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SYSTEMATIC REVIEW

A comprehensive exploration of nongeostationary satellite systems in the mining industry: emphasizing AI, ethical considerations, and communication strategies

Una exploración integral de los sistemas de satélites no geoestacionarios en la industria minera: énfasis en IA, consideraciones éticas y estrategias de comunicación

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

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

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Corresponding author: Petros Chavula

ABSTRACT

Introduction: non-geostationary satellite (NGSO) constellations—particularly LEO/MEO—are transforming mining by providing low-latency connectivity and taskable Earth observation to remote, infrastructure-poor sites.
Objectives: include mapping NGSO applications across exploration, planning, and operations; assessing AI's role in tasking, routing, and analytics; and examining governance and ESG implications, with a focus on Africa and East Africa.
Method: involved a PRISMA-aligned systematic review (protocol registered) synthesising primary and secondary evidence on NGSO-enabled EO and communications in mining. A random-effects meta-analysis was planned if three or more comparable studies reported the same outcome; otherwise, a structured narrative synthesis with predefined subgroups (LEO vs MEO, EO vs backhaul, open-pit vs underground, Africa vs elsewhere) was used.
Results: showed that across more than 30 use cases, NGSO backhaul and EO tasking consistently reduced time to insight for pit progression, tailings surveillance, and asset tracking; simulations indicated routing improvements of approximately 10 % on tree topologies and 30 % on mesh networks at N=500, demonstrating tangible latency and capacity benefits for safety-critical workflows. Continuity was enhanced through multi-sensor PNT (GNSS/inertial/vision plus radio localisation) and hierarchical link adaptation that rapidly re-parameterises under noise, weather, or interference. AI added value by improving tasking and congestion control in edge and cloud inference, though it required cascaded models, compression, and uncertainty gating to meet compute and bandwidth constraints. Governance themes—such as data protection, transparency, and community benefit—were recurring enablers of adoption.
Conclusion: when combined with resilient positioning, adaptive operations, and credible ESG safeguards, NGSO combined with AI can significantly enhance mining efficiency, safety, and sustainability; priorities include standardised KPIs, transparent cost models, and long-term pilot deployments.

Keywords: Nongeostationary Satellite Systems; Mining Industry; Artificial Intelligence; Data Acquisition; Communication Strategies; Ethical Considerations.

RESUMEN

Introducción: las constelaciones de satélites no geoestacionarios (NGSO)—en especial LEO/MEO—están transformando la minería al ofrecer conectividad de baja latencia y observación de la Tierra programable en sitios remotos con poca infraestructura.
Objetivos: cartografiar aplicaciones NGSO en exploración, planificación y operaciones; evaluar el papel de la IA en asignación de tareas, enrutamiento y analítica; y examinar implicaciones de gobernanza/ASG, con énfasis en África y África Oriental.
Método: revisión sistemática alineada con PRISMA (protocolo registrado) que sintetizó evidencia primaria/secundaria sobre OT/comunicaciones habilitadas por NGSO en minería. Se planificó metaanálisis de efectos aleatorios cuando ≥3 estudios comparables reportaron el mismo desenlace; de lo contrario, síntesis narrativa estructurada con subgrupos predefinidos (LEO vs MEO, OT vs backhaul, cielo abierto vs subterránea, África vs otros).
Resultados: en >30 casos de uso, el backhaul NGSO y la tarea de OT redujeron consistentemente el "time-to-insight" para avance de banco, vigilancia de relaves y seguimiento de activos; simulaciones mostraron ganancias de enrutamiento de ≈10 % (árbol) y ≈30 % (malla) con N=500, evidenciando beneficios tangibles en latencia y capacidad. La continuidad mejoró con PNT multisensor (GNSS/inercial/visión + localización por radio) y adaptación jerárquica del enlace. La IA añadió valor desde la tarea y el control de congestión hasta la inferencia en borde/nube, requiriendo modelos en cascada, compresión y umbrales de incertidumbre. Los facilitadores de adopción incluyeron protección de datos, transparencia y beneficio comunitario.
Conclusión: combinadas con posicionamiento resiliente, operaciones adaptativas y salvaguardias ASG creíbles, NGSO+IA pueden mejorar sustantivamente la eficiencia, seguridad y sostenibilidad mineras; se priorizan KPIs estandarizados, modelos de costo transparentes y pilotos longitudinales.

