African Strategies for Competitiveness: Integrating Technology, Resources, and Policy Frameworks

Abstract

Our chapter provides an analysis of the emerging potential arising from the integration of rare earth element (REE) and critical mineral (CM) mining, advanced technology, and state governance frameworks across the African continent. Traditional economic analyses frequently isolate these fields, evaluating mineral extraction, technology adoption, and state policy as separate trajectories. In contrast, our chapter presents an integrated analytical concept, demonstrating that the future starting point of African enhanced resource autonomy co-determines, and is determined by, the convergence of these three domains. By grounding the evaluation in resource dependency theory, digital autonomy, and an adapted Penta Helix (5H) framework, we analyze how national governance models shape both local development trajectories (specifically on REE mining) and the receipt of technology-driven benefits. Through selected case studies (empirical profiles of the D.R. of the Congo, South Africa, Madagascar, Namibia, Mozambique, and other countries), our analysis maps the functioning realities, localized resource bottlenecks, and problematic points inherent in global distribution networks. We examine how advanced technology can introduce transparency into supply chains and prevent mineral-processing inefficiencies, and evaluate which policy changes may help counter resource-related inefficiencies and lessen domestic socio-environmental risks. We also argue that transforming unused mineral resources into long-term development capital requires African countries to move away from fragmented national competition. By following cooperative (or co-competitive) regional industrial strategies and increasing domestic processing under the AfCFTA, the continent can protect its resource assets from geopolitical pressure and keep a sustainable position within the global division of labor.

Keywords: Critical minerals (CMs); rare earth elements (REEs); state governance; emerging technologies; artificial intelligence (AI); Penta Helix model (5H model); policy innovation; value-chain diversification; resource dependency; economic autonomy.

1. Introduction

The increase in global demand for rare earth elements (REEs) and critical minerals (CMs) reflects their foundational role in driving present technological progress and green modernization. These strategic resources serve as indispensable components in the construction of advanced hardware, ranging from artificial intelligence (AI) compute clusters and permanent-magnet electric vehicle (EV) motors to high-capacity renewable energy grids and defense systems. Specific light rare-earth elements (LREEs) such as neodymium, praseodymium, lanthanum, and cerium, alongside heavy rare-earth elements (HREEs) such as dysprosium and yttrium, are now important for manufacturing microchips, semiconductors, and power storage units that support Western/Asian technology ecosystems. Within this global macroeconomic race, the African continent holds a powerful but historically compromised position, accounting for about a third of the world's proven mineral resources. Despite this substantial geological resource base, the continent's actual market power and capacity to extract economic rents remain substantially limited. This situation is sustained by fragmented domestic legislation, weak local institutional capacity, limited infrastructure for domestic processing, and persistent colonial-era patterns of asymmetric economic use.

The extraction of REEs/CMs in Africa has become a central point for economic development, technological advancement, and global supply chain security. These minerals, essential for modern technologies such as electric vehicles, renewable energy systems, and advanced electronics, are increasingly sought after by industrialized economies. However, their mining, management/governance, and technological use in Africa are integrated with socio-economic, environmental, and governance challenges. Understanding this interlinkage is useful to ensuring sustainable development, equitable resource distribution, and long-term economic stability on the continent.

A geographic concentration of midstream processing and downstream manufacturing capacity represents the global macroeconomic framework for these resources. This asymmetry introduces intense instabilities into global technology markets. While raw mineral deposits are distributed globally, China maintains a monopoly over the midstream separation and refining segments of the value chain, controlling over 90% of global REEs separation capacity (USGS, 2026). This concentration is the direct result of decades of intentional state industrial policy and sustained public capital support. By absorbing localized environmental costs and subsidizing domestic processing plants, Chinese actors successfully undercut global competition, making independent midstream projects financially unrealistic for private capital markets. The severe geopolitical and economic risks embedded in this uneven market structure materialized via a series of geopolitical incidents. As trade pressures intensified following the imposition of far-reaching import tariffs by Western economies, Beijing leveraged its dominant position within the metallurgical supply chain. In 2024, China enacted export restrictions on gallium, germanium, and antimony. All these materials are essential to produce global semiconductor and defense-grade optics. This protectionist mode expanded in early 2025 through decrees imposing comprehensive export licensing restrictions on critical heavy REEs (HREEs), specifically samarium, gadolinium, terbium, dysprosium, lutetium, scandium, and yttrium. These targeted interventions fundamentally decoupled global supply availability from market signals, reasserting the primacy of autonomous geopolitical strategy over rule-based international trade.

The economic impact of these bottlenecks is intensified by the high price volatility characterizing the REE market. Unlike traditional base metals such as copper or zinc, which are traded on public exchanges, many rare earth oxides (REO) are traded under long-term bilateral contracts managed by state-owned firms in foreign countries. This opaque arrangement leaves the spot market illiquid and vulnerable to severe price swings. For example, the market price of neodymium oxide, which is a key component of permanent magnets used in EV motors, rose several times before returning to normal levels. That was a consequence as speculative global stockpiling met state-directed supply adjustments. This chaotic pricing behavior discourages private capital from outside China, as independent mining projects struggle to survive. Their effort is to keep long-term financial viability amid manipulated pricing cycles.

An economic evaluation of the CMs landscape reveals an underlying vulnerability known as byproduct dependency. Of the 20 strategic minerals most vital to technology, aerospace, and defense manufacturing, about half are obtained exclusively as secondary outputs from the refining of major base metals. From a technological perspective, this means the supply of these important inputs is entirely decoupled from their independent market prices; an acute spike in gallium demand cannot easily activate increased production if the primary aluminum market is in a cyclical downturn. Finding substitutes for these metals also remains difficult without harming product performance or raising manufacturing costs. Rapid changes in downstream technology utilization could worsen these vulnerabilities. The automotive and energy storage sectors have rapidly moved toward lithium iron phosphate (LFP) battery chemistry, which now accounts for about half of the global EV market. Although this transition was designed to circumvent traditional nickel and cobalt supply bottlenecks, it has unintentionally created new dependencies. Manufacturing LFP cells and newer sodium-ion systems requires purified phosphoric acid and high-purity manganese sulfate. The processing networks for these specific chemical inputs are almost entirely centralized in China, meaning these refined chemical sectors will likely act as the macroeconomic bottlenecks.

