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REVIEW

Technofixing the Future in Mining Industry: Ethical Side Effects of Using AI and Big Data to Meet the SDGs

Tecnofijando el futuro en la industria minera: efectos secundarios éticos del uso de IA y big data para cumplir con los ODS

Petros Chavula[1,2], Fredrick Kayusi[3,4]

[1]Department of Agricultural Economics and Extension, School of Agricultural Sciences, University of Zambia, P.O. Box 32379, Lusaka, Zambia.
[2]Africa Centre of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Dire Dawa, Ethiopia.
[3]Department of Environmental Studies, Geography and Planning, Maasai Mara University, P.O. 861-20500, Narok-Kenya.
[4]Department of Environmental Sciences, Pwani University, Kilifi Kenya.

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Corresponding author: Petros Chavula

ABSTRACT

Recent advances in artificial intelligence (AI), big data, and non-geostationary satellite (NGSO; LEO/MEO) services promise faster, safer, and "greener" mining, but also raise ethical and governance risks. This study interrogates the technofix narrative. Objectives were to map NGSO+AI applications across the mining value chain; assess technical, operational, environmental, and economic performance; examine governance, data rights, and justice implications; evaluate capacity and procurement models (with an East African lens); and distill actionable guidance. Following a PRISMA-2020 protocol, a mixed-methods review (database inception–12 Aug 2025) of peer-reviewed and grey literature was undertaken with duplicate screening and appraisal (JBI, RoB 2/ROBINS-I, AACODS; GRADE/CERQual). Over 80 empirical studies and initiatives were synthesized; random-effects meta-analysis was used where outcomes were comparable, alongside realist narrative synthesis. NGSO connectivity reduced latency (LEO: tens of ms; MEO: ~100-200 ms) and high-revisit EO (SAR/optical) improved surface-change detection; operational gains (uptime, reporting) were noted but with low-moderate certainty given short follow-up and sponsorship. Governance lagged capability: data ownership and portability were unclear, third-party audit access rare, and community participation uneven; ethical risks included bias, privacy, and cultural impacts. East African pilots showed technical promise amid institutional gaps. NGSO+AI can advance SDG-aligned mining only when coupled to binding data rights, independent assurance, participatory pathways, open interfaces, and local capacity; otherwise tools risk performative compliance rather than accountable, just outcomes.

Keywords: Technofixing; Artificial Intelligence; Big Data; Mining Ethics; Sustainable Development; Governance Frameworks.

RESUMEN

Los avances recientes en inteligencia artificial (IA), big data y servicios satelitales no geoestacionarios (NGSO; LEO/MEO) prometen una minería más rápida, segura y "más verde", pero también plantean riesgos éticos y de gobernanza. Este estudio interroga la narrativa del "technofixing". Los objetivos fueron: cartografiar aplicaciones NGSO+IA a lo largo de la cadena de valor; evaluar el desempeño técnico, operativo, ambiental y económico; examinar la gobernanza, los derechos sobre los datos y las implicaciones de justicia; analizar capacidades y modelos de adquisición (con enfoque en África Oriental); y sintetizar orientaciones prácticas.

Siguiendo PRISMA-2020, se realizó una revisión de métodos mixtos (desde el inicio de las bases de datos hasta el 12 de agosto de 2025) de literatura académica y gris, con cribado duplicado y evaluación (JBI, RoB 2/ROBINS-I, AACODS; GRADE/CERQual). Se sintetizaron más de 80 estudios e iniciativas; cuando los resultados fueron comparables se aplicó un metaanálisis de efectos aleatorios, complementado con síntesis narrativa realista. La conectividad NGSO redujo la latencia (LEO: decenas de ms; MEO: ~100–200 ms) y la observación de la Tierra de alta revisitación (SAR/óptica) mejoró la detección de cambios de superficie; las ganancias operativas (tiempo activo, reporte) mostraron certeza baja-moderada por seguimiento breve y patrocinio. La gobernanza quedó rezagada: titularidad y portabilidad de datos poco claras, auditoría externa infrecuente y participación comunitaria desigual; los riesgos éticos incluyeron sesgos, privacidad e impactos culturales. Los pilotos en África Oriental mostraron promesa técnica en medio de brechas institucionales. NGSO+IA puede impulsar una minería alineada con los ODS solo si se acompaña de derechos de datos vinculantes, aseguramiento independiente, vías participativas, interfaces abiertas y capacidad local; de lo contrario, las herramientas arriesgan un cumplimiento performativo más que resultados responsables y justos.

Palabras clave: Tecnosolución; Inteligencia Artificial; Big Data; Ética en Minería; Desarrollo Sostenible; Marcos de Gobernanza.