Palabras clave: Sistemas de Satélites No Geoestacionarios; Industria Minera; Inteligencia Artificial; Adquisición de Datos; Estrategias de Comunicación; Consideraciones Éticas.

INTRODUCTION

The global economy depends heavily on natural-resource industries—including agriculture, fisheries, mining, forestry, and oil and gas—whose efficient operations increasingly rely on space-enabled services such as Earth observation (EO), telecommunications, navigation, and search-and-rescue.[1,2,3,4,5] Yet resources are finite, and current consumption trajectories signal looming shortages without stronger stewardship and sustainability measures.[1] Within this context, mining stands out for its potential both to benefit from and to shape EO capabilities. This article examines how non-geostationary satellite (NGSO) systems—especially medium Earth orbit (MEO) and low Earth orbit (LEO) constellations—can advance mining sector performance and sustainability.[2,4,5,6,7,8,9,10] NGSO architectures offer high throughput, global coverage, and low latency suitable for broadband and Internet-of-Things applications and are now commercially deployed worldwide.[1,2] Mining's remote, distributed operations demand ubiquitous, resilient connectivity for sensing, automation, worker safety, and environmental monitoring; many firms are pursuing similar digitalization goals.[8,9] While geostationary satellites provide mature EO and backhaul, their latency can be limiting; LEO systems improve latency but may raise cost and scaling challenges. NGSO constellations—augmented by artificial intelligence (AI)—present a compelling alternative to optimize resource allocation, reduce operational costs, and close performance gaps.[10,11]

Planning and operating NGSO networks for mining is nontrivial: joint satellite-network design, capacity and coverage optimization, handover control, inter-satellite links, and spectrum access all interact.[1,2,3,4,5,6,7,8] Classical mixed-integer formulations capture these trade-offs, but post-launch uncertainty and scale increasingly motivate AI-based, least-committed approaches—albeit with nontrivial computing requirements for training and deployment.[1,2,3,4,5,6,7,8,9] Market dynamics further complicate adoption: operators face evolving regulations, intensifying competition, and rapid technology cycles across single-orbit and multi-tier constellations.[2,3,4,6,12] Applications span EO and space-debris early warning alongside broadband services, underscoring the breadth of NGSO use cases.[1,13,14,15,16,17,18,19,20,21,22] These issues are particularly salient for Africa—especially East Africa—where mineral-led industrialization demands rapid gains in mapping, surveying, positioning, and analytics to enable safer, more efficient extraction; deploying NGSO services can accelerate remote-site connectivity while raising governance and ethical considerations around fairness, accountability, privacy, security, and inclusion in AI-enabled workflows.[1,2,3,4,5,6,7,8,9]

Accordingly, this study pursues four objectives: to map the NGSO landscape for mining, emphasizing MEO/LEO system qualities and key players; to catalogue more than thirty envisioned, day-specific NGSO use cases with an emphasis on global service coverage; to assess AI's role in NGSO design, deployment, and operations for mining EO and communications; and to discuss implications for African—particularly East African—deployment, including ethical, regulatory, and policy enablers.

METHOD

We conducted a systematic review to map and critically appraise how non-geostationary satellite (NGSO) systems—particularly LEO and MEO constellations—support mining through Earth observation (EO) and communications, including the role of artificial intelligence (AI) in design, deployment, and operations. Methods followed PRISMA 2020 and JBI guidance. A protocol was registered a priori on the Open Science Framework; any subsequent amendments were dated and logged. Searches covered database inception to 12 August 2025 and targeted both peer-reviewed and grey literature to capture technical performance, operational outcomes, environmental monitoring, and African (with East African) deployment contexts.

Review design and registration

The review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020). The protocol (research questions, eligibility, outcomes, and synthesis plan) was registered on OSF prior to screening. Deviations, if any, were documented with rationale and implications for interpretation.

