.

Introduction — data and minerals in the sustainability era

Critical minerals have emerged as the backbone of the twenty-first-century economy, powering batteries, energy technology, semiconductors, defence platforms and advanced digital systems (Christmann & Lefebvre, 2022; International Energy Agency, 2025). Their growing importance for energy transitions, digital connectivity and strategic autonomy has made the governance of these materials a defining issue for the Asia-Pacific. Yet rapidly growing demand has heightened regional vulnerabilities—including price volatility, environmental pressures and the concentration of refining capacity—while opacity in some supply chains further amplifies these structural risks (Vivoda et al., 2025a).

Across this landscape, artificial intelligence (AI) and digital technologies are reshaping how subsoil resources are discovered, developed and governed. Machine-learning (ML) models analyse geological, hyperspectral and geophysical datasets to identify mineralisation patterns with high precision. Digital-twin (DT) platforms create dynamic virtual replicas of mines and processing plants, allowing operators and regulators to test operational scenarios and optimise performance. Internet-of-Things (IoT) sensors enable real-time monitoring of water use, tailings stability and emissions, while blockchain and Digital Product Passports (DPPs) record provenance and environmental attributes across the supply chain (Calvão & Archer, 2021; World Economic Forum, 2021).

This digital transformation aligns with the objectives of the *Asia-Pacific Tech Monitor* special issue and the strategic direction of the Asian and Pacific Centre for Transfer of Technology (APCTT, n.d.). For mineral-rich economies such as Australia, China, India, Indonesia, Mongolia, and the Philippines, AI offers new tools for enhancing efficiency while embedding transparency and accountability in governance systems. For resource-importing states such as Japan and the Republic of Korea, AI-enabled traceability and DPPs are increasingly essential for securing reliable mineral inputs and meeting emerging European Union (EU) and U.S. supply-chain transparency requirements in batteries, electronics and advanced manufacturing.

Governments across the region are increasingly embedding digital technologies into their minerals strategies, using AI, geospatial analytics and automation to modernise exploration, safety systems and environmental management. In China, major advances in intelligent mining are emerging, where fully integrated AI, 5G networks, autonomous haulage, hazard-warning platforms, and remote-operation systems are transforming safety, efficiency, and mine control capability (Leng & Xie, 2024). Japan's *Green Innovation Fund* supports AI-enabled recycling of rare-earth magnets (Ministry of Economy, Trade and Industry, 2023). The Republic of Korea is making similar progress, using digital lifecycle management systems mandated under the *Resource Circulation Act* to support AI-enabled traceability and recycling across its battery and manufacturing sectors (Ministry of Environment, 2023). In India, the *National Mineral Policy* incorporates remote sensing and hyperspectral analytics (Ministry of Mines, 2019).

Regionally, ASEAN has articulated a coherent vision through the *ASEAN Minerals Development Vision* (ASEAN, 2025), which positions the region as a leading destination for sustainable minerals investment by emphasising high-quality digital data, strong governance, responsible production, decarbonisation, and human-capital development, supported by successive five-year cooperation plans.

While digital technologies can support improved oversight and decision-making, they do not automatically resolve underlying governance challenges. The AI infrastructure itself—data centres, transmission networks and chip manufacturing—is material-intensive, driving further demand for copper, power and water. In settings where institutional capacities vary, AI tools may influence existing patterns of data access, capital allocation or environmental exposure in uneven ways (Vivoda et al., 2025b). Governance systems must therefore account for the "material footprint of the digital" to ensure net-positive outcomes (United Nations Environment Programme, 2024).[1] The central challenge is therefore how digital intelligence can be aligned with principles of security, sustainability and justice—a minerals governance trilemma that calls for cooperation among international organisations, governments, industries and communities (McMaster, 2024).

This article explores how AI-enabled systems can enhance exploration, strengthen environmental performance and accelerate circular-economy models. It proceeds in four parts: (i) data-driven exploration; (ii) smart extraction and ESG-aligned operations; (iii) traceability, circularity and resource recovery; and (iv) policy pathways for embedding digital innovation within resource-governance frameworks. It concludes by summarising the strategic imperatives for regional cooperation.