INTRODUCTION

Minerals and metals are central to the UN 2030 Agenda for Sustainable Development and to the growth of low-carbon, digital economies. As governments and markets classify resources as "critical," "responsible," or "green," expectations are rising for provenance accreditation, end-to-end transparency, and credible environmental, social, and governance (ESG) performance across mineral value chains.(1,2,3,4) This scrutiny is exposing the limitations of promotional "green" claims and placing mining—an industry whose social and ecological footprint spans exploration to waste—under pressure to demonstrate responsibility with verifiable evidence rather than narratives. In response, proponents increasingly advance "technological fixes" that promise cleaner extraction, safer operations, and higher resource efficiency through metals recovery, predictive maintenance, material-flow analytics, methane leak detection, and the integration of Big Data, artificial intelligence (AI), and the Internet of Things (IoT) from pit to port.(5,6,7)

Think-tanks and industry platforms amplify these proposals via glossy roadmaps and foresight exercises that emphasize rapid deployment and early wins, often shaping research, innovation, and public funding priorities.(8) Against the backdrop of climate emergency, biodiversity loss, pandemic-era inequality, and social unrest, such agendas portray mining as a necessary enabler of sustainability transitions.(9,10) Yet the framing of techno-fixes as catch-all solutions can obscure critical questions: Which problems are being solved, for whom, at what scales, and with what trade-offs? What governance arrangements ensure that data-driven systems enhance accountability rather than merely optimize production?

Globally, mining governance has struggled to internalize cross-boundary environmental and social costs. While UN member states endorsed the SDGs as a universal, interconnected framework, many jurisdictions retain legal and fiscal regimes that prioritize investment attraction and export growth over participatory decision-making, cumulative-impact management, and transboundary stewardship.(11,12,13,14,15) This imbalance perpetuates a representation paradox: directly affected communities and planetary interests have limited influence over project design and oversight, whereas demand-side actors—manufacturers, financiers, and consumers—shape standards and incentives with considerable power.(8,9,10,11,12,13,14,15) Firms increasingly adopt AI and Big Data to navigate regulatory complexity, drive traceability, and tighten supply efficiency, but core pressures remain: greenhouse-gas emissions, freshwater consumption, land disturbance, and legacy liabilities.(16,17,18,19) Delivering on climate, biodiversity, social-equity, and human-rights commitments therefore requires governance that couples technological capability with enforceable accountability.

Industry dynamics reinforce this pivot. Investors, lenders, and customers tie access to capital and markets to ESG ratings, disclosure regimes, and chain-of-custody verification, while "no-go" areas, free, prior, and informed consent (FPIC), and grievance mechanisms expand expectations for responsible conduct.(24,25,29,30,31) These shifts create incentives for credible transparency—but also for performative compliance and data-driven greenwashing unless independent oversight and meaningful participation are built in.(26,27,28)

The African context sharpens these tensions. Frequently cast as the "final mining frontier," the continent combines exceptional geological potential with infrastructural gaps, uneven regulatory capacity, and complex political economies. Western-designed AI/Big Data systems are promoted as quick solutions for efficiency, environmental performance, and safety, yet they may import epistemic biases, neglect local knowledge, and displace context-appropriate practices.(3,4,32) Many frontier states face limited readiness to govern data ownership, privacy, cybersecurity, algorithmic risk, and vendor lock-in. A more equitable pathway would center

African agency in co-design, testing, and deployment; blend indigenous and experiential knowledge with digital tools; and build institutions capable of stewarding socio-technical systems toward public value.[3,4,32] Methods such as ethnographic action research, participatory design, and "design emergence" can help align solutions with local priorities, iterating from low-cost prototypes to scalable systems while avoiding irreversible misalignments.[3,8,32]

East Africa illustrates both promise and peril. Historically, the region's formal mining sector was tightly state-controlled through statutes and state-owned enterprises; liberalization since the late 1990s has attracted multinational investment across Uganda, Rwanda, Kenya, Tanzania, and South Sudan.[11,12,13,14,15,16,17,18,19,20,21,22,23,24,25] Today, a minerals boom—entangled with energy geopolitics—fuels expectations of growth, poverty reduction, and long-term revenue management.[26,28,29] At the same time, climate vulnerability, land and water pressures, and rapid demographic change heighten social and ecological risk. Investors and governments increasingly rely on AI-enabled monitoring, remote sensing, and ESG dashboards to track compliance and performance. But key questions remain: Do these systems genuinely improve accountability and outcomes for all affected groups? How do they redistribute power, knowledge, and risk? And what institutional capacities are required to ensure that data-rich governance enhances, rather than erodes, social license and environmental stewardship?[8,11,26,27,28,29]

This study addresses these questions by interrogating the techno-fix narrative in mining through the lenses of governance, ethics, and equity, with a particular focus on East Africa. It examines how AI and Big Data are articulated as solutions; how they are being designed, procured, and implemented; and how they interact with regulatory regimes, community expectations, and sustainability commitments across the value chain. By triangulating policy analysis with on-the-ground perspectives, the study seeks to move beyond generalized claims to evidence of what works, where, and why.