Eligibility criteria (PICOS/PEO)

Population: mining sector contexts (exploration, planning, operations, logistics, safety, and environmental monitoring) across open-pit and underground settings worldwide, with planned subgroup analyses for Africa/ East Africa. Intervention/Exposure: NGSO (LEO/MEO) satellite-enabled services for EO/remote sensing, positioning, or connectivity (e.g., broadband/IoT backhaul), including AI-enabled components (e.g., tasking, image analysis, routing, scheduling). Comparators: geostationary (GEO) satellite services, terrestrial networks, legacy non-satellite approaches, or no comparator. Outcomes: technical (latency, throughput, availability, coverage, revisit), operational (productivity, downtime, incident rates), environmental (detection accuracy, lead time for anomalies, compliance support), and economic (CAPEX/OPEX proxies, cost per site/bit). Study designs: experimental, quasi-experimental, observational, case studies, pilot deployments, and techno-economic assessments reporting empirical data. Inclusion: English-language primary studies and high-quality secondary syntheses; relevant standards/white papers were eligible as contextual evidence and appraised separately. Exclusion: studies without mining relevance; GEO-only or terrestrial-only without NGSO linkage; purely speculative pieces lacking methods/results; editorials and brief news items.

Information sources

The study focused on searching Scopus, Web of Science Core Collection, IEEE Xplore, ACM Digital Library, Inspec, ScienceDirect, SpringerLink, and ProQuest Dissertations & Theses. To capture standards and operator evidence, we screened ITU, 3GPP, CCSDS, national regulator repositories, and major operator/consortium technical reports. Google Scholar aided grey-literature discovery. Backwards/forward citation chasing was conducted for all included records, and field experts were contacted to identify in-press or difficult-to-locate materials.

Search strategy

Concept blocks combined NGSO terms with mining and AI/EO/connectivity constructs. An example Scopus string was: ("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 and synonyms were added iteratively. We hand-searched key venues (e.g., *Remote Sensing of Environment*, *ISPRS Journal*, *Minerals*, *IEEE TGRS*, IGARSS proceedings) and industry conferences.

Study selection (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 resolved disagreements. Reasons for exclusion at full text were recorded. A PRISMA 2020 flow diagram summarizes identification, screening, eligibility, and inclusion.

Data extraction

A pilot-tested template captured bibliographic data; orbit/class (LEO/MEO), constellation details, service type (EO/communications/positioning), AI role (none/inference/optimization/autonomy), mining use-case category, deployment setting and geography, comparators, outcome definitions, effect estimates, runtime and compute constraints, and funding/source. Extractors worked independently in duplicate; discrepancies were

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reconciled by consensus.

Risk of bias and quality appraisal

The study also applied JBI checklists appropriate to study design; RoB 2 for randomised trials; ROBINS-I for non-randomised studies; and the AACODS checklist for grey literature/technical reports. Where image-analytic AI was central, we additionally recorded dataset provenance, annotation procedures, and validation (e.g., cross-site testing). Study-level judgments informed synthesis weighting and GRADE certainty ratings.

Data synthesis

Given expected heterogeneity, we prespecified a mixed-methods approach. Where ≥3 sufficiently comparable studies reported the same outcome (e.g., latency, availability), we performed random-effects meta-analysis, reporting pooled estimates with 95 % CIs, Cochran's Q, and I^2. For count outcomes (e.g., incident rates), rate ratios were synthesized; continuous outcomes used standardized mean differences when needed. If meta-analysis was infeasible, we conducted structured narrative synthesis with harvest plots and vote-counting by direction of effect, linked to risk-of-bias profiles. Planned subgroups included orbit class (LEO vs MEO), service type (EO vs communications), mine type (open-pit vs underground), and region (Africa/East Africa vs other). Sensitivity analyses excluded high-risk-of-bias and industry-funded-only studies. Where data permitted, meta-regression explored moderators (e.g., revisit rate, bandwidth, AI involvement level).

Certainty of evidence

The study also used GRADE to rate certainty (high/moderate/low/very low) per critical outcome, considering risk of bias, inconsistency, indirectness, imprecision, and publication bias. Summary-of-findings tables present effect sizes and certainty judgments for technical, operational, environmental, and economic endpoints.

Ethics and dissemination

Ethical approval was not required because only publicly available studies were analyzed. We plan open-access dissemination of the full dataset (search strings, screening decisions, extraction forms) and submission of results to a peer-reviewed journal, with presentations at EO/mining and satellite communications conferences.

Protocol amendments

Any changes to eligibility, outcomes, or synthesis methods after registration were documented (date, reason, impact) and reported alongside the results.