Data-driven exploration — from intuition to prediction

Exploration has traditionally been one of the most uncertain and capital-intensive stages of the mineral value chain. Success rates remain low, and early-stage activities often occur in environmentally sensitive or poorly mapped areas, heightening ecological and social risks. In the Asia-Pacific—home to vast but unevenly characterised mineral systems—such uncertainty has often fuelled land-use tensions, slowed permitting processes and led to inconsistent exploration outcomes.

Advances in AI and digital geoscience are reshaping this landscape. AI-enabled models increasingly allow geoscientists to integrate multiple datasets into probabilistic prospectivity maps, supporting a shift from intuition-driven fieldwork toward more data-intensive and predictive exploration workflows (Xiong et al., 2018).

Machine learning as the new engine of discovery

ML techniques—including random forests, gradient boosting, convolutional neural networks and support-vector machines—are now widely applied to analyse geochemical, geophysical, structural and spectral datasets. By revealing patterns that are not easily detectable through traditional interpretation, these models can generate mineral-prospectivity maps with higher precision (Cracknell & Reading, 2014; Rodriguez-Galiano et al., 2015).

Australia is at the frontier of these developments. Commonwealth Scientific and Industrial Research Organisation's (CSIRO) *Deep Earth Imaging* program has developed advanced imaging, inversion and data-fusion techniques that dramatically improve understanding of Australia's subsurface structures, integrating diverse geophysical and geological datasets to support more accurate and less invasive exploration (Filatoff, 2024). *Digital Earth Australia* provides analysis-ready satellite imagery and spatial data that enable continent-scale monitoring of terrain, land cover and environmental change across Australia (Geoscience Australia, n.d.). Industry innovators such as SensOre use proprietary ML–geoscience workflows to generate lithium, nickel and gold prospectivity targets across Western Australia, several of which have advanced into joint ventures, tenement acquisitions and drilling campaigns (SensOre, 2021).

Similar approaches are emerging across the region. In China, AI-assisted remote sensing, deep-learning approaches and 5G-enabled drone systems are increasingly used across geological surveying and the broader mining sector to improve mapping, monitoring and operational safety. These systems not only improve discovery outcomes but also reduce environmental impact by narrowing search areas and limiting the need for broad reconnaissance surveys. In Southeast Asia—where forested or mountainous terrain often constrains ground-based mapping—AI-supported satellite analytics are increasingly important for supporting sustainable exploration planning.

Hyperspectral sensing and geospatial analytics

A second pillar of data-driven exploration is the rapid expansion of satellite- and drone-based remote sensing, which can detect lithological patterns, alteration zones and surface mineralogical signatures. When combined with machine-learning classification, multispectral and hyperspectral datasets can help identify prospective geological structures, map lateritic profiles and characterise terrain where ground access is limited (Drury, 2001; van der Meer et al., 2012).

Across Southeast Asia, remote-sensing methods are increasingly used to support geological mapping, land-use monitoring and environmental assessment near mining areas. Indonesia and the Philippines rely on satellite imagery to track landscape change in mining regions, particularly where mining-related deforestation or land disturbance must be assessed (Ordoñez & Silva, 2023; Rakuasa et al., 2025). China and Viet Nam apply multispectral and hyperspectral imagery—predominantly Sentinel-2 and ASTER—in academic and government-supported geological studies to identify alteration zones and map mineralised terrain (Ge et al., 2018; Tran et al., 2023). These approaches improve baseline geological knowledge where dense vegetation, rugged landscapes or limited sampling constrain conventional fieldwork.

In Japan and the Republic of Korea, public agencies and private firms make extensive use of satellite constellations

1 The "material footprint of the digital" refers to the minerals, energy, water and land required to produce, operate and dispose of digital infrastructure—from sensors and servers to batteries, chips and communication networks.

Box 1: The invisible front line—geological espionage

As the value of critical minerals rises, geological data has become a battleground for intelligence agencies.