To address this asymmetric approach, we propose a novel approach. In our design, African countries must surpass raw-material exportation and adopt a digital-commodity approach to anchor domestic midstream refining infrastructure. By linking the physical extraction of ores to verifiable data systems, African producers can avoid the contract networks controlled by midstream monopolies. Our analysis shows how African mining processes, broadly conceived, advanced big-data-driven technologies and multi-level state control, converging to affect both local development and technological autonomy. By evaluating the regulatory, industrial, and geopolitical realities across the continent, this chapter moves beyond theoretical discussions of policy to offer a reality-focused concept that shows how data verification and administrative reforms can protect domestic resources and assets from external volatility, providing practical development trajectories for government officials, industry executives, and international researchers.

2. Literature Review

The growing global demand for critical minerals and rare earth elements (REEs), driven by the transition toward low-carbon technologies and digital transformation, has placed African countries at the center of emerging geopolitical and economic dynamics. Sub-Saharan Africa possesses a substantial share of global reserves of key minerals such as cobalt, lithium, platinum group metals, and rare earth elements, positioning the region as a strategic supplier for the global energy transition and advanced technological development (International Monetary Fund [IMF], 2024; International Energy Agency [IEA], 2024). However, despite this resource wealth, African economies have historically struggled to translate mineral abundance into sustained economic growth and industrial transformation. This literature review examines the intersection of natural resource endowment, governance, technological development, and industrial policy in African countries, with particular attention to the role of critical minerals within the broader frameworks of resource economics, digital innovation, and institutional capacity [International Monetary Fund]. The mainstream literature on resource-rich economies provides critical insight into the challenges facing African mineral producers. Auty (1993, 1998) and Sachs and Warner (1996) demonstrate that countries endowed with abundant natural resources often experience slower economic growth. This theory attributes underperformance to factors such as volatility in commodity prices, weak institutional frameworks, limited diversification, and rent-seeking behavior (Auty - Sustainable Development Research).

In the African context, these dynamics are visible. Many resource-rich countries, including the Democratic Republic of the Congo (DRC) and Zambia, remain heavily dependent on mineral exports, with limited domestic processing or value addition. This reliance on primary commodities reinforces vulnerabilities, including exposure to global price fluctuations and constrained industrial development (Sachs & Warner, 1996). The persistence of these challenges suggests that resource availability alone is insufficient to drive development. Instead, institutional quality and governance structures play a decisive role in determining whether mineral wealth translates into economic transformation (Auty, 1998) [Richard Auty - Resource Abundance and Economic Growth]. This theoretical foundation is essential for understanding current debates on the governance of critical minerals in Africa. Recent literature highlights the increasing importance of African resources within global supply chains for energy transition technologies. According to the IEA (2024, 2025), minerals such as cobalt, lithium, and rare earth elements are essential inputs for batteries, renewable energy systems, and advanced electronics (International Energy Agency Publications). The IMF (2024) estimates that Sub-Saharan Africa holds approx..30% of global critical mineral reserves, positioning the region as a key actor in future industrial ecosystems. Nevertheless, Africa's participation in these value chains remains limited primarily to extraction. Most countries export raw or minimally processed minerals, while higher-value activities such as refining, manufacturing, and technology integration are concentrated in developed economies and emerging industrial powers such as China. This pattern reinforces the structural constraints identified in earlier resource economics literature (S&P Global Research).

Ndubuisi et al. (2025) argue that overcoming this limitation requires a strategic shift toward regional industrialization and value chain integration. Specifically, the authors emphasize the importance of regional cooperation under frameworks such as the African Continental Free Trade Area (AfCFTA), which could facilitate economies of scale, infrastructure sharing, and coordinated policy design. By regionalizing mineral production and processing, African countries could enhance their bargaining power and capture a greater share of value-added activities (AfCFTA Secretariat Policy). Similarly, Simmons and Marcilly (2024) highlight the potential of resource nationalism and down streaming policies, drawing on the example of Indonesia. These strategies involve restricting raw material exports and incentivizing domestic processing industries. While such policies carry risks, including reduced foreign investment, they offer a possible pathway for African countries to move beyond extractive dependency and toward industrial upgrading [Benchmark Mineral Intelligence Insights].

The integration of advanced technologies, particularly AI, big data analytics, and digital traceability systems, presents new opportunities for transforming the governance and efficiency of mineral value chains. Schwab (2016) situates these developments within the broader context of the Fourth Industrial Revolution, characterized by the convergence of physical, digital, and biological systems. In the African mining sector, the application of advanced technologies has the potential to address long-standing governance challenges. For example, digital traceability tools can improve transparency in supply chains, enabling better monitoring of mineral origins and reducing the risks associated with illicit trade and environmental degradation. This is relevant in economies such as the DRC, where informal mining and weak regulatory oversight have historically undermined governance outcomes. The UNESCO (2021) framework on the ethics of AI emphasizes the need to ensure that technological adoption is accompanied by ethical/regulatory standards. In the context of African resource governance, this includes protecting data autonomy, ensuring equitable access to technological benefits, and preventing the entrenchment of new forms of advanced technology dependency. Moreover, the IEA (2025) highlights the role of digital tools in enhancing supply chain resilience and sustainability. AI-driven forecasting, automated monitoring systems, and digital product passports can support more efficient resource management and compliance with environmental, social, and governance (ESG) standards [Deloitte & WEF Customs Digitalization Perspectives]. However, the effectiveness of these tools depends on institutional capacity and infrastructure, which remain uneven across the continent.