The study has six integrated objectives: (i) to map the landscape of AI/Big Data "techno-fixes" proposed or deployed across mining activities—from exploration and extraction to processing, logistics, and waste—and to characterize the benefits they claim;[5,6,7,8] (ii) to evaluate, using illustrative East African cases, how these systems perform in practice with respect to safety, environmental integrity, traceability, and operational efficiency, identifying enabling and inhibiting conditions;[11,12,13,14,15,16,17,18,19,26,27,28,29] (iii) to analyze governance arrangements (laws, standards, contracts, and oversight mechanisms) shaping data ownership, access, interoperability, and redress, and to assess their adequacy for delivering accountability and protecting righ ts;[11,12,13,14,15,24,25,26,27,28,29,30,31] (iv) to examine ethical and justice implications—including representation, consent, bias, and distribution of risks and benefits—for workers and communities, with attention to epistemic inclusion of local and indigenous knowledge;[3,4,32] (v) to assess state and community capacities for procuring, auditing, and sustaining data-intensive systems, and the risks of dependency or vendor lock-in; and (vi) to generate actionable guidance—policy options, institutional designs, and co-design practices—that align AI/Big Data adoption in East African mining with SDGs, climate and biodiversity commitments, and nationally determined development priorities.[1,2,3,4,9,10]

METHOD

Study design and rationale

The study conducted a mixed-methods evidence synthesis to examine how AI/Big Data "techno-fixes" in mining—enabled in part by non-geostationary satellite (NGSO; LEO/MEO) Earth-observation and communications—perform technically and, crucially, how they interact with governance, accountability, and equity. The design integrates: (i) a PRISMA-guided systematic review of primary empirical studies on NGSO-supported mining applications (EO, positioning, connectivity) and AI/analytics across the value chain; and (ii) a documentary governance and ethics review of laws, standards, contracts, ESIAs, oversight/audit reports, grievance records, and supply-chain initiatives with emphasis on Africa, particularly East Africa. This dual track allows us to evaluate "what works" and "under what conditions," directly reflecting the study's six objectives.

Protocol and registration

A protocol specifying questions, eligibility, outcomes, and synthesis plans was registered a priori on the Open Science Framework. Any amendments were time-stamped with rationale and implications for interpretation. Reporting follows PRISMA 2020 and JBI guidance for reviews of effectiveness and evidence syntheses.

Eligibility criteria

Populations/contexts: Mining activities from exploration to waste management in open-pit and underground settings globally, with planned subgroup analyses for Africa and East Africa. Interventions/exposures: NGSO-enabled services (EO/remote sensing, positioning, broadband/IoT backhaul) and AI/Big Data components (e.g., tasking, computer vision, anomaly detection, routing/scheduling, predictive maintenance, ESG/traceability analytics).

Comparators: GEO satellites, terrestrial networks, legacy non-satellite approaches, or no comparator.

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Outcomes:

- Technical: latency, throughput, availability, coverage, revisit; detection/segmentation accuracy where applicable.
- Operational/safety: productivity, downtime, incident/near-miss rates, positioning reliability.
- Environmental/compliance: detection lead-time for spills/land-use change, methane leak detection, monitoring sensitivity/specificity, contribution to permitting/compliance.
- Economic: CAPEX/OPEX proxies, cost per bit/site, avoided downtime.
- Accountability/justice (governance track): traceability coverage, public disclosure, independent auditability, FPIC evidence, grievance resolution, data ownership/access, vendor lock-in indicators, inclusion of local/indigenous knowledge.

Study designs: Experimental, quasi-experimental, observational, case studies, pilot deployments, techno-economic assessments reporting empirical data; high-quality secondary syntheses for context.

Inclusions/exclusions

English-language primary studies; standards/white papers included as contextual evidence and appraised separately. Exclude GEO-only or terrestrial-only work without NGSO linkage; purely speculative pieces lacking methods/results; editorials/news briefs; mining-irrelevant studies.

Information sources

Bibliographic databases: Scopus, Web of Science Core Collection, IEEE Xplore, ACM Digital Library, Inspec, ScienceDirect, SpringerLink, ProQuest Dissertations & Theses.

Standards and operator sources: ITU, 3GPP, CCSDS, national regulator repositories, and major operator/consortium technical reports.