RESULTS

Stakeholder demand and business context

Across the corpus, AI-enabled non-geostationary satellite (NGSO) applications generated substantial interest among mining operators, service providers, and regulators, reflecting persistent pressure to raise productivity while containing OPEX/CAPEX under volatile commodity cycles.[4,5] Studies consistently emphasized that competitive advantage hinges on turning fragmented, unstructured, high-volume data into actionable intelligence for planning, real-time operations, and compliance. Firms increasingly converge on similar digital goals, risking look-alike investments; however, simulation-driven AI (e.g., digital twins of pits, haulage, and processing) emerged as a differentiator by de-risking design choices, optimizing fleet/tasking, and uncovering new profit pools as companies build in-house capabilities in data collection, curation, and learning.[4,5]

Operational and technical performance in harsh environments

NGSO constellations (LEO/MEO) were reported to mitigate coverage gaps and latency constraints for remote sites, enabling EO tasking, private LTE/5G backhaul, machine telemetry, and safety systems where terrestrial networks are weak or absent.[2,3,4,5,6,7,8,9,10,11] For underground operations—where satellites cannot penetrate rock—NGSO links most effectively serve as resilient backhaul for leaky-feeder, Wi-Fi, or mesh networks, improving situational awareness and accelerating incident response.[3,4,5,6,7,8,9,10,11] Positioning proved pivotal: accurate localization anchors map-building and autonomy, preventing drift in robotic platforms operating along high-curvature trajectories. Evidence favored multi-sensor fusion (multi-GNSS plus radio localization, inertial, and vision-based SLAM) with robust fallbacks; link loss events were operationally critical and required fast re-acquisition, store-and-forward buffers, and edge analytics to maintain continuity.[2] One line of work examined radio-based localization under communication constraints and proposed client-side calibration that needs only a small set of accurately mapped samples and no network modification—improving reliability while preserving deployment simplicity.[2]

Key findings for mining use cases

First, NGSO connectivity materially reduces time-to-data and supports near-real-time EO/analytics for pit progression, slope stability, tailings monitoring, and asset tracking—areas where delays magnify safety and cost risks.[2,3,4,5,6,7,8,9,10,11] Second, the economic case strengthened where NGSO substituted costly microwave spurs or long fiber hauls, or where dynamic tasking/outage resilience prevented production losses. Third, in strategic and security contexts (e.g., during supply shocks), assured communications and rapid sensing limited downtime and improved regulatory reporting.[3,4,5,6,7,8,9,10,11] Overall, findings align with the sector's need to raise throughput with fewer stoppages, while meeting rising expectations for environmental and social performance.[2,3,4,5,6,7]

Data interpretation: link adaptation and resilience

Studies converged on the importance of adaptive link management. Systems that continuously estimate and tune reception parameters—e.g., center frequency/channelization, symbol rate, polarization, coding and modulation (AMC), and decoder settings—maintained higher availability under noise, weather, and interference. Hierarchical estimation pipelines were effective: coarse, fast detectors at the edge (embedded at gateways or user terminals) flagged parameter shifts; cloud/ground processors then refined estimates using higher-resolution models and longer observation windows, sharing updated parameters across ground systems to reduce operator workload.[22] In contested or congested RF environments, rapid re-parameterization and spectrum agility limited service degradation. Mathematically explicit signal models (including platform and environmental error sources) and the use of synthetic "dummy" signals for bootstrapping improved time-to-lock and robustness—an approach validated on both simulated and field datasets.[22] Compared with static configurations, adaptive pipelines yielded shorter recovery times after fades/outages and more stable effective throughput.[1,2,3,4,7,8,9,10,11]

AI's role across the NGSO stack

Beyond analytics, AI was reported to assist at multiple layers: (i) EO tasking and scheduling (which scene, when, and with what sensor), (ii) routing and congestion control across inter-satellite links, (iii) predictive maintenance of terminals and gateways, and (iv) autonomy for on-orbit and edge processing to reduce downlink load.[3,4,5,6,7,8,9,10,11] Importantly, compute constraints at the edge favored compact models or cascaded approaches (fast heuristics gating heavier inference), with cloud retraining and federated updates where bandwidth permitted.[1,2,3,4,5,6,7,8,9] Studies noted governance priorities—security, privacy, and auditability—particularly for safety-critical applications and cross-border operations.[1,2,3,4,7,8,9,10,11]

African and East African implications

Evidence highlighted strong fit for Africa—especially East Africa—where long distances and sparse terrestrial networks elevate the value of NGSO backhaul and rapid EO for exploration, environmental compliance, and logistics. Priority opportunities include tailings/TSF monitoring, illegal encroachment detection, haul-road optimization, and connectivity for remote camps and clinics, with policy attention to spectrum, landing rights, data protection, and equitable access.[2,3,4,5,6,7,8,9,10,11] Partnerships with national regulators and local integrators were recurrent enablers.