Effective governance is a determinant of resource outcomes in Africa. The literature consistently emphasizes that weak regulatory frameworks, corruption, and limited enforcement capacity undermine the potential benefits of mineral wealth. The need for robust governance is particularly acute in the context of critical minerals, where high global demand increases the incentives for illicit activities. The joint report by the UN Office on Drugs and Crime (UNODC) and the UN

Interregional Crime and Justice Research Institute (UNICRI) (2024) highlights the prevalence of illegal mining, smuggling, and organized crime in mineral-rich regions (UNODC Research and Reports). These activities not only reduce government revenues but also contribute to environmental degradation and social instability. Strengthening legal frameworks and enforcement mechanisms is therefore essential for ensuring that resource exploitation contributes to sustainable development. At the national level, legislative reforms such as South Africa's Mineral Resources Development Bill (Republic of South Africa, 2025) aim to improve regulatory oversight, promote local content, and enhance state participation in the mining sector [South African Government Gazetted Bills]. Such reforms reflect a broader trend toward increased state involvement in resource governance, often motivated by the desire to capture greater economic benefits and address historical inequalities [Natural Justice - SA Mining Policy Analysis]. However, the effectiveness of these initiatives depends on implementation capacity and institutional coherence. Without strong administrative structures and accountability mechanisms, policy reforms may fail to achieve their intended outcomes (Zambia Ministry of Mines Legal Gazette).

The environmental implications of mineral extraction and processing represent another critical dimension of the literature. The production of rare earth elements and other critical minerals is associated with significant environmental risks, including waste generation, water pollution, and land degradation (U.S. Environmental Protection Agency [EPA], 2012). In Africa, these risks are often amplified by localized ecological conditions, such as those impacting the Vara Mada project area in Madagascar, where advanced chemical extraction requires highly structured environmental safeguards and community equity sharing to prevent long-term environmental liability [Energy Fuels Corporate Registry].

3. Methodology and Theoretical Framework

To understand these fragmented resource supply chains, our methodology rejects traditional binary public-private economic models. Instead, we integrate resource dependency theory, digital autonomy concepts, and an adapted Penta-Helix (5H) analytical framework. Resource dependency theory (Sachs, 1996) explains how African countries, despite their enormous mineral resources, remain exposed to global market instabilities and geopolitical tensions. In this context, the theory illustrates how African economies, despite their vast geological resources, are in a weaker position in the global division of labor. They function only as suppliers of unseparated raw materials, while downstream advanced economies obtain most of the macroeconomic value. This subordinate position intersects directly with the concept of the Fourth Industrial Revolution (Schwab, 2016), which applies a new approach to extractive industries via considering automation, cyber-physical systems, and AI. While advanced technologies, such as automation, digital tools, predictive maintenance, automated ore sorting, and real-time monitoring, enhance efficiency and safety, they do not necessarily resolve historical inequalities. When these advanced networks are embedded in an institutional vacuum, they often activate the resource curse dynamics identified by Auty (1998). Auty's framework shows how weak governance, poor administrative transparency, and unclear licensing systems enable narrow domestic elites or transnational actors to capture resource rents, thereby fueling corruption, intensifying economic inequality, and sparking localized social conflicts.

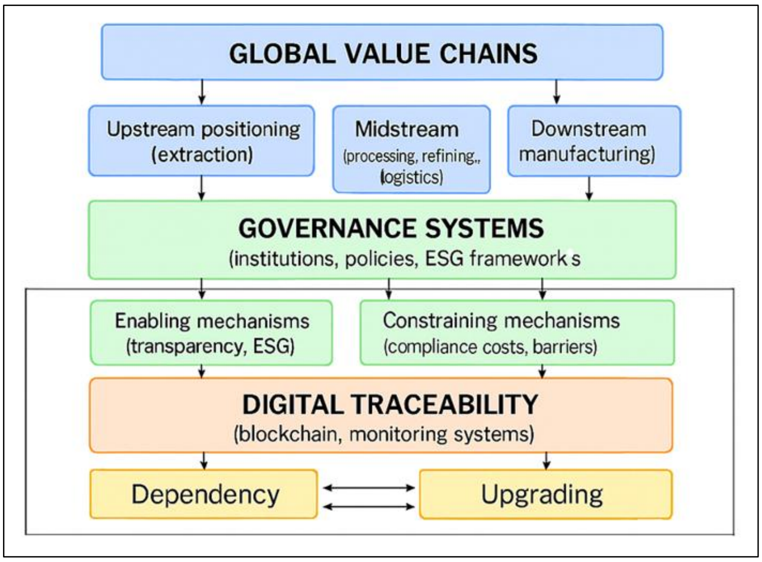
Evaluative Dimension	Traditional Triple Helix (3H) Model	Used Penta Helix (5H) Framework

Stakeholder Scope	Restricted to government bodies, industrial firms, and academic sectors	Expanded to include civil society groups
Technology Role	Treated as an isolated finished commercial output from university laboratories	Viewed as a conditional instrument shaped by data ownership and local capacity
Social Inclusion	Local populations are viewed as passive bystanders or mere labor pools	Grassroots groups hold active legal standing in resource sharing and monitoring.
Market Integration	Assumes predictable trade lines driven by standard supply-demand laws	Factoring in geopolitical monopolies, spot price volatility, and export limits
Resource Focus	Prioritizes top-down field efficiency and maximized volume export tracking	Centers on long-term sustainability, local processing, and social equity

Table 3. Locations of REEs (African continent).
Note: The XXXXX
Source: Author's own elaboration based on Sachs (1996), Auty (1998), and USGS (2026) data.

