DIGITAL STEWARDSHIP IN MINING POLICY: A SYSTEMATIC REVIEW OF GREEN TECH IMPLEMENTATION

PENGELOLAAN DIGITAL DALAM KEBIJAKAN PERTAMBANGAN: KAJIAN SISTEMATIS IMPLEMENTASI TEKNOLOGI HIJAU

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Abstract. *The accelerating degradation of mining-affected ecosystems demands a reconceptualization of regulatory architecture. This systematic literature review (SLR), conducted in accordance with the PRISMA 2020 protocol, examines the global trajectory of digital stewardship as an emergent governance paradigm in the extractive industries sector (2021—2026). Grounded in Elinor Ostrom's Institutional Analysis and Development (IAD) Framework, this study analyzes how artificial intelligence (AI), Internet of Things (IoT), and digital monitoring systems are reshaping the rules-in-use within mining governance action arenas. Drawing on peer-reviewed articles, sustainability reports, and regulatory documents from four major mining jurisdictions, comparative policy analysis reveals a significant governance gap between Indonesia's Mineral and Coal Mining Law (Minerba Law No. 3/2020) and digital governance benchmarks established in Australia, Canada, and Norway. While these jurisdictions have institutionalized digital stewardship through dedicated policy roadmaps, regulatory sandboxing, and mandatory ESG disclosure standards, Indonesia's framework remains anchored in conventional, periodically-inspected compliance paradigms. This study proposes a five-point Policy Roadmap for Indonesian green mining and argues that digital stewardship constitutes a contemporary form of planetary guardianship—a technological expression of ecotheological responsibility toward shared Earth resources consistent with the conference theme of transdisciplinary sustainability.*

Keywords: *Digital Stewardship; Mining Policy; Green Technology; IAD Framework; Ecotheology; Sustainable Governance; PRISMA.*

Abstrak. *Degradasi ekosistem kawasan pertambangan yang terus berlangsung menuntut rekonseptualisasi arsitektur regulasi pertambangan global. Kajian literatur sistematis ini, yang dilaksanakan sesuai protokol PRISMA 2020, menginvestigasi trajektori global dari konsep digital stewardship (pengelolaan digital) sebagai paradigma tata kelola yang berkembang dalam sektor industri ekstraktif pada periode 2021—2026. Berlandaskan Kerangka Analisis dan Pengembangan Institusional (IAD) dari Elinor Ostrom, penelitian ini menganalisis bagaimana kecerdasan buatan (AI), Internet of Things (IoT), dan sistem pemantauan digital sedang mengubah rules-in-use di arena aksi tata kelola pertambangan. Berdasarkan sintesis artikel ilmiah, laporan keberlanjutan, dan dokumen regulasi dari empat yurisdiksi pertambangan utama, analisis perbandingan kebijakan mengungkap kesenjangan tata kelola yang signifikan antara Undang-Undang Minerba (UU No. 3/2020) dan standar tata kelola digital yang berlaku di Australia, Kanada, dan Norwegia. Studi ini mengusulkan Lima Peta Jalan Kebijakan bagi pertambangan hijau Indonesia, dengan argumen bahwa pengelolaan digital merupakan bentuk kontemporer dari penjagaan planet—ekspresi teknologis dari tanggung jawab ekotheologis terhadap sumber daya bumi bersama.*

Kata Kunci: *Pengelolaan Digital; Kebijakan Pertambangan; Teknologi Hijau; Kerangka IAD; Ekotheologi; Tata Kelola Berkelanjutan; PRISMA.*

1. INTRODUCTION / PENDAHULUAN

Mining governance stands at a critical inflection point. The global extractive sector accounts for an estimated 4—7% of global greenhouse gas emissions, driven primarily by fossil fuel combustion in heavy machinery, ore processing, and smelting operations (ICMM, 2022). These figures, combined with the sector's documented record of water contamination, habitat destruction, and community displacement, signal compounding institutional failures that conventional, periodically-inspected regulatory instruments have proven inadequate to resolve.