Limitations and gaps

Heterogeneity in study designs, proxy outcomes (e.g., engineering KPIs vs. production KPIs), and incomplete reporting of cost models limited meta-analytic synthesis in several domains. Few studies provided longitudinal evidence linking NGSO interventions to sustained productivity or incident-rate reductions; underground use cases still rely on hybrid architectures. Future work should report standardized technical (latency, revisit, availability) and operational endpoints, disclose annotation/validation practices for AI models, and examine total cost of ownership across life-of-mine horizons.[2,4,5,6,7,22] Overall, the synthesis indicates that AI-enabled NGSO solutions are maturing into practical enablers of safer, more efficient, and more transparent mining—provided deployments prioritize resilient positioning, link adaptation, and governance commensurate with the sector's risk profile.[2,3,4,5,6,7,8,9,10,11,22]

DISCUSSION

Network design implications for NGSO-enabled mining

Our routing experiments demonstrate material headroom over naïve strategies—~10 % on tree topologies and ~30 % on fully connected meshes at N = 500—translating directly into lower latency and higher effective capacity for time-critical mining workflows (e.g., safety telemetry, fleet control).[2,3,4,5,6,7] In operational terms, NGSO routing should be framed on a time-expanded contact graph that captures inter-satellite link (ISL) dynamics, gateway visibility, and task deadlines. Single-source trees approximate optimal costs where traffic is hub-biased (e.g., toward regional processing hubs), while mesh routing with admission control is preferable under bursty, many-to-many loads. [2,3,4,5,6,7] Policy-driven path selection (e.g., latency-first for collision avoidance, availability-first for EO downlinks) and pre-emption tiers align the network with mining KPIs such as incident response time, mean time to repair, and tailings monitoring revisit intervals.[2,3,4,5,6,7,8,9,10,11]

Positioning, timing, and continuity of operations

Reliable positioning anchors autonomy and map-building; drift on high-curvature robot paths degrades perception and increases stoppages. Evidence supports multi-sensor fusion—multi-GNSS with dual-frequency corrections plus inertial and vision/SLAM—augmented by radio localization, with client-side calibration requiring only a handful of accurately mapped samples and no network changes.[2] Continuity hinges on rapid re-acquisition and graceful degradation: store-and-forward buffers at the edge, delay-tolerant networking, and mission fallbacks that maintain safety interlocks during fades. Hierarchical link adaptation—coarse detection at terminals followed by fine parameter estimation on ground/cloud—stabilizes availability under noise, weather, or jamming, with shared parameter updates reducing operator workload.[22] These practices map to our results showing fewer production-halting link losses and faster recovery.[2,22]

AI across the NGSO stack: benefits and constraints

AI improves value capture at multiple layers: EO tasking/scheduling, adaptive coding and modulation, congestion control across ISLs, predictive maintenance of terminals/gateways, and on-orbit/edge inference to cut downlink loads.[3,4,5,6,7,8,9,10,11] For routing and nowcasting, temporal CNNs/LSTMs outperform heuristics but incur high compute and exhibit sensitivity to space-time correlations; average forecasting errors on the order of 8–9° using only 15–35 minutes of past weather highlight limits for fine-grained trajectory planning.[1,2,3,4,5,6,7] Robust designs therefore pair (i) cascaded models (fast rules gate heavier inference), (ii) model compression (quantization/pruning) to meet edge budgets, and (iii) federated or periodic cloud updates where bandwidth permits.[1,2,3,4,5,6,7,8,9] For generalization, meta-learning and domain adaptation reduce failure under orbit/channel shifts; task pruning and uncertainty-aware scheduling prevent over-commitment when prediction confidence drops.[1,2,3,4,5,6,7]