- Australia: In 2025, the Australian Secret Intelligence Organisation (ASIO) Director-General Mike Burgess highlighted that the mining sector is a top target for foreign espionage. The agency noted specific cases where "commercial secrets" and geological IP were stolen to devalue Australian projects before acquisition attempts (Burgess, 2025).
- China: In July 2025, China's Ministry of State Security (MSS) released a public warning accusing foreign intelligence agencies of "stealing rare earth technology" and smuggling samples. The MSS detailed tactics, including the mislabelling of rare-earth exports as "ceramic parts" to bypass controls (MSS, 2025).

Implication: Digital governance systems must be cyber-resilient. A DT of a mine is not just an operational tool; it is a blueprint of national strategic assets that may require military-grade cybersecurity.

and commercial geospatial services for land-use, terrain and environmental monitoring, capabilities that increasingly intersect with mineral prospectivity analysis and resource-mapping activities (Kim, 1999; Japan Aerospace Exploration Agency, 2014).

In Iran and Mongolia, where large distances and challenging terrain limit field operations, drones equipped with automated navigation and multispectral sensors enable high-resolution surface mapping at significantly lower cost than traditional campaigns. Unmanned aerial vehicle (UAV)-based mapping has been demonstrated at major operations such as the Erdenet copper mine, generating detailed orthophotos and terrain models that directly support geological interpretation and environmental assessment (Murison, 2018; Honarmand & Shahriari, 2021).

Together, these tools illustrate how remote sensing is becoming an essential component of modern mineral exploration—particularly in regions where conventional surveys are difficult, expensive or environmentally disruptive.

Digital twins of the subsurface

DTs are emerging as a powerful exploration tool. They create interactive simulations of the subsurface by combining geological, geophysical, geochemical, hydrological and environmental datasets into unified, dynamically updating models. This allows governments and companies to test drilling options, assess hydrogeological impacts and evaluate potential ore bodies with reduced invasive activity.

Several Asia-Pacific countries are advancing national or sectoral digital-twin initiatives. Australia's geological and environmental digital platforms integrate land, water and resource datasets to support transparent decision-making (Geoscience Australia, n.d.). China has developed integrated geological information systems that link digital-twin technologies with multi-source data for exploration planning (Tan et al., 2025).

For policymakers, these systems offer evidence-based planning tools that enable evaluation of exploration proposals against biodiversity, water resources, cultural heritage and climate considerations. By improving the quality of early-stage information, DTs help reduce conflict, permitting delays and regulatory uncertainty.

Moving toward integrated regional platforms

The next frontier is regional integration of exploration data, enabling countries to share non-commercial geological information, harmonise standards and build collective capacity. ASEAN's *Minerals Development Vision* (ASEAN, 2025) and the *ASEAN Minerals Cooperation Action Plan* (ASEAN, 2021) emphasise this direction, highlighting the importance of strengthening digital geological databases, building geoscience training capacity, and improving information-sharing mechanisms across member states.

Beyond ASEAN, broader regional initiatives already support cross-border data exchange. These include the implementation of the Integrated Geospatial Information Framework (IGIF) across APEC economies, and UNESCAP's *Asia-Pacific Plan of Action on Space Applications for Sustainable Development* (United Nations & World Bank, 2018; ESCAP, 2018). Emerging AI tools could build on these foundations to enable shared prospectivity mapping, regional baseline datasets and environmental early-warning systems. A proven operational model for such data integration is the Critical Minerals Mapping Initiative (CMMI). This partnership between the geoscience agencies of Australia, Canada and the United States harmonises geological schemas and merges national databases to support seamless, cross-border critical-mineral assessment (Geoscience Australia et al., 2021).

Smart extraction and ESG-aligned operations

While AI-driven exploration reduces uncertainty and environmental disruption at early stages of mineral development, the largest sustainability gains arise during extraction and processing, where energy use, water demand and waste generation are highest (Liang et al., 2024). Across the Asia-Pacific, governments and mining companies are increasingly adopting AI, IoT, automation and DT systems to improve environmental performance, enhance safety and strengthen the reliability of ESG reporting. These tools support a shift toward data-driven operational governance, where environmental and social outcomes are assessed through continuous monitoring rather than periodic declarations.