Elinor Ostrom's Institutional Analysis and Development (IAD) Framework provides a powerful diagnostic lens for understanding these failures. In the IAD framework, mining ecosystems constitute archetypal common-pool resources: subtractable, rivalrous, and chronically subject to the tragedy of the commons (Hardin, 1968; Ostrom, 1990). The Action Arena in mining governance—where operators, regulators, communities, and civil society interact—has historically been characterized by information asymmetry, regulatory capture, and weak enforcement feedback loops (Polski & Ostrom, 1999; Poteete et al., 2010). These structural defects enable environmentally destructive practices to persist long after regulatory intervention should have corrected them.

Digital Stewardship—defined in this study as the systematic deployment of artificial intelligence (AI), Internet of Things (IoT) sensors, and digital monitoring systems to govern extractive operations in real-time—represents a potential restructuring of these rules-in-use. Unlike conventional compliance frameworks that operate through periodic inspections and ex-post sanctions, digital stewardship mechanisms create continuous data streams that fundamentally alter the information environment within the action arena. They shift governance from reactive to proactive, from opaque to transparent, and from episodic to perpetual (Franks, 2015; Mancini & Sala, 2018).

The convergence of this technological shift with the ICONTREES 2026 conference theme—"Beyond the Cosmos: Transdisciplinary Perspectives on Ecotheology and Global Sustainability"—is not incidental. Ecotheology posits that humanity bears a moral and spiritual obligation of stewardship toward the Earth's ecosystems (Northcott, 2013; White, 1967). Across Abrahamic traditions, the concept of stewardship—Arabic khalifah; Hebrew shomer; Latin dispensator—positions humanity as guardian and custodian, not sovereign owner, of natural resources (Bergmann, 2021; Hessel & Ruether, 2000). When filtered through this theological lens, digital stewardship in mining is not merely a governance innovation; it is a contemporary articulation of what it means to be a faithful custodian of shared planetary resources.

Indonesia presents a critical case study. As the world's largest producer of nickel—accounting for over 50% of global mine output in 2023—and a significant exporter of coal, bauxite, and copper, Indonesia's regulatory architecture directly shapes the environmental fate of ecosystems covering hundreds of thousands of hectares (IEA, 2023; World Bank, 2022). The Minerba Law No. 3/2020 established an ambitious framework for mineral resource governance, but its provisions for digital environmental accountability remain limited, creating an identifiable and consequential policy gap (Ministry of Energy and Mineral Resources, 2022).

This study addresses three research questions: (1) What is the current global state of digital stewardship institutionalization in mining governance? (2) What policy gaps exist between Indonesia's Minerba Law and international digital governance benchmarks? (3) What concrete policy interventions are required to transition Indonesia toward digitally governed green mining? In answering these questions, this study: provides a PRISMA-compliant systematic review of digital stewardship in extractive governance; applies the IAD framework to analyze technology-mediated rule changes in the mining action arena; and delivers a concrete Policy Roadmap for Indonesia's transition to green mining.

2. RESEARCH METHOD / METODE PENELITIAN

This study employs a Systematic Literature Review (SLR) methodology guided by the PRISMA 2020 Statement (Page et al., 2021). The PRISMA protocol was selected for its rigor in ensuring methodological transparency, reproducibility, and comprehensiveness in secondary data synthesis—attributes essential for policy-relevant knowledge production (Moher et al., 2009).

2.1 Search Strategy and Databases

A structured search was conducted across four primary academic databases: Scopus, Web of Science (WoS), IEEE Xplore, and Google Scholar. Grey literature searches covered the World Bank, ICMM, OECD, and governmental portals including Australia's Department of Industry, Science and Resources; Indonesia's Ministry of Energy and Mineral Resources (ESDM); Natural Resources Canada; and Norway's Norges Bank Investment Management. The primary Boolean search string was: ("digital stewardship" OR "digital governance" OR "AI mining" OR "IoT monitoring") AND ("mining policy" OR "extractive governance" OR "mineral regulation") AND ("sustainability" OR "green technology" OR "environmental monitoring"). The search was restricted to January 2021—April 2026.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria: (a) peer-reviewed articles in indexed journals (Scopus Q1—Q3); (b) sustainability and ESG reports from major mining institutions; (c) regulatory documents from national governments; (d) publications addressing mining governance, digital technologies, and sustainability in combination; (e) publications in English or Bahasa Indonesia. Exclusion criteria: (a) publications focused solely on oil, gas, or renewable energy without reference to hard-rock mining; (b) grey literature without institutional affiliation; (c) publications prior to January 2021; (d) duplicate records; (e) non-peer-reviewed opinion pieces.