Governance/ethics sources: national gazettes and mining laws/regulations; ESIAs and license terms; oversight/audit and grievance records; corporate sustainability/ESG and assurance reports; regional policy frameworks (e.g., Africa Mining Vision), supply-chain initiatives (e.g., EITI-related materials), and relevant NGO/legal case repositories.

Grey literature discovery used Google Scholar. Backward/forward citation chasing was performed on all included records. Where needed, domain experts were contacted to locate in-press or hard-to-find documents.

Search strategy

Concept blocks combined NGSO terms with mining and AI/EO/connectivity constructs. Example (Scopus): (“non-geostationary” OR NGSO OR LEO OR MEO OR “satellite constellation*”) AND (mining OR “mineral extraction” OR “open-pit” OR underground) AND (“Earth observation” OR “remote sensing” OR connectivity OR broadband OR IoT) AND (AI OR “machine learning” OR “computer vision”).

Database-specific subject headings/synonyms were added iteratively. Hand-searching covered key venues (e.g., *Remote Sensing of Environment*, *ISPRS Journal of Photogrammetry and Remote Sensing*, *Minerals*, *IEEE TGRS*, IGARSS proceedings) and industry conferences. Searches covered inception to 12 August 2025.

Study selection and PRISMA flow

Records were de-duplicated and screened in two stages (title/abstract; full text) by two independent reviewers using predefined forms; a third reviewer adjudicated disagreements. Reasons for full-text exclusion were logged. A PRISMA 2020 flow diagram summarizes identification, screening, eligibility, and inclusion for both the technical and governance tracks.

Data extraction

A pilot-tested template captured: bibliographic metadata; orbit/class (LEO/MEO), constellation details; service type (EO/communications/positioning); AI role (none/inference/optimization/autonomy); mining use-case; deployment geography and setting; comparators; definitions and measures of outcomes; runtime/compute constraints; funding/source. For EO/AI studies, we additionally recorded dataset provenance, annotation methods, validation design (including cross-site/out-of-distribution testing), and guardrails against data leakage.

For governance/ethics documents, a coding framework mapped: legal authorities and standards; data rights (ownership, access, interoperability); audit/assurance mechanisms; FPIC and participation; grievance and remedy; traceability scope and verification; provisions for environmental monitoring and cumulative impact; cybersecurity/privacy; vendor lock-in and procurement terms; and evidence of indigenous/local knowledge integration. Extraction was performed in duplicate with reconciliation by consensus.

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Risk of bias and quality appraisal

The study applied JBI checklists appropriate to study design; RoB 2 for randomized trials; ROBINS-I for non-randomized studies; and AACODS for grey literature/technical reports. For EO/AI performance studies, we recorded threats to validity (sampling bias, class imbalance, overfitting/leakage, inadequate external validation) and reporting completeness (dataset access, code availability). Governance/ethics sources were appraised for authority, methodological transparency, and independence (e.g., third-party assurance vs self-report).

Data synthesis

Given anticipated heterogeneity, we prespecified a mixed-methods synthesis:

Quantitative. Where ≥3 comparable studies reported the same outcome (e.g., latency, availability, detection F1), we performed random-effects meta-analysis, reporting pooled estimates with 95 % CIs, Cochran's Q, and I^2. Count outcomes (e.g., incident rates) used rate ratios; continuous outcomes used mean differences or SMDs. Sensitivity analyses excluded high-risk-of-bias and industry-funded-only studies; publication bias was explored with funnel plots and Egger's tests when feasible.

Qualitative/realist. For intervention-context-mechanism-outcome (ICMO) mapping, we conducted a realist-informed narrative synthesis linking technical capabilities to governance conditions (e.g., data access rules, auditability, participation) to explain "what works, for whom, in which contexts." A framework synthesis aligned findings to SDG-relevant domains (climate, biodiversity, equity, rights) and to accountability constructs (traceability, FPIC, grievance effectiveness).

Subgroups/meta-regression. Planned subgroups: orbit class (LEO vs MEO), service type (EO vs communications), mine type (open-pit vs underground), region (Africa/East Africa vs other), and AI involvement level. Where data permitted, meta-regression explored moderators (e.g., revisit rate, bandwidth, external validation, independent assurance).

Certainty of evidence

Furthermore, the study used GRADE to rate certainty (high/moderate/low/very low) for quantitative outcomes and GRADE-CERQual for qualitative/governance findings, considering risk of bias, inconsistency, indirectness, imprecision, and publication bias. Summary-of-findings tables present effect sizes and certainty judgments across technical, operational, environmental, economic, and accountability endpoints.

Reflexivity and limitations

Documented reviewer expertise and potential conflicts, used dual independent screening/extraction to reduce bias, and noted evidence gaps (e.g., limited public data on commercial deployments, scarcity of independent audits in frontier regions).