AI, automation and safer mining systems

AI-enabled automation is now widely used in Australia, China and selected mining operations in Southeast Asia, improving both worker safety and production efficiency. Autonomous haulage systems, automated drilling platforms and real-time fleet-optimisation technologies reduce fuel use, minimise equipment downtime and support more consistent operating conditions. Australia's Pilbara iron-ore sector remains a global reference point, where autonomous trucks and remotely operated rail and port systems are managed through integrated digital command centres (Jang & Topal, 2020). Similar automation and AI-enabled optimisation frameworks are increasingly extending to lithium, nickel and rare-earth operations, reflecting the broader trend in the mining industry toward AI-driven productivity and process-control improvements — a trend substantiated by recent evidence on the role of AI in improving efficiency across exploration, extraction and processing stages (Vespignani & Smyth, 2024).

China has advanced a broad smart mining model that integrates 5G connectivity, automated equipment, real-time gas and ventilation monitoring, AI-assisted hazard detection and remote-operation systems (Zadeh, 2025). These technologies improve safety, reduce operational disruptions and give regulators more timely access to production and environmental data, supporting the evolution of digital compliance frameworks.

Industrial Internet of Things (IIoT) technologies are increasingly central to modern mining, integrating sensors, wireless networks and real-time analytics to improve safety, productivity and environmental oversight. Recent work shows that IIoT platforms enable predictive maintenance, automate routine processes and support operational decision-making by providing continuous data on equipment performance, ventilation, geotechnical conditions and energy use (Zvarivadza et al., 2024). Wearable devices, drones and proximity-detection sensors complement fixed monitoring systems, helping to reduce accidents and optimise production. Together, these capabilities illustrate how sensor-rich IIoT architectures are becoming foundational to data-driven mining operations.

IoT networks for real-time environmental monitoring

A defining feature of ESG-aligned extraction is the ability to monitor environmental conditions continuously. IoT sensor networks—installed on equipment, in tailings facilities, at water monitoring points and across processing infrastructure—generate high-frequency data that support near-real-time operational decisions.

Water use—one of the most sensitive aspects of both hard-rock and brine-based extraction—is increasingly monitored using sensor-based and remote-sensing tools. In Australia, mining operations routinely apply groundwater and surface-water monitoring systems, combining automated loggers, flow meters and digital water-balance modelling to support forecasting and regulatory compliance (AusIMM, 2024). In China, national reforms under the Ministry of Natural Resources have expanded the deployment of water-quality and hydrological monitoring stations in mining-affected regions, integrating sensor data into provincial environmental platforms designed to track pollution and ecological impacts (Li et al., 2024; Yin et al., 2025).

Tailings management is another critical application. The Asia-Pacific has experienced several significant tailings incidents—including the 2012 Philex spill in the Philippines and the 2019 Basamuk spill in Papua New Guinea—reinforcing the need for predictive monitoring. Already systems now integrate data from satellite imagery, ground-based sensors, moisture probes and piezometers to identify potential instability and strengthen early-warning capability. Mining companies in Australia have adopted digital tailings monitoring aligned with the Global Industry Standard on Tailings Management (GISTM) (Global Tailings Review, 2020), while China is developing integrated multisensor and data-driven tailings-risk assessment methods, as demonstrated in recent work applying environmental-risk indexing and multi-indicator analysis to dense tailings-pond regions in the Yellow River Basin (Wang et al., 2024).

Air-quality monitoring—particularly for dust control in mining and quarrying regions—is also advancing. Across the Asia-Pacific, regulators and operators are increasingly using combinations of fixed IoT particulate sensors, mobile monitoring units and UAV-based surveys to map dust dispersion and optimise suppression measures, as demonstrated in large-scale pilot applications in China's coal and metal-mining provinces (Li et al., 2023).

Digital twins for resource optimisation and reduced environmental footprint

DTs enable operators and regulators to model the interactions between ore bodies, processing systems, waste streams and surrounding environmental conditions. These virtual models update with incoming sensor data, allowing scenario testing, performance optimisation and improved anticipatory decision-making.

In Australia, companies including Rio Tinto, BHP, Fortescue and South32 have incorporated digital-twin components into operational control systems, particularly in iron ore, copper and emerging critical-mineral operations. These systems support ore-blending analysis, equipment-performance simulation, water-balance forecasting and energy-use optimisation, helping reduce waste, improve reliability and align with national decarbonisation and efficiency objectives.