2.3 Screening and Selection Protocol

Records retrieved from database searches were screened in two stages following the PRISMA 2020 flow diagram framework (Page et al., 2021). Stage one involved title and abstract screening against inclusion and exclusion criteria. Stage two involved full-text assessment of records passing stage one. The final synthesis corpus comprised peer-reviewed articles, corporate sustainability reports, and regulatory and policy documents covering five jurisdictions: Australia, Canada, Norway, Indonesia, and global institutions (ICMM, World Bank, OECD, IEA).

2.4 Data Extraction and Synthesis

Data were extracted using a structured coding matrix capturing: (1) jurisdiction; (2) technology type (AI, IoT, satellite monitoring, integrated digital platform); (3) governance dimension addressed; (4) IAD dimension (action arena configuration, rules-in-use, governance outcomes); and (5) policy maturity level on a four-point scale: Ad Hoc, Emerging, Institutionalized, and Advanced. Synthesis was conducted through thematic analysis and narrative synthesis (Popay et al., 2006), complemented by comparative policy analysis.

3. RESULT AND DISCUSSION / HASIL DAN PEMBAHASAN

3.1 Global Landscape of Digital Mining Governance

The review reveals a pronounced global convergence around digital stewardship as the emerging governance standard in progressive mining jurisdictions. Three primary technology clusters

appear consistently across the reviewed literature and policy documents: (1) AI-assisted environmental compliance and predictive monitoring; (2) IoT-based real-time environmental data collection at mine sites; and (3) integrated digital reporting platforms for ESG disclosure. These technology clusters are most comprehensively institutionalized in Australia, Canada, and Norway (Department of Industry, Science and Resources, 2021, 2023; Natural Resources Canada, 2022; Norges Bank Investment Management, 2022).

Australia's Resources Technology and Critical Minerals Processing Roadmap (Department of Industry, Science and Resources, 2021), and its successor Critical Minerals Strategy 2023—2030 (Department of Industry, Science and Resources, 2023), represent the most comprehensive institutionalization of digital stewardship in the Asia-Pacific. The roadmap establishes clear goals for increasing the capability of digital monitoring systems, fostering industry-government data collaboration, and positioning Australia as a regional hub for resources technology. These goals are operationalized through binding license conditions that require digital environmental reporting at major mine sites.

Canada's Critical Minerals Strategy (Natural Resources Canada, 2022) integrates adaptive governance mechanisms and regulatory streamlining with digital disclosure expectations across the entire mineral value chain—from exploration to recycling. Norway's Government Pension Fund Global (GPFG), governed by published Guidelines for Observation and Exclusion (Norges Bank Investment Management, 2022), applies ethics-based criteria that exclude mining companies failing to meet environmental standards, creating powerful financial incentives for ESG-compliant digital governance. In IAD terms, these systems are restructuring the fundamental parameters of the mining action arena. Information asymmetry—historically the greatest advantage of extractive operators vis-a-vis regulators—is being systematically dismantled (Ostrom, 2010; Poteete et al., 2010).

3.2 Indonesia's Regulatory Architecture: A Critical Assessment

Indonesia's Mineral and Coal Mining Law (UU No. 3/2020, the Minerba Law) represents a significant legislative achievement in centralizing mining authority and establishing environmental performance standards. The law introduced provisions for environmental reclamation funds, community development obligations, and enhanced ESDM oversight authority. However, the Minerba Law's treatment of digital governance is conspicuously thin.

The law contains no provisions mandating IoT-based environmental monitoring, no regulatory framework for AI-assisted compliance, and no digital reporting standards equivalent to international ESG disclosure frameworks such as ISSB S2 (ISSB, 2023) or the OECD due diligence guidance (OECD, 2016). Environmental reporting remains largely periodic and self-reported—conditions identified by governance scholars as structurally conducive to regulatory arbitrage (Franks, 2015; Mudd, 2010). The Ministry of Energy and Mineral Resources' Strategic Plan 2020—2024 (2022) acknowledges the need for digital transformation but remains at the strategic planning level, with limited binding regulatory force.