Ethics and dissemination

No human subjects were involved; ethical review was not required. We will make search strings, screening decisions, extraction forms, and coded governance datasets openly available and submit results to a peer-reviewed journal, with presentations at EO/mining and satellite-communications fora.

Protocol amendments

Any post-registration changes to eligibility, outcomes, or synthesis methods were dated, justified, and reported alongside results.

RESULTS

The searches returned a heterogeneous corpus spanning peer-reviewed studies, pilot deployments, operator and consortium reports, standards documents, and governance and ESG materials. Most primary research centered on Earth-observation applications in open-pit contexts, while underground operations and long-horizon, mine-scale evaluations were less common. Connectivity evidence consisted largely of LEO/MEO backhaul and IoT gateway pilots. Governance and ethics materials were dominated by regulatory texts, environmental and social impact assessments (ESIAs), corporate sustainability and assurance reports, and policy frameworks pertinent to traceability. Industry sponsorship and vendor authorship were frequent among technical sources, with relatively few independently audited deployments; this shaped subsequent certainty judgments.

Regarding Objective 1, the landscape analysis showed four recurring NGSO-enabled functions across the mining value chain. First, sensing and monitoring used high-revisit optical and SAR imagery for land-disturbance and tailings surveillance, interferometry for subsidence, and multispectral or thermal analytics for proxies of water quality, alongside targeted methane detection. Second, positioning and operational support included augmentation of localization and tasking for semi-autonomous equipment. Third, connectivity and backhaul leveraged LEO/MEO broadband and IoT links to sustain telemetry, safety systems, remote supervision, and compliance data streams in remote sites. Fourth, analytics and AI encompassed computer vision for change detection and hazard identification, optimization for routing, scheduling, and predictive maintenance, and ESG or traceability analytics that fused satellite with on-site data. While EO applications appeared comparatively mature, NGSO connectivity remained unevenly documented and fully autonomous AI-driven control loops were still rare beyond controlled pilots.(2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28)

For Objective 2, technical performance favored NGSO over GEO or terrestrial-only baselines in remote contexts, with LEO links delivering latencies in the tens of milliseconds and MEO typically around 100–200 milliseconds. Availability depended on terminal siting, sky view, and weather for specific bands, whereas EO revisit from LEO constellations supported near-continuous surface monitoring when tasking and cloud-gap strategies combined SAR and optical streams. Detection accuracy in AI pipelines varied with dataset provenance and validation rigor; studies that used cross-site or out-of-distribution testing reported more conservative and credible metrics than single-site reports. Operationally, deployments associated NGSO-enabled telemetry with improved equipment utilization, faster incident reporting, and reduced data dropouts that enabled near-real-time supervision of mobile assets. Evidence for reductions in incident or near-miss rates existed but was constrained by short follow-up periods and co-occurring safety initiatives, leading to low-to-moderate certainty.(26,27,28)

Environmental and compliance outcomes were strongest where EO-AI workflows flagged surface changes relevant to regulatory oversight—such as unpermitted clearing or tailings beach geometry shifts—while translation from anomaly flagging to verified risk reduction depended on ground truthing and integration into management processes, which were often incomplete. Methane detection performance varied by sensor class; targeted sensors characterized larger plumes reliably, whereas wide-swath instruments provided screening with higher false-positive risk. Economic reporting was sparse; when provided, avoided downtime and deferred terrestrial build-outs dominated the benefits, but cost models and accounting practices were too heterogeneous for high-certainty conclusions. Subgroup findings indicated LEO advantages for latency-sensitive links and high-revisit monitoring, MEO strengths for higher throughput at moderate latency, and a strong bias toward open-pit contexts, with underground benefits primarily in backhaul from subsurface gateways. Studies with independent validation yielded more conservative but more credible effects.(6,7,8,9,10,11,12,13,14,15,16,17,18)

Findings for Objective 3 highlighted a growing, but inconsistent, incorporation of satellite-derived evidence into traceability and assurance regimes. Although concession boundaries and land-use change were increasingly referenced, the scope and verifiability of chain-of-custody claims varied substantially. Data rights and access provisions were seldom explicit in publicly available contracts, exposing operators and regulators to vendor lock-in and limiting data portability. Auditability hinged on whether raw and processed data, as well as model artifacts, were retained and shareable with regulators or communities—conditions uncommon in proprietary deployments. Participation and free, prior, and informed consent (FPIC) were rarely articulated for data-intensive monitoring schemes; ESIAs typically listed remote sensing methods but did not define how affected communities could access data products or integrate them into grievance processes. Where assurance statements existed, they tended to emphasize disclosure completeness rather than model validity or independent field verification. Overall, institutions capable of converting data into enforceable accountability lagged behind technical capabilities.(5,6,7,8)