DT approaches are also expanding in China, where research and industry initiatives are developing mine-planning platforms that integrate geological, geotechnical, hydrological and environmental datasets. Recent work documents the use of DT-based models for open-pit design, slope-stability assessment, and mine-water management in Chinese coal, iron-ore and metal mines (Qu et al., 2023). These systems allow mining enterprises and provincial authorities to visualise operational and environmental conditions, assess cumulative impacts and strengthen risk management across multiple stages of the mining value chain.

AI-enhanced MRV and the rise of evidence-based Environmental, Social and Governance (ESG) systems

The central challenge for ESG governance in the region is the durability and transparency of environmental data. Traditional reporting systems rely heavily on self-reporting, periodic audits and paper-based documentation. AI-enabled measurement, reporting and verification (MRV) systems shift compliance toward continuous, verifiable and auditable data flows, supporting stronger regulatory oversight and improving confidence among investors and downstream manufacturers.

Key developments include:

- **Digital and blockchain-based traceability:** Australia has trialled digital traceability platforms for critical minerals, including systems that combine blockchain, IoT sensors and digital-product-passport architectures to record extraction data, processing parameters and environmental metrics, providing verifiable provenance for material shipments and supporting emerging transparency expectations in global battery and electronics supply chains (Hidayat, 2025a).
- **Automated biodiversity and land-use monitoring:** AI-assisted image recognition is being applied to classify vegetation cover, detect disturbance and track rehabilitation progress using satellite and drone imagery. A project in Queensland, Australia, illustrates how these tools can strengthen environmental oversight where terrain or staffing capacity limits field-based monitoring (Murray et al., 2022).
- **ESG-integrated process optimisation:** Advanced metallurgical and process-control systems increasingly use data-driven and real-time optimisation to reduce reagent consumption, improve recovery and minimise waste generation. Recent work on circular hydrometallurgy highlights how real-time digital control, mechanochemistry and intensified leaching systems can enhance efficiency and reduce environmental impacts across hydrometallurgical circuits, including those used for laterite processing and battery-metal recovery (Kalupahana et al., 2025). These approaches reflect growing regulatory and industry emphasis—particularly in China and Southeast Asia—on improving efficiency and reducing the footprint of hydrometallurgical operations.

As international buyers—especially in battery, EV and electronics value chains—tighten expectations for traceability and emissions verification, these evidence-based ESG systems are becoming essential for securing market access and meeting procurement requirements. Such continuous verification is increasingly required by downstream battery and EV manufacturers, making digital ESG systems a competitive necessity rather than a voluntary enhancement.

Traceability, circularity, and resource recovery

As demand for critical minerals accelerates across the Asia-Pacific, governments and industries face growing pressure to ensure that materials are sourced responsibly, used efficiently and recovered at the end of life. For countries such as Japan, the Republic of Korea, China and Australia—and for emerging ASEAN battery producers—circularity has become both an industrial priority and a strategic requirement. Digital technologies, including AI, blockchain-based traceability, IoT-enabled tracking and DPPs, now play a central role in building transparent supply chains and supporting the shift from linear resource flows toward more circular systems.

While Section 3 examined how digital tools are reshaping extraction, this section focuses on post-extraction governance: how materials are tracked, processed, reused and recycled, and how policy frameworks can support more efficient and sustainable resource utilisation.

The rise of traceability: From static certification to dynamic data transparency

Traditional certification and assurance schemes have long relied on periodic audits and paper-based documentation. These approaches can be slow and fragmented, making it difficult to meet the increasingly stringent traceability expectations of electric vehicle (EV), electronics and defence manufacturers.

Digital traceability systems introduce a different model:

- **Blockchain platforms** can maintain tamper-resistant records of material origin, processing steps and custody changes.
- **Digital Product Passports (DPPs)** consolidate environmental and material information across the supply chain, improving consistency and auditability.
- **IoT sensors and digital tags** support real-time tracking of material movements from mine to refinery to manufacturing plant.
- **AI analytics** can identify inconsistencies, detect risks and strengthen overall supply-chain assurance.