To prevent technological deployment from reinforcing these extractive patterns, our framework integrates the digital sovereignty debate (UNESCO, 2021). Digital sovereignty refers to a nation's capacity to govern its data architectures, software codebases, and technical infrastructure. In the realm of REE mining, this paradigm underscores the urgent need for African economies to develop and own local AI tools and data management systems, thereby avoiding an absolute dependency on proprietary software from foreign technology providers. Without such autonomy, technological integration risks becoming a new avenue for foreign firms to get effects. Traditional public policy models of the recent past relied usually on the classic “triple helix” framework, which maps interactions exclusively among government ministries, industrial firms, and academic institutions. In contrast, our adapted 5H framework broadens the analytical focus to examine how local community actions, academic research entities, market mechanisms (especially pricing), and state institutions and legal systems co-determine one another. Within this evaluation, the five codependent actors are defined as follows: state governance is responsible for drafting mining codes, issuing mineral permits, and allocating extraction rents; industrial firms comprise corporate mine operators, foreign engineering consortia, and software developers driving field operations; academic institutions are represented by domestic universities and research laboratories building local data literacy and analyzing specific geochemical profiles. Civil society organizations encompass local populations, artisanal mining associations, and environmental advocacy groups that act as verification entities. At the same time, international trade networks, spot-pricing volatility, and downstream buyers drive global market forces. Within this 5H architecture, sustainable and equitable resource management is not a top-down state mandate or a dominantly market-driven outcome, but an adaptive equilibrium.

The conceptual framework of this chapter purposefully functions at the boundary of three historically isolated domains: strategic resource geology, institutional governance, and advanced digital technologies. To micro-economists or software engineers, combining the physics of metallurgical extraction with the macro-politics of state autonomy and machine learning (ML) may appear non-standard. Trying to evaluate a broader focus spectrum (three areas) seems not as attractive as an analysis supported by precise data, but it allows a more integrated understanding of mutual interdependencies.



Scheme 1. Locations of REEs (African continent).
Note: The XXXXX
Source: Author's own elaboration

Conventional academic structures routinely enforce a division of labor in which scientists from each field work in isolation from one another. We argue, however, that treating these seemingly isolated areas as independent is a conceptual deficit and ontological weakness that underappreciates the broader nature of current resource dependency. Nowadays, increased ecological awareness and global green modernization mean that REEs cannot be seen only as physical elements with specific characteristics. They become a geopolitical/competitiveness instrument embedded in state regulatory frameworks and a digital asset whose value lifecycle is determined by the data systems that monitor its transit. Therefore, isolating the material resource from the state's political authority or the market's digital infrastructure weakens the analysis's explanatory power, leaving it incapable of capturing how value is generated, contested, and captured in the modern world.

Using our "triangle" approach may bring potential objections. From a methodological point of view, expanding the analytical focus across three rather diverse areas may indicate a weakened academic focus. This potential skepticism towards our overly broad methodology, despite its being based on a traditional preference for narrow specialization, misunderstands the mechanism for dealing with resources. Our point is different. Weak (or weakened) state governance and corruption in extraction zones do not arise from policymakers lacking theoretical legal codes. They persist because of the inherently technical nature of information asymmetries. Global firms exploit the legal vacuum between a state's legal mandates and its capacity to verify operational data in real time. By explicitly introducing advanced data architectures as a co-determining variable alongside state governance, our framework directly bridges this gap. Technology provides the empirical visibility and objective verification that law requires to become enforceable, while legal frameworks provide the autonomous authority that prevents technology from becoming a corporate monopoly. Far from weakening the focus, this “triangular” conceptualization provides a useful analytical tool for understanding the multi-level bottlenecks in current global/continental supply chains, transforming methodological unconventionality into a well-designed new approach. We see the potential counter-arguments. One is that such a framework may overestimate technology (known as “technological determinism”) by treating it as a universal solution to various tasks. Skeptics among both policymakers and businesspeople routinely point out that introducing advanced ML channels or digital product passports into environments characterized by weak state capacity or active conflict cannot resolve historical inequalities, as corrupt actors will often find ways to avoid, compromise, or physically manipulate digital tracking systems. It is possible to accept this argument, but we would reject the conclusion that technical integration is therefore useless. The core contribution of our adapted 5H model is its explicit insistence that, whatever technology, advanced technology included, does not operate in a social vacuum. By evaluating digital system platforms only as co-dependent variables that are constantly shaped by, and shaping, corporate managers, academic institutions, civil society organizations, and state bodies, we see technology as high-potential. The integration of blockchain or AI is not presented here as a neutral software fix, but as a site of intense political struggle over data ownership and the distribution of economic rents. When technical verification is legally embedded into updated national mining codes, it becomes an optional corporate tool and becomes a binding instrument of macroeconomic oversight. This unique combination shows that while technology without governance remains blind, governance without technology remains paralyzed, thereby justifying this original triadic framework as a vital prerequisite for genuine resource autonomy.

4. Research Questions

By addressing the differing points between advanced technological arrangements and institutional capacity, this chapter moves beyond abstract policy theorizing. To operationalize the 5H framework and investigate how data verification can shield domestic assets from external volatility, our research addresses two main research questions:

- RQ 1: How can advanced AI, ML algorithms, and other advanced technology systems be efficiently applied to promote transparency and equity in fragmented supply chains?
- RQ 2: What specific institutional and global legal frameworks can ensure better resource governance across African REE and CM mining sectors while protecting domestic industrial policies from external geopolitical pressure?

There will be no complete answer to these research questions as the situation across several countries on the African continent is quite complex in terms of basic human needs, such as food and health. However, such other, more social contexts may find their place rather in non-economic experts and are not the focus of our chapter.