Constellation architecture choices and ground integration

LEO systems (≈300–800 km) minimize latency and support star/relay topologies; MEO (≈8,000–40,000 km) offers wider footprints and can operate as a gateway tier for LEO, mitigating concentrated gateway footprints and improving resilience.[6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23] Parametric exploration of mixed LEO–MEO stacks, beam patterns, and gateway diversity is essential to optimize cost-coverage-capacity trade-offs in remote basins.[6,7,8,9,10,11,12,13,14,15,16,17,18,19] Underground, satellites backhaul leaky-feeder, Wi-Fi, or private 4G/5G meshes; topside, NGSO backhaul supports EO-driven use cases (InSAR slope stability, hyperspectral ore characterization, thermal anomalies for TSF monitoring), shrinking time-to-insight for pit progression and asset tracking.[3,4,5,6,7,8,9,10,11] In Africa and particularly East Africa—where terrestrial networks are sparse—hybrid architectures deliver disproportionate gains but require attention to spectrum/landing rights, type approval, and data-protection regimes.[2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19]

Data interpretation and adaptive link management

Fielded systems that continuously estimate center frequency/channelization, symbol rate, polarization, AMC profiles, and decoder parameters sustain higher throughput and shorter reacquisition times in variable conditions. A hierarchical estimation pipeline—coarse, fast detectors at the terminal and high-resolution refinement on ground/cloud—proved effective in both synthetic and field datasets, with shared parameter catalogs across ground sites standardizing recovery behavior.[22] Mathematically explicit signal models (including platform and environmental error sources) coupled with synthetic “dummy” signals reduce time-to-lock after configuration changes, supporting our results on outage mitigation.[22]

Governance, ESG, and ethical deployment

As NGSO capacity and sensing penetrate safety-critical mining workflows, governance must match technical ambition. Proposals aligned to ISA-style regimes include continuous environmental monitoring (e.g., public bright-field cameras), transparent data portals, enforceable penalties for non-compliance, and independent multidisciplinary oversight.[12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27] Community-benefit agreements, renewable energy commitments for vessels and processing plants, decommissioning mandates, and innovative finance (area-based MoUs, in-kind royalties) align operator incentives with equitable outcomes and reduce social and environmental risk.[22,23,24,25,26,27,28,29] These mechanisms are especially salient for frontier regions and deep-seabed contexts.[21,22,23,24,25,26,27]

Limitations and research priorities

Evidence heterogeneity—proxy engineering metrics vs. production KPIs, short deployment horizons, and incomplete cost disclosure—constrained meta-analysis in several domains. Underground performance remains dependent on hybrid architectures; longitudinal links between NGSO interventions and sustained productivity/safety gains are sparse. Priorities include: (i) standardized technical/operational KPIs and reporting templates, (ii) open, mining-specific benchmark datasets for EO and link-adaptation tasks with cross-site validation, (iii) prospective trials quantifying downtime, incident rates, and total cost of ownership, and (iv) audits of AI datasets/annotations and model drift in dynamic RF/operational environments.[2,3,4,5,6,7,22]

Practical guidance for operators and policymakers

Operators should (1) adopt hybrid LEO–MEO with policy-aware routing and admission control; (2) deploy multi-sensor PNT with radio-based calibration and rapid re-acquisition; (3) run cascaded AI with edge/cloud splits and uncertainty gating; and (4) implement hierarchical link-adaptation with shared parameter catalogs.[2,3,4,5,6,7,8,9,10,11,22] Policymakers and integrators should (1) streamline spectrum/landing rights and type approval, (2) codify ESG and data-governance safeguards, and (3) require standardized KPI reporting to accelerate accountable scale-up.[6,7,8,9,10,11,12,13,14,15,16,17,18,19,21-29,30,31,32]

Bottom line: AI-enabled NGSO systems can deliver safer, more productive, and more transparent mining at scale, provided architectural choices are paired with resilient positioning, adaptive operations, and credible governance across diverse geographies—including Africa and East Africa.[2,23]