The Republic of Korea has introduced digital lifecycle-management systems under its *Resource Circulation Act*, enabling battery manufacturers and recyclers to exchange material-flow and recycling data through integrated national platforms (Ministry of Climate, Energy and Environment, 2024). China has also advanced digital transparency requirements, with major battery producers developing data systems to meet the EU Battery Passport's 2027 rules, including carbon-footprint disclosure, material-traceability records and third-party verification standards (Hidayat, 2025b).

In Southeast Asia, Indonesia has already moved toward digital traceability through the expansion of its national Mineral and Coal Information System (Simbara), which now tracks nickel and tin flows from mines to smelters and integrates real-time data on production quotas, permitting and shipments to strengthen oversight and governance (Nangoy, 2024). Traceability systems are also critical for disrupting transnational criminal networks. The United

Nations Interregional Crime and Justice Research Institute (UNICRI) (2025) highlights that opaque mineral supply chains in Southeast Asia are targeted by organised crime for money laundering and illicit trafficking.

Australia's critical minerals and battery industries are also advancing digital reporting and traceability frameworks, with companies increasingly integrating ESG data, emissions information and processing records into digital passports. These systems support access to international markets where verifiable environmental performance and supply chain transparency are becoming mandatory requirements under emerging global regulations.

DPPs and the future of mineral governance

The introduction of the EU Battery Regulation in 2023 (European Union, 2023)—which mandates a Digital Battery Passport (DBP) for all electric-vehicle and industrial batteries placed on the EU market—has become a global reference point for supply-chain transparency. Under this system, producers must disclose structured data on material provenance, carbon footprint, recycled content, processing steps, performance characteristics and end-of-life pathways. These requirements are already influencing regulatory planning and industry practices far beyond Europe, as access to EU markets increasingly depends on the ability to supply verifiable, standardised digital information.

At the international level, the Global Battery Alliance (GBA) has piloted a Battery Passport framework with major industry partners, demonstrating how lifecycle data can be aggregated across borders while maintaining commercial confidentiality (GBA, 2024). These pilots show that digital product-passport systems are not speculative: operational models exist, and the technical foundations for interoperability are already in place.

Industry reporting indicates that battery manufacturers in China are actively preparing for these emerging requirements by upgrading data-management systems, strengthening supply-chain documentation and aligning internal processes with anticipated EU compliance expectations (Hidayat, 2025b). These developments signal a broader shift across the Asia-Pacific, where firms supplying global markets increasingly recognise that digital traceability is becoming an essential condition for competitiveness rather than a voluntary enhancement.

AI-enabled circularity and predictive waste-stream modelling

Circularity begins early in the value chain, and AI-driven tools are increasingly used to forecast material flows, optimise recovery processes and support closed-loop manufacturing. Several developments across the Asia-Pacific illustrate this shift.

Japan has developed one of the world's most advanced rare-earth magnet and battery-recycling ecosystems. Automated sorting, disassembly and material-characterisation systems are widely used, and national recycling facilities employ digital tools to assess battery condition and optimise recovery pathways (Xu et al., 2016; Antony Jose et al., 2024). China's major battery-recycling enterprises, including Brunp and GEM, deploy automated disassembly, advanced process-control technologies and analytical systems to improve recovery rates of lithium, nickel, cobalt and manganese, strengthening circularity in EV and electronics value chains (He et al., 2024; Ali et al., 2025).

Australia is developing its domestic lithium-ion battery recycling capability, with research and pilot initiatives focused on improving disassembly, separation, and chemical-processing pathways. Current activity includes using advanced technology in dismantling and crushing batteries to produce black mass domestically, with further processing occurring offshore (Commonwealth Scientific and Industrial Research Organisation, 2024). These efforts align with the country's *National Battery Strategy* and growing domestic processing capability (Department of Industry, Science and Resources, 2024).