5. Analysis

5.1. General Analysis

The operational viability of reforming African mineral networks depends on a structural shift in the basic assumptions that conceptualize natural resources not merely as bulk geomechanical exports but as data-rich elements within highly visible distribution networks. Under this digital-commodity linkage approach, the physical extraction of ores is systematically tied to the digital data architectures that monitor, trace, and validate their value lifecycle. This framework provides a mechanism for host countries to bypass the opaque bilateral contract networks controlled by midstream processing monopolies, shifting the function of digital systems from corporate operational optimization to instruments of state-led macroeconomic governance. The performance of this integrated system is evaluated across four distinct but interconnected operational domains. They are, first, the interaction between extraction techniques and processing coordination; second, the formalization of national social systems and artisanal labor; third, multi-level governance networks regulating revenue transparency; and fourth, state-directed innovation mechanisms driving domestic engineering expertise. Empirical developments between 2025 and mid-2026 confirm that this digital-commodity integration has transitioned into a specific regulatory tool. Forward-looking state frameworks increasingly expect to use distributed database infrastructures to meet supply chain transparency requirements set by international market standards. Integrating decentralized data validation networks directly into mineral concession frameworks enables national ministries to mitigate the long-standing information asymmetries that have historically allowed global firms to underreport export volumes and values. This technological model uses computational tools to restructure the calculation and distribution of mining rents, utilizing the digital product passport as an institutional mechanism. By pairing real-time satellite telemetry with Internet of Things (IoT) sensor arrays at the point of origin, states construct an immutable digital footprint for exported materials from the mine gate to final delivery. Quantitative economic indicators demonstrate that this level of technological verification yields a clear market advantage, generating a distinct pricing premium on global spot markets compared to uncertified, non-traceable mineral shipments. To withstand the severe infrastructure deficits and power grid instabilities that characterize remote extraction zones, these micro-level data networks must be engineered as energy-passive, low-power hardware configurations or powered directly by decentralized, solar-powered microgrids at the mine surface, thereby ensuring uninterrupted cryptographic logging even during localized macroeconomic or energy blackouts.

While the structural contradictions of Africa's critical minerals sector can be understood at the continental level, their concrete manifestations vary significantly across individual countries. The empirical dimension reveals that challenges related to governance, technological dependency, and value capture are not uniform but instead appear in distinct configurations shaped by institutional capacity, resource endowment, and historical trajectories. One of the most prominent patterns is the model of extractive dominance, observable in countries with high concentrations of strategic minerals. In such contexts, national economies are strongly tied to the export of one or a few key commodities, creating asymmetric relationships with global markets. This configuration generates export revenues but reinforces constraints on industrial development. Global demand for raw materials incentivizes continued extraction, while the incentives for domestic processing remain weak. As a result, these economies become locked into a reinforcing cycle where extraction is prioritized, and industrial diversification remains marginal.

In contrast, emerging REE and CM projects in countries that are not traditional mining centers represent attempts at strategic diversification. These projects signal a shift toward integrating into new segments of global value chains associated with advanced technologies. However, their transformative potential is limited by the absence of domestic technological ecosystems. The lack of local expertise, research infrastructure, and industrial capacity means that these projects are typically developed in partnership with external actors. While such partnerships facilitate access to capital and technology, they also reproduce patterns of external dependency under more technologically advanced conditions.

From a governance perspective, two broad approaches can be identified. The first is a technocratic approach, which seeks to address sectoral inefficiencies via regulatory reforms, digitalization, and the implementation of transparency mechanisms. The second is a political-economy approach, which emphasizes the strategic role of the state in shaping industrial development and capturing economic rents. In practice, these approaches often coexist in hybrid forms, reflecting both institutional ambition and constraints. In countries with relatively stronger institutional capacity, regulatory frameworks have been expanded to formalize mining activities, improve licensing systems, and enhance oversight. But the gap between formal regulation and actual implementation remains substantial. Administrative fragmentation, limited enforcement capacity, and political interference frequently undermine the effectiveness of these frameworks. This creates an environment in which formal institutions coexist with informal practices, leading to inconsistent governance outcomes. In countries with weaker institutional capacity, informal and semi-formal mining activities play a dominant role. These activities are often deeply embedded in local livelihoods and socio-economic structures. Attempts to regulate or formalize them through top-down approaches frequently encounter resistance or lead to unintended consequences, such as exclusion or criminalization of small-scale actors. This highlights the pressure between governance objectives and socio-economic realities, suggesting that technocratic solutions alone are insufficient.

The role of advanced technologies introduces another critical dimension. Digital tools, including AI, automated monitoring systems, and traceability platforms, have the theoretical potential to improve efficiency and transparency within mineral value chains. These technologies can reduce information asymmetries, enhance regulatory oversight, and support compliance with environmental and governance standards. However, their implementation in African contexts is uneven and often externally driven.

A key issue lies in technological dependency. The development and deployment of digital infrastructure are often controlled by external actors, raising concerns about data autonomy and long-term strategic autonomy. While digital systems can enhance operational performance, they also create new forms of dependency, particularly when local institutions lack the capacity to manage or regulate these technologies independently. This suggests that technological adoption, in the absence of institutional and knowledge development, may reinforce rather than mitigate inequalities. Another important empirical pattern relates to the persistence of illegal mining and mineral smuggling. These activities are not isolated anomalies but are linked to broader political and economic systems. In many cases, they coexist with formal mining operations and are interconnected via complex networks involving local communities, intermediaries, and external actors. Efforts to address these issues through stricter regulation or enforcement often fail to account for their underlying drivers, including poverty, lack of alternative livelihoods, and governance gaps. As a result, policy interventions may be ineffective unless they address these root causes. State-led industrial policy represents a growing trend across several African countries. Governments are increasingly seeking to promote local value addition, enhance domestic processing capacity, and capture a larger share of mineral revenues. While these initiatives reflect a shift away from purely extractive models, their implementation remains challenging. Industrial policy requires long-term coordination, stable regulatory environments, and high investment in infrastructure and human capital. In many cases, these prerequisites are only partially met, leading to fragmented or inconsistent outcomes.

Environmental considerations complicate the empirical landscape. The expansion of mineral extraction and processing, particularly for REEs, is associated with ecological risks. Managing these risks requires both regulatory capacity and access to advanced processing technologies. However, environmental governance often lags behind economic priorities, creating trade-offs between short-term revenue generation and long-term sustainability. This is especially evident in contexts where external demand pressures incentivize rapid extraction.