The absence of mandatory real-time monitoring creates information asymmetry in the action arena that systematically advantages mining operators over regulatory agencies and affected communities. A comparison with Australia's framework is instructive: while Australia mandates digital environmental reporting as a license condition, Indonesia treats such monitoring as optional and largely voluntary. This is not merely a technical gap; it represents a fundamental difference in the institutional design of accountability mechanisms within the action arena (Ostrom, 1990, 2005).

3.3 Comparative Policy Analysis: Global vs. Indonesian Digital Stewardship

Table 1 presents the comparative analysis of digital stewardship policy effectiveness across four mining jurisdictions along eight governance dimensions. Policy maturity classifications are based on primary source documents: Australian Government (2021, 2023), Natural Resources Canada (2022), Norges Bank Investment Management (2022), and Indonesia's ESDM Strategic Plan (2022). The four-point maturity scale follows the framework described in Section 2.4.

Table 1. Comparative Analysis of Digital Stewardship Policy Effectiveness in Mining Governance

Governance Dimension	Australia	Canada	Norway	Indonesia
IoT Real-Time Environmental Monitoring	Institutionalized	Institutionalized	Emerging	Ad Hoc
AI-Assisted Compliance Systems	Advanced	Institutionalized	Emerging	Absent
Supply Chain Transparency Frameworks	Emerging	Institutionalized	Institutionalized	Absent
Open-Data Environmental Reporting	Advanced	Institutionalized	Institutionalized	Absent
Regulatory Sandboxing Mechanisms	Institutionalized	Advanced	Institutionalized	Emerging
Community Digital Access & Participation	Institutionalized	Institutionalized	Advanced	Ad Hoc
Mandatory ESG Digital Reporting Standards	Advanced	Advanced	Advanced	Emerging
Adaptive Licensing Frameworks	Institutionalized	Advanced	Institutionalized	Absent

Source: Author analysis based on primary government documents (Department of Industry, Science and Resources, 2021, 2023; Natural Resources Canada, 2022; Norges Bank Investment Management, 2022; ESDM, 2022).

Note: Advanced = mandatory, measurable, technology-specific legal provisions with enforcement; Institutionalized = embedded in binding policy with formal timelines; Emerging = strategic plans without binding force; Ad Hoc = voluntary or project-level only; Absent = no regulatory provision.

The comparative analysis demonstrates that Indonesia scores at the Ad Hoc or Absent level on five of eight governance dimensions. The most critical absences are in mandatory ESG digital reporting, AI-assisted compliance systems, supply chain transparency frameworks, and adaptive licensing—the dimensions that published policy evidence most strongly links to improved environmental outcomes (OECD, 2016, 2019; World Bank, 2017, 2022). This profile is consistent with broader findings in extractive governance literature that highlight Indonesia's historical reliance on paper-based, self-reported compliance mechanisms (Mancini & Sala, 2018; Mudd, 2010).

3.4 IAD Framework Analysis: The Digital Action Arena

Through the IAD lens, digital stewardship restructures three fundamental parameters of the mining action arena. First, regarding the information environment: digital monitoring systems create what Ostrom (2005) calls common knowledge—shared awareness of resource conditions that reduces strategic information advantages. When both operators and regulators access the same real-time environmental data, monitoring transaction costs fall and accountability becomes structural rather than procedural (Ostrom, 2010).

Second, regarding boundary rules: digital platforms enable new forms of community participation in mining governance. Open-data portals and participatory monitoring systems can extend the boundary of the action arena to include affected communities as legitimate actors—a development with profound implications for distributive justice and environmental accountability

(McGinnis, 1999; Kooiman, 2003). Third, regarding payoff rules: digital compliance systems can enable adaptive enforcement, where permit conditions and environmental bonds adjust based on real-time performance data rather than periodic inspections—fundamentally innovating the payoff structure of mining governance (Global Tailings Review, 2020; Biermann et al., 2012).

3.5 Ecotheological Dimensions of Digital Stewardship

The ICONTREES 2026 conference theme invites a transdisciplinary reading of digital stewardship that extends beyond technical policy analysis. From an ecotheological perspective, the concept of stewardship across Abrahamic traditions—Arabic khalifah, Hebrew shomer, Latin dispensator—positions humanity as guardian and custodian, not sovereign owner, of natural resources (Northcott, 2013; Bergmann, 2021). This relational ontology stands in direct opposition to the extractive logic that has historically driven mining-induced ecological destruction.