Objective 4 revealed recurring ethical and justice concerns tied to representation, consent, bias, and benefit distribution. Models trained on non-local imagery or limited event catalogs underperformed in unfamiliar terrains, undermining reliability and fairness. Consent and privacy frameworks for community-visible monitoring were seldom defined, particularly in peri-urban or informal settlements adjacent to mine sites. Most data products primarily served operator and investor use-cases, with limited community access or interpretability. Integration of indigenous and local knowledge into AI tasking or validation was sporadic; where participatory mapping or "citizen sensing" was piloted, label quality improved and outputs became more interpretable, yet such practices remained the exception. The strength of evidence for these ethical findings was low to moderate due to reliance on documentary sources and a small number of detailed case studies.(2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23)

Addressing Objective 5, sustained performance depended on local capacity to procure, operate, and audit NGSO-plus-AI systems. Common bottlenecks included reliable power and cybersecurity for remote terminals, integration with legacy SCADA and MES environments, and scarcity of staff fluent in geospatial machine learning and MLOps. Procurement frequently bundled terminals, bandwidth, and analytics under single vendors, complicating independent evaluation, data escrow, and exit strategies. Conversely, deployments that specified open interfaces, data portability, and model documentation (e.g., datasheets and model cards) demonstrated better interoperability and oversight potential, and facilitated progressive technology transfer.(3,5,9,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28)

Synthesizing across objectives for Objective 6, three design principles emerged. First, technical monitoring only translated into accountability where contracts and regulatory instruments explicitly defined data rights, third-party auditability, and links to grievance and remedy mechanisms; absent these, dashboards risked performative compliance. Second, external validity mattered: SAR–optical fusion, cross-site validation, and explicit uncertainty reporting reduced false assurance and improved decision relevance. Third, openness and capacity building were decisive for sustainability: standard interfaces, portable data, and local training reduced lock-in, supported regulator uptake, and enabled communities to interpret and act on evidence.[26,27,28]

The East African subgroup, though thinner in volume, aligned directionally with global patterns. NGSO connectivity pilots improved telemetry and video backhaul where terrestrial networks were unreliable, enabling near-real-time operational reporting. EO-driven monitoring supported concession surveillance, mapping of artisanal and small-scale mining landscapes, and detection of land-use change around protected or community areas. Institutional readiness, however, was uneven: licensing and ESIA documents seldom clarified ownership, sharing, or public access to derived data products; capacity gaps limited routine operation of AI pipelines without external service providers; and mechanisms for community participation and FPIC in data-intensive monitoring were inconsistently applied. Although policies referenced remote sensing for oversight, systematic integration into inspections, sanctions, or benefit-sharing remained rare, meaning tools more often enhanced internal situational awareness than public accountability.[6,7,8,9,10,11,12]

Risk-of-bias assessments using JBI, RoB 2, ROBINS-I, and AACODS identified small samples, single-site designs, short follow-up, incomplete disclosure of datasets and code, and frequent industry sponsorship as dominant limitations. Using GRADE, certainty was judged moderate for technical endpoints such as latency, availability, and change-detection performance due to consistent direction of effect across multiple sources, but low for operational, environmental, and economic outcomes because of confounding and imprecision. Governance and ethics syntheses, appraised with GRADE-CERQual, carried low-to-moderate confidence given their reliance on documentary evidence and limited independent audits.

Taken together, the evidence indicates that NGSO-enabled sensing and connectivity, when coupled with AI, materially improve observability and responsiveness across mining operations; however, these capabilities do not consistently produce accountability or justice outcomes without explicit data rights, independent assurance access, and participatory pathways. Durable value arises where deployments are procured and governed for openness, validation, and local capacity building—conditions especially salient for East African regulators, operators, and communities aiming to align mining with the SDGs, climate and biodiversity commitments, and national development priorities.

DISCUSSION

Industry narratives portray an imminent leap to fully automated, data-driven mining, yet our evidence shows a more uneven, path-dependent reality. NGSO (LEO/MEO) constellations and AI/Big Data analytics have clearly improved observability—lower latency connectivity, higher revisit sensing, and faster incident awareness—but translation into durable safety, environmental, and accountability gains remains contingent on governance, validation, and local capacity. Put differently: technical capability is now ahead of institutional readiness. That gap explains why dashboards sometimes optimize production without reliably improving disclosure, auditability, or remedy for affected communities.[5,6,7,8,9,10,11,12,13,14,15,16,17,18]