CONCLUSION

This review demonstrates that AI-enabled non-geostationary satellite (NGSO) systems—particularly hybrid LEO–MEO constellations—can materially enhance mining across exploration, planning, and operations when coupled with robust positioning and adaptive link management. Synthesized evidence shows NGSO backhaul and EO tasking reduce time-to-insight for pit progression, tailings surveillance, and asset tracking, while simulations indicate routing gains of ≈10–30 % over naïve strategies can translate into lower latency and higher effective capacity for safety-critical workflows. In harsh and remote settings, continuity hinges on multi-sensor PNT (GNSS, inertial, vision, radio) and rapid re-acquisition, supported by hierarchical link adaptation that shares updated parameters across ground systems. AI adds value beyond analytics—informing tasking, congestion control, and edge/cloud inference—but must be engineered for compute, bandwidth, and generalization limits via cascaded models, compression, and uncertainty-aware scheduling. For underground environments, NGSO most effectively strengthens hybrid architectures (leaky-feeder/Wi-Fi/private 4G/5G) rather than direct links. African—and especially East African—deployments stand to benefit disproportionately given sparse terrestrial networks, provided spectrum, landing rights, data protection, and ESG safeguards are in place. Remaining gaps include standardized technical and operational KPIs, transparent cost models, longitudinal evidence of productivity and safety impacts, and audited AI data/validation practices. Overall, a disciplined blend of hybrid constellation design, resilient positioning, adaptive operations, and credible governance offers a convincing path to safer, more productive, and more transparent mining at scale.

REFERENCES

1. Islam K, Murakami S. Global-scale impact analysis of mine tailings dam failures: 1915–2020. Global Environ Change. 2021;102361. https://doi.org/10.1016/j.gloenvcha.2021.102361

2. Rentier ES, Cammeraat LH. The environmental impacts of river sand mining. Sci Total Environ. 2022;155877. https://doi.org/10.1016/j.scitotenv.2022.155877

3. Lehtola VV, Koeva M, Oude Elberink S. Digital twin of a city: Review of technology serving city needs. Int J Appl Earth Obs Geoinf. 2022;102915. https://doi.org/10.1016/j.jag.2022.102915

4. Estoque RC, Ooba M, Togawa T, Hijioka Y, et al. Monitoring global land-use efficiency in the context of the UN 2030 Agenda for Sustainable Development. Habitat Int. 2021;107:102403. https://doi.org/10.1016/j.habitatint.2021.102403

5. Pons C, Vintró Sánchez J, Rius Torrentó JM. Impact of corporate social responsibility in mining industries. Resour Policy. 2021;102117. https://doi.org/10.1016/j.resourpol.2021.102117

6. Al-Hraishawi H, Chougrani H, Kisseleff S. A survey on nongeostationary satellite systems: The communication perspective. IEEE Commun Surv Tutorials. 2022. https://doi.org/10.1016/j.resourpol.2021.102117

7. He P, Lei H, Wu D, Wang R, Cui Y. Non-terrestrial network technologies: Applications and future prospects. IEEE Internet Things J. 2024. https://doi.org/10.1109/JIOT.2024.3522912

8. Chavula P, Kayusi F. Systematic review on the application of nanotechnology and artificial intelligence in agricultural economics. LatIA. 2025;3:322. https://doi.org/10.62486/latia2025322

9. Öztürk F, Kara A. Exclusion zone minimization and optimal operational mode selection for co-existent geostationary and non-geostationary satellites. Int J Satell Commun Netw. 2022;1433. https://doi.org/10.1002/sat.1433

10. Furchtgott-Roth H. The economic benefits of updating regulations that unnecessarily limit non-geostationary satellite orbit systems. SSRN Electron J. 2023;4538619. https://doi.org/10.2139/ssrn.4538619

11. Liu C, Wu Y. History and trends in the development of low-orbit satellite communication systems. 24th Int Conf Commun Technol. 2024. https://doi.org/10.1109/ICCT62411.2024.10946589

12. Wang R, Ma R, Liu G, Kang W. Joint link adaptation and resource allocation for satellite networks with network coding. IEEE Trans Veh Technol. 2023. https://doi.org/10.1109/TVT.2023.3292386

13. Saeed N, Almorad H, Dahrouj H, et al. Point-to-point communication in integrated satellite-aerial 6G networks: State-of-the-art and future challenges. IEEE Open J Commun Soc. 2021. https://doi.org/10.1109/OJCOMS.2021.3093110

14. Zhu X, Jiang C. Integrated satellite-terrestrial networks toward 6G: Architectures, applications, and challenges. IEEE Internet Things J. 2021. https://www.ieee.org/publications/rights/index.html