White (1967) argued that the Western Christian tradition's anthropocentric reading of scripture contributed to the historical roots of the ecological crisis. Hessel and Ruether (2000) represent a key strand of the ecotheological response, arguing that Christian ecology must ground environmental ethics in a commitment to the well-being of both Earth and humans. Digital stewardship in mining extends this theological concept into the algorithmic domain: real-time environmental accountability and community-accessible monitoring data represent technological articulations of the guardian's obligation—to see clearly, account honestly, and act responsibly toward shared resources.

For a nation whose archipelagic ecology encompasses 17,000 islands and some of the world's richest marine and terrestrial ecosystems directly affected by extractive activity, the failure to institutionalize digital monitoring is not merely a policy shortcoming. It represents a failure of the guardian relationship toward shared planetary commons—a breach of ecotheological covenant that demands institutional correction (Sachs, 2015; Taleb & Sandis, 2014).

4. CONCLUSION / KESIMPULAN

This systematic review establishes that digital stewardship has emerged as the dominant paradigm in progressive mining governance, yet Indonesia's regulatory architecture remains significantly misaligned with this trajectory. Through the IAD Framework, we demonstrate that this misalignment is institutional—reflecting structural deficits in the information environment, boundary rules, and payoff mechanisms governing Indonesia's mining action arena. The ecotheological framing reveals these gaps as failures of planetary guardianship, demanding correction on both governance and ethical grounds.

Drawing on evidence from four jurisdictions and verified primary policy documents, this study proposes the following five-point Policy Roadmap for Indonesian Green Mining:

Policy Roadmap Point 1 — Mandatory Real-Time Digital Monitoring (2026—2027): Amend Minerba Law No. 3/2020 to mandate IoT-based environmental monitoring at all IUP-OP (Izin Usaha Pertambangan Operasi Produksi) sites, with real-time data integration into a national ESDM monitoring dashboard accessible to regulators, civil society, and affected communities. This directly addresses the information asymmetry identified through IAD analysis as the primary structural defect of Indonesia's mining action arena.

Policy Roadmap Point 2 — Regulatory Sandbox for Digital Innovation (2026—2028): Establish a MINERBA Digital Regulatory Sandbox under ESDM authority, enabling mining companies to pilot AI-assisted compliance systems under controlled conditions with adaptive

licensing provisions. This mechanism, institutionalized in Canada's Critical Minerals Strategy (Natural Resources Canada, 2022), allows regulatory learning without premature commitment to specific technology standards.

Policy Roadmap Point 3 — Mandatory Open-Data Environmental Reporting Framework (2027): Develop a mandatory digital reporting standard for all mining license holders aligned with ISSB S2 (2023) climate-related disclosure requirements and OECD (2016) due diligence guidance. Public access to environmental performance data—consistent with Australia's Critical Minerals Strategy (Department of Industry, Science and Resources, 2023)—would enable independent verification by civil society and academic institutions.

Policy Roadmap Point 4 — Community and Indigenous Stewardship Integration (2026—2030): Incorporate indigenous ecological knowledge and community stewardship values into digital governance frameworks through participatory monitoring platforms that formally recognize traditional custodianship of mining-affected lands. This aligns technological governance with ecotheological principles of relational accountability (Bergmann, 2021; Hessel & Ruether, 2000) and with Indonesia's constitutional recognition of adat community rights.

Policy Roadmap Point 5 — International Digital Governance Alignment (2027—2029): Align Indonesia's mining ESG reporting standards with ISSB S2 (2023) and OECD due diligence guidance (2016), and develop digital supply chain transparency mechanisms for nickel and cobalt exports consistent with critical minerals accountability frameworks endorsed by the World Bank (2017, 2022). This positions Indonesia as a responsible supplier in global clean energy mineral markets, reducing regulatory and investment risk.

The evidence reviewed is unequivocal: the cost of inaction—measured in environmental degradation, market access risk, and the erosion of Indonesia's custodial responsibility toward its extraordinary ecological inheritance—far exceeds the cost of transformation. Digital stewardship is not merely a governance innovation. In the deepest sense, it is the technological fulfilment of the guardian's covenant with the Earth.

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