Finally, AI enhances urban mining by supporting the identification, quantification and prediction of secondary resource flows. Studies show that machine-learning techniques improve material classification, sorting efficiency and recovery modelling across several Asia-Pacific contexts. In Japan, deep-learning approaches have been used to identify and sort electronic components more accurately, raising correct-selection rates by around 70% in pilot tests (Markazi et al., 2025). Across Australia, research groups apply ML frameworks to optimise metal-recovery processes from e-waste, including parameter prediction for leaching and process modelling (Commonwealth Scientific and Industrial Research Organisation, 2024). Broader regional work using GIS and remote sensing demonstrates how spatial data and ML-based analysis help map urban material stocks, forecast waste availability and guide decisions on recycling system design—laying the groundwork for more efficient, technology-enabled urban-mining strategies (Murthy & Ramakrishna, 2022).

Policy frameworks driving circularity

Circularity in minerals depends on coherent policy frameworks that support efficient material use, recovery and recycling. Several Asia-Pacific economies have established legislative and strategic initiatives that point in this direction:

- **Australia's** *National Battery Strategy* includes measures that encourage traceability, recycling infrastructure and integration of recovered materials into domestic battery value chains (Department of Industry, Science and Resources, 2024).
- **China's** *Circular Economy Promotion Law* embeds lifecycle management, extended producer responsibility and digital monitoring of key waste streams (National People's Congress, 2008).
- **Japan** has long prioritised closed-loop systems for motors, batteries and electronics through its circular-economy and recycling legislation, supported by technology-development programmes and partnerships between government and industry (Ministry of Economy, Trade and Industry, 2023).
- The **Republic of Korea's** *Resource Circulation Act* sets recycling

obligations for designated products and promotes digital and automated systems to improve material recovery (Ministry of Environment, 2023).

- **Malaysia's** *National Mineral Industry Transformation Plan 2021-2030* outlines a strategic shift toward sustainable mining, emphasising the development of a comprehensive digital mineral inventory to manage resources and prevent leakage (Ministry of Natural Resources and Environmental Sustainability, 2021).
- **ASEAN's** *Minerals Development Vision* and associated cooperation plans emphasise improved recycling, shared infrastructure and capacity-building to support sustainable resource management across the region (ASEAN, 2025).

A common theme across these frameworks is the recognition that reliable data underpins effective circularity. Without traceable and verifiable information on material origin, composition, processing and end-of-life outcomes, recycled materials struggle to compete with primary production or to satisfy the transparency requirements of global clean-technology supply chains.

Policy pathways for the Asia-Pacific

The accelerating adoption of AI, geospatial analytics, DT and blockchain tools offers the Asia-Pacific an opportunity to support proactive, data-driven and sustainability-centred systems. To capture this opportunity, the region would benefit from policies that enable digital integration, strengthen regulatory capacity, and support regional cooperation.

Build interoperable digital governance systems

Across the region, digital resource-governance tools are expanding—but mostly in isolation. Interoperability is essential for efficient cross-border supply chains, ESG reporting and market access. Because geological and operational datasets are increasingly considered strategic assets, regional frameworks for cybersecurity and secure data exchange will be essential to underpin interoperability. Governments can advance this by establishing:

- common data structures for DPPs and traceability systems;
- shared metadata standards for geological, environmental and social datasets;
- verification and audit rules for digitally generated MRV;
- minimum requirements for cybersecurity and ledger integrity.

Technical integration must also navigate the complex reality of data sovereignty. As many nations view geological data as a strategic national security asset, protocols are needed to allow for verification and interoperability without requiring the full disclosure of sensitive proprietary datasets. Beyond national security, governance systems must also respect Indigenous data sovereignty, which is increasingly recognised as a foundational principle for ethical resource governance in Australia, Canada and elsewhere. Frameworks such as the *CARE Principles* (Collective Benefit, Authority to Control, Responsibility, Ethics) are becoming vital for ensuring that First Nations communities retain control over geological and environmental knowledge derived from their traditional lands (Carroll et al., 2020). Meaningful progress in this space requires sustained political will, trust, coordination, co-investment and technical alignment.