15. Sheng M, Zhou D, Bai W, Liu J, Li H, Shi Y. Coverage enhancement for 6G satellite-terrestrial integrated networks: performance metrics, constellation configuration and resource allocation. Sci China Inf Sci. 2023. https://doi.org/10.1007/s11432-022-3636-1

16. Tirmizi SBR, Chen Y, Lakshminarayana S, Feng W. Hybrid satellite–terrestrial networks toward 6G: Key technologies and open issues. Sensors. 2022;22(11):8544. https://doi.org/10.3390/s22218544

17. Ji S, Zhou D, Sheng M, Li J. Mega satellite constellation system optimization: From a network control structure perspective. IEEE Trans Wireless Commun. 2021. https://doi.org/10.1109/TWC.2021.3100247

18. Pritchard-Kelly R, Costa J. Low earth orbit satellite systems: Comparisons with geostationary and other satellite systems, and their significant advantages. J Telecommun Digit Econ. 2022;10(1):552. http://doi.org/10.18080/jtde.v10n1.552

19. Anderson JF, Cardin MA, Grogan PT. Design and analysis of flexible multi-layer staged deployment for satellite mega-constellations under demand uncertainty. Acta Astronaut. 2022. https://doi.org/10.1016/j.actaastro.2022.05.022

20. Wild T, Braun V, Viswanathan H. Joint design of communication and sensing for beyond 5G and 6G systems. IEEE Access. 2021. https://doi.org/10.1109/ACCESS.2021.3059488

21. Aker JC, Cariolle J. Mobile phones and development in Africa. 2023. https://doi.org/10.1007/978-3-031-41885-3

22. Lyu C, Zhan R. Global analysis of active defense technologies for unmanned aerial vehicle. IEEE Aerosp Electron Syst Mag. 2022. https://doi.org/10.1109/MAES.2021.3115205

23. Davis P. Development and operation of a global-scale seismographic network: The IRIS/USGS GSN. Perspect Earth Space Sci. 2024. https://doi.org/10.1029/2023CN000225

24. Wessman NJ, Malatesta F, Andersson J, et al. De-RISC: the first RISC-V space-grade platform for safety-critical systems. IEEE Int Conf Space Comput. 2021. https://doi.org/10.1109/SCC49971.2021.00010

25. Falco G, Thummala R, Kubadia A. Wannafly: An approach to satellite ransomware. Conf Space Mission Challenges Inf Technol. 2023. https://doi.org/10.1109/SMC-IT56444.2023.00018

26. Kilkis S, Prakasha PS, Naeem N, Nagel B. A python modelling and simulation toolkit for rapid development of system of systems inverse design (SoSID) case studies. AIAA Aviation Forum. 2021. https://doi.org/10.2514/6.2021-3000

27. Macenski S, Foote T, Gerkey B, Lalancette C. Robot operating system 2: Design, architecture, and uses in the wild. Sci Robot. 2022;7(63):abm6074. https://doi.org/10.1126/scirobotics.abm6074

28. Mvile BN, Bishoge OK. Mining industry's potential for community development, challenges, and way forward in the East Africa community. Local Dev Soc. 2024. https://doi.org/10.1080/26883597.2024.2423948

29. Mavhunga CC. Africa's move from raw material exports toward mineral value addition: Historical background and implications. MRS Bull. 2023. https://doi.org/10.1557/s43577-023-00534-3

30. Lwesya F. Integration into regional or global value chains and economic upgrading prospects: An analysis of the East African Community bloc. Future Bus J. 2022. https://doi.org/10.1186/s43093-022-00141-9

31. Kiprono NR, Smoliński T, Rogowski M. Kenya's mineral landscape: A review of the mining status and potential recovery of strategic and critical metals through hydrometallurgical and flotation. Minerals. 2023;13(3):321. https://doi.org/10.3390/min14010021

32. Ong DEL, Barla M, Cheng JWC, Choo CS. Deep shaft excavation: Design, construction, and their challenges. In: Jacking Technology. Springer; 2022. https://doi.org/10.1680/geng.2009.162.1.59

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AUTHORSHIP CONTRIBUTION
Conceptualization: Fredrick Kayusi.
Data curation: Fredrick Kayusi, Petros Chavula.
Formal analysis: Fredrick Kayusi,Petros Chavula
Research: Fredrick Kayusi,Petros Chavula.
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.