Finally, the temporal dimension of development plays a critical role. The global demand for critical minerals is accelerating rapidly, driven by the urgency of energy and technological transitions.

In contrast, the processes required to build domestic industrial capacity, strengthen institutions, and develop technological expertise are long-term. This contradiction mismatch creates pressure on African economies to give priority to immediate extraction over strategic transformation. As a result, opportunities for long-term value capture may be compromised in favor of short-term gains. Overall, the empirical dynamics of Africa's CMs sector reveal a complex and evolving landscape characterized by overlapping structural constraints and emerging opportunities. While there is clear potential to leverage mineral wealth as a driver of development, realizing this potential requires addressing fundamental challenges in governance, technological capability, and strategic coordination. Without such adjustments, the current trajectory is likely to perpetuate existing asymmetries, even in a rapidly changing global economy.

CM	Key application	
Lithium		
Cobalt		
Graphite		
Nickel		
Magnesium		
Gallium		
Platinum Group		

Table X: Critical Minerals
Source: Global Critical Minerals Outlook 2025 International Energy Agency. Revised version, June 2025 www.iea.org

Rare Earth Elements (REEs)

Element name	Symbol (Type)	Common uses- main applications
Lanthanum	La (LREEs)	Catalysts, optics, alloys, lamps, lighters
Cerium	Ce (LREEs)	glass polishing, catalysts, colorants, lighters, turbine blade coatings
Praseodymium	Pr (LREEs)	M, L, colorants, flints
Neodymium	Nd (LREEs)	M, L, C, electric motors, generators, alloys
Promethium	Pm (LREEs)	Nuclear batteries, luminous paints
Samarium	Sm (LREEs)	M, L, nuclear reactor control rods
Europium	Eu (LREEs)	TV screens, L, fluorescent lamps, nuclear reactors
Gadolinium	Gd (HREEs)	neutron shielding, lasers, C
Terbium	Tb (HREEs)	M, L, fluorescent lamps, sonar, fuel cells, alloys
Dysprosium	Dy (HREEs)	M, L, nuclear reactors, C
Holmium	Ho (HREEs)	L, Magnetic fields, colorants
Erbium	Er (HREEs)	Laser surgery, fiber optics
Thulium	Tm (HREEs)	X-ray technology, L
Ytterbium	Yb (HREEs)	L, nuclear medicine, seismology, alloys
Lutetium	Lu (HREEs)	PET scanners
Scandium	Sc (LREEs)	Aerospace alloys, lighting
Yttrium	Y (HREEs)	LEDs, TVs, superconductors, cancer treatment

Table X: Rare Earth Elements
Notes: The abbreviations used here are - L (lasers), M (magnets), C (computers).

Source: Global Critical Minerals Outlook 2025 International Energy Agency. Revised version, June 2025 www.iea.org

To guarantee lasting technical autonomy, African governments must allocate a portion of mining rents and resource taxes to specialized, state-managed innovation funds. These financial resources must be deployed to vertically integrate local universities and research laboratories directly into the extractive sector, building data literacy and engineering talent within national borders. Public funding should focus on developing open-source ML algorithms and advanced AI tools tailored specifically to local environmental codes and unique geochemical clay profiles. Strengthening this academic innovation pillar ensures that domestic operations no longer rely entirely on proprietary foreign technologies, thereby retaining the knowledge economy and the financial gains of the REE transition within the region. The integration of advanced technologies in critical mineral mining is transforming exploration and logistical operations in Africa. Innovations such as drone-based surveys, ML algorithms for mineral prediction, and blockchain for supply chain transparency are enhancing the accuracy and efficiency of resource discovery. In coordination, digital platforms and real-time data analytics are optimizing transportation networks, reducing costs, and improving the reliability of mineral exports. Satellite imagery, e.g., has enabled the identification of previously overlooked mineral deposits in remote regions, such as the Sahel and the Great Green Wall. However, the adoption of these technologies is uneven, with many African countries lacking the infrastructure, funding, and technical expertise to use their potential.

5.2. Case Studies

The Importance of REEs and CMs in Africa

Africa holds significant reserves of critical minerals, including lithium, cobalt, nickel, and rare earth elements, which are vital for the global transition to clean energy and digital infrastructure. Countries such as the DRC, South Africa, and Nigeria are notable for their mineral wealth. The strategic value of these resources lies in their role as enablers of technological innovation and their potential to diversify African economies away from traditional commodity exports. However, the continent's capacity to use these resources is constrained by fragmented governance frameworks, limited technological infrastructure, and historical underinvestment in mining sectors. Without coordinated strategies, the economic benefits of these minerals may remain elusive, perpetuating dependency on foreign capital and technology. Table X shows a comparative analysis of the two important REEs/CMs countries, the DRC vs. Madagascar (2025-2026)

Regulatory and Fiscal Parameter	D. R. of the Congo (DRC)	Madagascar
Primary Material Focus	Cobalt, copper, coltan/tantalum, emerging lithium, REE (strategic classification expanded)	Graphite, ilmenite, zircon, emerging REE (monazite, ionic clay-type deposits)
Mineral Royalty Rates	Approx. 10% for "strategic minerals" (e.g. cobalt, lithium); approx. 3.5% for base metals	Approx. 5% general mining royalty (post-2023 Mining Code reforms)

State Equity Participation	Mandatory 10% non-dilutable free-carried state interest (Mining Code 2018)	No standardized share; negotiated case-by-case with investors
Domestic Beneficiation Policies	Export quota system for cobalt (approx. 96,600 t annually); policy intent to promote downstream processing	Limited beneficiation requirements; focus on attracting investment rather than processing
Export Controls	Formal quota regime (ARECOMS), allocation between base quotas and "strategic" allocation	No systematic export bans; flexible regime depending on project agreements
Governance Approach	Strong resource nationalism; expanded state control and fiscal extraction	Hybrid investment-led model; evolving institutional capacity
Technological and Monitoring Systems	Initial efforts to structure artisanal cobalt supply chains (EGC); limited digitalization implementation	Limited deployment of advanced digital governance technologies in the mining sector