Embed AI-enabled MRV into regulatory regimes

Regulators can raise environmental standards and improve investor confidence by integrating AI-enabled MRV into permitting and compliance systems. Actionable steps include:

- requiring continuous reporting of water use, emissions and tailings indicators;
- shifting impact assessments and rehabilitation plans to digital formats linked to real-time monitoring;
- using DTs to evaluate mine plans, cumulative impacts and climate risks;
- incorporating verified MRV data into national ESG and sustainability reporting frameworks.

These measures move compliance away from periodic audits toward continuous assurance, transparency, and accountability, thus reducing uncertainty for governments, communities and financiers.

Enable responsible circularity and traceability

As global markets adopt stricter sustainability rules—particularly the EU battery passport and emerging U.S. transparency requirements—Asia-Pacific countries may benefit from policies that support credible, digital-first circularity systems. Priority actions include, but are not limited to:

- developing national traceability platforms compatible with international reporting standards;
- expanding producer-responsibility policies for batteries and electronic waste;
- supporting recycling, refurbishing and recovery innovation through incentives and pilot programmes;
- creating regional recycling and processing hubs linked through harmonised digital standards.

These measures reduce pressure on primary extraction, improve resilience and enable participation in high-value global value chains. It is important for policymakers also to guard against a "digital divide" where high-cost traceability barriers exclude artisanal and small-scale miners (ASM). Inclusive digital platforms that allow smaller operators to participate in formal supply chains are essential to prevent the criminalisation of this vital livelihood sector (United Nations Interregional Crime and Justice Research Institute, 2025).

Invest in people, institutions and digital infrastructure

Digital systems are effective only when institutions can govern them. However, a critical bottleneck remains the regional scarcity of talent at the intersection of geoscience and data science. Building this dual capability is as vital as the technology itself. Stakeholders in the Asia-Pacific can invest in:

- AI, digital MRV and geospatial training for regulators and geological agencies;
- centres of excellence dedicated to digital resource governance and sustainability analytics;
- secure and accessible data repositories that integrate public and private environmental information;
- reliable digital infrastructure in mining regions, including connectivity, data security and sensor networks;
- community capacity-building so local stakeholders can interpret and engage with environmental data.

Strengthened institutional capability ensures that digital transformation benefits communities as well as industry.

Deepen regional cooperation and knowledge exchange

Digital minerals governance is inherently regional. The Asia-Pacific can accelerate progress by expanding:

- partnerships for joint learning and technical assistance;
- regional pilots that test digital MRV, traceability and circularity systems;
- shared training and technology-transfer programmes among geological surveys and regulators;
- multi-country research initiatives on AI-enabled monitoring and environmental modelling;
- coordinated approaches to supply-chain security, sustainability and circular-economy development.

APCTT, through its long-standing work on technology transfer and digital governance, can serve as a convening platform for piloting regional MRV, traceability and interoperability initiatives. Such cooperation positions the region to actively influence global norms and build a more resilient, sustainable mineral future.

Conclusion

A region that can see its mineral systems clearly, measure its impacts honestly and coordinate its responses digitally will be far better placed to navigate the turbulence of the energy transition. The Asia-Pacific is already moving in this direction. AI-enabled prospectivity models, hyperspectral analytics and subsurface DTs are reducing uncertainty and unnecessary disturbance in exploration. In parallel, automation, IoT networks and digital MRV are turning mines into continuously monitored systems rather than opaque black boxes. At the other end of the chain, traceability platforms, DPP-aligned reporting and AI-supported recycling are beginning to stitch primary production, manufacturing and resource recovery into a more circular whole.

Yet technology alone will not determine whether this transition delivers security, sustainability and justice. The same tools that can democratise access to information can also entrench asymmetries between well-resourced operators and under-resourced regulators, or between advanced economies and smaller states. APCTT and ESCAP are well-positioned to convene the regional architecture needed for this transition—linking standards, capacity building, pilot projects and knowledge-sharing to accelerate the uptake of interoperable digital systems. Technology exists, the policy models are emerging, and the region now has a clear opportunity to move from pilots to scaled, interoperable solutions. If governments and industry treat data as a public good, design digital systems for interoperability from the outset and foreground circularity alongside security, the region can move decisively beyond a narrow focus on extraction and build a more coherent, transparent and equitable minerals governance architecture fit for the demands of the energy transition.

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