Interpreting technical performance in light of governance constraints. The corpus consistently showed LEO/MEO advantages over GEO/terrestrial baselines for remote operations—tens-of-milliseconds latency for LEO links, high-revisit SAR/optical fusion for surface change detection, and more resilient backhaul for telemetry. However, where studies implemented cross-site validation and independent assurance, effect sizes moderated and false-positive risks surfaced, especially for methane screening and tailings anomaly detection. These results caution against "autopilot" claims: control-tower narratives and black-box optimizers remain vulnerable to dataset shift, label quality issues, and opaque decision pipelines that complicate explanation and accountability.[5-18] Without ground-truthing protocols and model documentation, NGSO-enabled AI can entrench overconfidence rather than reduce risk.[6,7,8,9,10,11,12]

From traceability rhetoric to enforceable accountability. Market and policy pressures have expanded traceability language in corporate disclosures, but our review found that chain-of-custody claims frequently outpace underlying contractual rights and audit access. Data ownership and portability are rarely explicit; vendor bundling of terminals, bandwidth, and analytics creates lock-in and limits regulator or community scrutiny. Assurance statements often certify disclosure completeness rather than model validity or field verification, leaving a credibility gap between ESG narratives and verifiable performance.[23,24,25,26,27] The implication is straightforward: sensing and connectivity only become accountability tools when procurement and licensing embed data rights, third-party auditability, and clear pathways to grievance and remedy.[6,7,8,9,10,11,12]

Ethical side-effects: bias, explainability, and responsibility. Hype around algorithmic objectivity masks well-documented failure modes. Models trained on non-local imagery or narrow event catalogs underperform in new terrains; optimization targets chosen for throughput or cost can ignore distributional harms; and black-box pipelines weaken reasons-giving, diffusing responsibility when harm occurs.[5,6,7,8,9,10,11,12,13,14,15,16,17,18] Our synthesis also surfaced thin treatment of consent and privacy in community-visible monitoring near operations. These patterns reaffirm that "techno-fixes" can reallocate power and risk unless designed with representation, explainability, and due process at their core.[6,7,8,9,10,11,12]

Local knowledge, jobs, and cultural heritage. Automation and remote supervision can catch operational hazards faster, but they seldom identify social ones without deliberate design. Oral histories and place-specific knowledge protect historical, cultural, and archaeological sites; removing local interpreters from monitoring loops risks cultural loss and erodes social identity.[8,9,10,11] Projects that paired EO/AI with participatory mapping improved label quality and interpretability, suggesting a workable path: keep affected communities "in the loop," not at the margins.[6,7,8,9,10,11,12]

Privacy, cybersecurity, and data governance. NGSO-EO and hyper-connected operations expand the surface for misuse. Even when firms claim anonymization, modern re-identification is feasible; wide-area satellite coverage brings "every-inch" observability close to reality. Cross-border data sharing by operators, financiers, or vendors can expose communities and whistle-blowers, while arms-length data sales or acquisitions of civil-society actors undermine trust.[30,31,32] The results point to concrete safeguards: data minimization by design, privacy-preserving analytics, independent data escrow, and governance that separates operational control from oversight data pipelines.[6,7,8,9,10,11,12,13,14,15]

Environmental alignment without "technofix-itis." Demand for critical minerals is rising even as ore grades decline and climate targets tighten. NGSO-enabled sensing and connectivity can cut lead-times for detecting land-use change, tailings instability, or fugitive emissions, and can support higher process efficiency. Yet many targets to be "net-zero" rest on device-level swaps rather than system-level decarbonization plans, and companies often lack site-specific social and environmental risk intelligence.[9,10,11,12,13,14,15,16,17] The risk is technofix-itis: over-reliance on tools without clarifying responsibilities, trade-offs, and long-term liabilities. Evidence here argues for coupling monitoring with enforceable mitigation and transparent closure planning, not merely better dashboards.

East Africa: capability, consent, and regulatory uptake. In East Africa, pilots showed real wins—backhaul where terrestrial networks fail; EO-supported concession surveillance; mapping of ASM dynamics. But institutional readiness lagged: licenses and ESIAs seldom specified data rights or public access to derived products; FPIC and grievance integration for data-intensive monitoring were uneven; and sustained operation of AI pipelines depended on external providers.[6,7,8,9,10,11,12,24,26]

The Tanzania SDG-15 illustration underscores the broader point: voluntary frameworks alone are insufficient; regulatory capacity and legally enforceable data provisions are needed to avoid inequitable outcomes.[6] Absent these, NGSO + AI primarily enhance internal awareness, not public accountability. Stakeholder engagement and sustainable practice as system design, not outreach. Given shifting societal values, ESG expectations, and likely regulatory tightening, engagement cannot be an afterthought. Mapping stakeholder value chains, clarifying platform power (who controls data and interfaces), and co-designing monitoring objectives with communities and regulators reduce later conflict and greenwashing risk.[23] Companies that invest early in local capacity—training, data access literacy, and shared interpretation protocols—are better positioned to turn observability into trustworthy performance. Policy and implementation implications. Four recommendations from the source material align closely with our evidence and can be operationalized.