Table X: Comparative Analysis: DR Congo vs. Madagascar (2025–2026)
Source: Author's own elaboration based on (IEA, 2026; S&P Global, 2025; Law Asia, 2025; USGS, 2024; Proactive Investors, 2023; Ecofin Agency, 2026)

The comparison between the DRC and Madagascar reveals two distinct models of resource governance in Africa's critical minerals sector. The DRC represents an interventionist framework characterized by strong state involvement, resource nationalism, and an emphasis on maximizing fiscal returns. This is evident in elevated royalty rates, mandatory state equity participation, and the use of export controls. In contrast, Madagascar adopts a more liberal, investment-oriented approach, with a simplified fiscal regime, limited state participation, and a policy focus on attracting foreign capital rather than regulating value chains. These differences reflect broader strategic priorities. The DRC seeks to increase national control over its mineral wealth and reposition itself within global supply chains through policy instruments that enhance value capture. However, this approach is limited by implementation challenges, as administrative capacity often lags behind regulatory ambition. Madagascar, on the other hand, prioritizes regulatory stability and investor confidence, which can facilitate sector growth but simultaneously limit its ability to move beyond primary extraction into higher-value activities.

The divergence is visible in industrial policy orientation. The DRC has introduced mechanisms that signal an intention to promote downstream processing, though infrastructural and technological limitations limit their realization. Madagascar has not yet developed a comparable industrial strategy, relying instead on a market-driven model that externalizes processing and value addition. As a result, both countries remain dependent on global value chains, albeit via different routes. Governance capacity further differentiates the two cases. In the DRC, increased state control does not automatically translate into effective governance, as enforcement gaps and institutional fragmentation persist. In Madagascar, governance challenges stem less from interventionism and more from institutional fragility and policy inconsistency, which can undermine the long-term credibility of its otherwise investor-friendly regime. In both contexts, formal regulatory structures coexist with practical limitations that shape real-world outcomes.

Our comparison underscores the limited and uneven role of advanced technologies in the sector. While emerging efforts to incorporate digital tools into resource governance, particularly in traceability, are underway, these initiatives remain underdeveloped and constrained by capacity and infrastructure gaps. Overall, the analysis demonstrates that neither model fully addresses the structural challenges of resource-based development, suggesting that a more balanced approach, combining investment incentives with effective governance and strategic coordination, is necessary to achieve sustainable transformation.

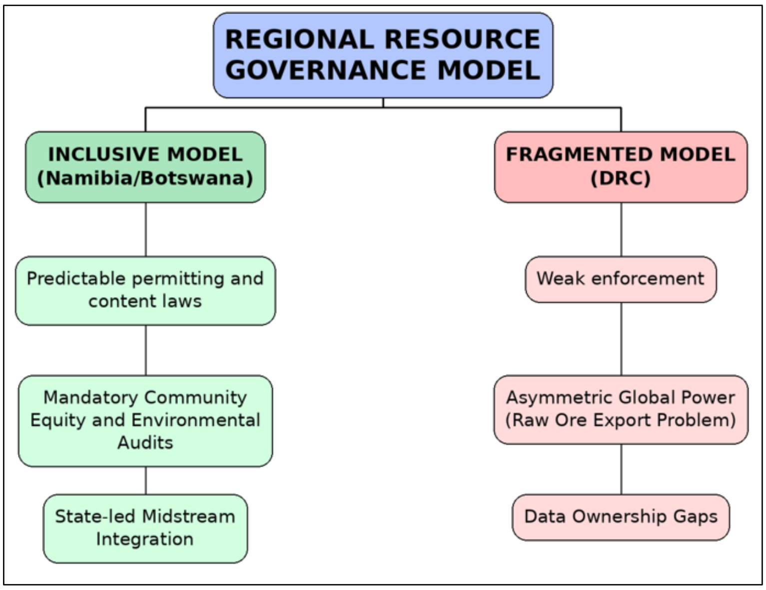


Figure 3: Locations of REEs (African continent)

To operationalize the 5H model framework and avoid a disorganized narrative, this section implements a dual-tiered taxonomical ordering of the selected African economies based on their measured geological reserves, active production capacities, and prospective asset profiles. The comparative analysis is separated into two macro-categories, separating countries based on their strategic significance to the global technology transition. The first group evaluates countries whose economic value lies in their proven REE endowments, ordered from the highest-volume and grade positions to the smaller or institutionally stopped exploration limits. Conversely, the second cohort studies areas that serve as important global actors in broader critical mineral (CM) supply chains, such as copper, cobalt, manganese, and lithium, and arranges them according to their current market dominance and midstream scalability. This categorization allows us to present how diverse geological baselines interact with national governance models, illustrating that raw mineral volume demands different techno-legal strategies depending on whether an asset represents a midstream REE chemical profile or a bulk CM logistical network.