First, align AI and Big Data with a healthy planet: prohibit clearly harmful applications, and make "smart mining" conditional on open publication of laureated areas, end-to-end impact assessment transparency, and auditable aftercare; license terms should codify data rights, audit access, and escalation to remedy.[5-18,23-27] *Second, fund data commons:* prevent enclosure by requiring escrow of EO/monitoring products and metadata (including model cards and validation reports) under controlled public-good licenses; finance independent curation so regulators and communities can interrogate claims without vendor mediation. *Third, build aware, capable societies:* invest in regional training pipelines for geospatial/ML, privacy, and safety engineering; require participatory sensing and FPIC for data-intensive monitoring; and support venues where competing evidence can be tested and debated.[8,9,10,11,23,24,25,26,27] *Fourth, channel data to neutral NGOs:* when state capacity or trust is limited, route oversight data through neutral, reputable intermediaries with safeguards to protect communities, and publish redacted summaries to limit re-identification risk. Together these steps instantiate the design principles that emerged from the results: pair monitoring with institutional mechanisms; prioritize validation and transferability; and build openness and capacity.

Regulatory frameworks: from voluntary codes to enforceable rules. Voluntary initiatives signal norms but lack teeth. The inequities of the global data ecosystem mean developed actors capture more benefits and impose externalities on weaker jurisdictions. Bridging the regulatory gap requires soft-law coordination and hard-law instruments that travel across borders—standard clauses on data rights and portability, audit trails for EO/AI systems, mandatory incident reporting, and interoperable grievance mechanisms—plus resourcing regulators to use them.[6,23,24,25,26,27]

Limitations and future research. Evidence gaps mirror the field's nascency: small, single-site samples; short follow-up; sparse economic reporting; and few independent audits. Longitudinal designs that tie NGSO-enabled monitoring to actual reductions in incidents, emissions, and conflicts are rare but necessary. Comparative studies of procurement models (bundled vs open), external validation regimes, and participatory methods would clarify "what works, where, and why." Regionally, East Africa would benefit from a registry of data-intensive monitoring deployments, pre-specification of outcomes, and standardized release of redacted oversight datasets to enable cumulative learning.[23,24,25,26,27,32]

Bottom line. NGSO + AI are powerful instruments for seeing and coordinating complex mining systems. Our review shows they deliver tangible technical gains (connectivity, revisit, detection), but these do not automatically become social or environmental gains. The difference is made by contracts, capacity, and co-governance: explicit data rights and auditability, validated and explainable models, and local institutions capable of using evidence to shape practice and remedy. Where those conditions are met, techno-fixes can support responsible mining; where they are not, they risk becoming sophisticated new ways to do old things.[5,6,7,8,9,10,11,12,13,14,15,16,17,18,23,24,25,26,27]

CONCLUSION

NGSO constellations and AI/Big Data already deliver tangible technical gains in mining—lower-latency connectivity, high-revisit sensing, and faster incident awareness—but these improvements translate into sustainable development only when coupled to governance that guarantees data rights, auditability, participation, and remedy. Our synthesis shows that, without enforceable provisions, "techno-fixes" risk optimising production while leaving accountability, equity, and environmental performance uncertain, particularly in East Africa, where regulatory capacity, FPIC practice, and long-term technology transfer remain uneven. Aligning mining with the SDGs, therefore, requires moving from voluntary codes to binding arrangements: open standards and data portability in procurement; third-party access to raw/processed data and model artefacts; privacy-preserving oversight; participatory mapping and community data access; and capacity building for regulators and local operators. Priorities for research include longitudinal evaluations linking NGSO/AI deployments to verified reductions in incidents, emissions, and conflicts; comparative studies of open vs bundled procurement; and robust external validation of EO/AI pipelines. In short, NGSO + AI can help meet societal demand for responsible minerals, but only when institutions are designed so that better observability becomes verifiable accountability and just outcomes, not merely better dashboards.

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Conceptualization: Fredrick Kayusi.
Data curation: Fredrick Kayusi, Petros Chavula.
Formal analysis: Fredrick Kayusi,Petros Chavula
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Methodology: Fredrick Kayusi.
Software: Fredrick Kayusi, Petros Chavula.
Validation: Fredrick Kayusi, Petros Chavula.
Display: Fredrick Kayusi, Petros Chavula.
Drafting - original draft: Fredrick Kayusi.
Writing - proofreading and editing: Fredrick Kayusi, Petros Chavula.