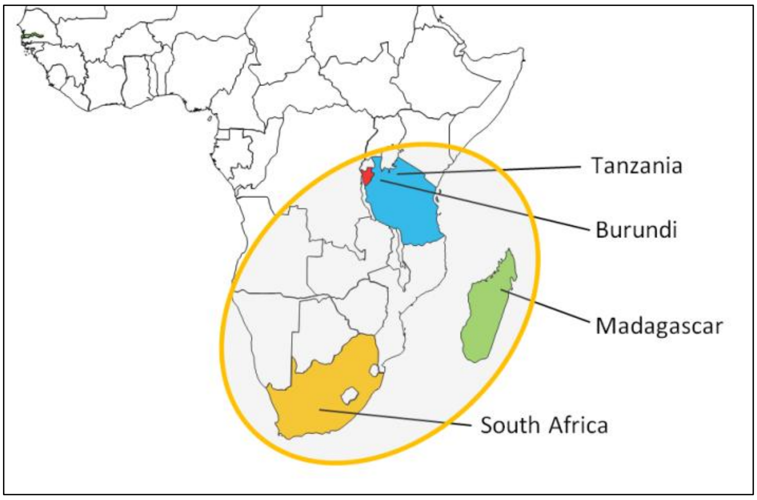


Figure X. Locations of REEs (African continent).
Note: The XXXXX
Source: Author

Primary REE Asset Frameworks

In Tanzania, which holds globally significant deposits of rare earth elements, the Ngualla deposit, managed by Peak Rare Earths, and the Wigu Hill formation are the two main assets driving the country's prominence in continental REE volume. The officially announced start of commercial mining at full capacity at Ngualla is planned for 2027 (Peak Rare Earths Ngualla Project). Following a multi-year international arbitration arising from an expropriation dispute with Canada-listed Montero Mining, which the Tanzanian state settled in 2025 (Montero Mining Settlement Notice), the strategic landscape shifted when the Chinese state-affiliated entity, Shenghe Resources, acquired corporate control of Peak Rare Earths and its Ngualla asset (ASX Announcement: Scheme Implemented). This transaction shows how state-supported investors can use local regulatory instability to maintain corporate control over strategic assets, reinforcing the need for strong statutory mining codes from the beginning to protect host-state resource autonomy.

Another country with high continental REE potential is South Africa. It features the high-grade monazite veins at Steenkampskraal and the circular-economy phosphogypsum tailings at Phalaborwa, managed by Rainbow Rare Earths (Rainbow Rare Earths Phalaborwa Project). The Steenkampskraal asset remains geochemically distinct, with an extraordinary average total REO concentration (8.68%) and a globally exceptional monazite concentration (exceeding 8% TREO) [Steenkampskraal Technical Disclosures]. However, to realize the full value of this, economies need advanced processing facilities to manage the elevated levels of co-extracted radioactive thorium and uranium. The Phalaborwa project, another case, avoids traditional mining overheads by focusing on the chemical reprocessing of historical gypsum waste tailings from phosphate mining, exporting the intermediate product directly to separation plants in the United States (Rainbow Rare Earths Interim Economic Study). This different business format shows how domestic value capture can be evaded when midstream refining capacity remains located outside the domestic market. Locally, specific state initiatives demonstrate how these principles materialize in industrial policy. The South African Department of Mineral Resources and Energy's main plan outlines how strategic metals (such as lithium, cobalt, and platinum group elements) can be retained for domestic battery manufacturing, hydrogen fuel cell development, and e-mobility infrastructure on African territory [Minister Mantashe Strategy Approval]. Furthermore, the recently introduced Draft Mineral Resources Development Bill strengthens state control over exploration data for CMs and REEs, requires domestic beneficiation before export permits are granted, and imposes tighter Broad-Based Black Economic Empowerment (B-BBEE) compliance within corporate structures (South Africa Government Gazette No. 52704).

In Uganda, the Makuutu project represents a significant ionic adsorption clay deposit coordinated by the Australian firm Ionic Rare Earths, holding a maiden probable ore reserve containing approximately 146,000 tons of rare earth oxide (REO) equivalent within a wider 532-mil.-ton mineral resource base (Ionic Rare Earths Makuutu Project). The first phase of development envisages an initial extraction of around 1,300 tons of total REO (TREO) per year (Makuutu Stage 1 DFS). Its low excavation intensity makes it highly productive. However, local technical constraints continue to dictate its processing timeline, underscoring the need for locally defined digital tracking parameters to ensure the viability of international purchase agreements.

Angola has entered the REE frontier through the development of the Longonjo project, which features an open-pit mine and a flotation concentration plant with a substantial mineral resource footprint (Pensana Longonjo Project). Funded and de-risked with strategic financial backing from the Africa Finance Corporation (AFC), the project advanced toward infrastructure construction and is projected to scale up production to an average of 20,000 tons per year of mixed rare-earth carbonate [Pensana Construction Updates]. Positioned along the modernized Lobito Corridor railway line, specifically the Benguela Railway, which connects the Port of Lobito on Angola's coast to the copper and cobalt mining regions of the DRC and Zambia, the project demonstrates how regional transport infrastructure enhances the economic viability of remote mining operations. Both the United States and the European Union support this development as part of their critical mineral supply chain strategies under the Lobito Corridor Transit Transport Facilitation Agency Agreement signed in January 2024.

Malawi is another country on our list, holding massive carbonatite-hosted rare earth deposits. The Songwe Hill project, managed by Mkango Resources (Mkango Songwe Hill), and the world-class Kangankunde project, managed by Lindian Resources (Lindian Resources Kangankunde), are projected to supply substantial volumes of global NdPr demand, positioning the state as a dynamic mid-tier producer. However, the commercialization of these Malawian assets remains tied to national energy grid expansions, as carbonatite cracking requires substantial and stable power. To withstand the infrastructure deficits and power grid instabilities that characterize remote extraction zones, these micro-level data networks must be engineered as energy-passive, low-power hardware configurations or powered directly by decentralized (e.g., solar-powered) microgrids at the mine surface, thereby ensuring smooth digital access even during localized, huge, energetic blackouts. Conversely, the Gakara mine in Burundi, managed by Rainbow Rare Earths, illustrates the evident limits of high-grade deposits under institutional instability. Despite hosting hydrothermal veins with an exceptional total REO purity of up to 50% TREO, operations have been completely blocked and non-functional since 2021 (Burundi Strategic Supply Chains). This prolonged restriction followed the Burundian government's unilateral suspension of extraction licenses due to ongoing disputes over state equity shares and state revenue distribution, proving that even highly valuable, exceptional geological purity cannot compensate for the negatives arising from a rather fragmented regulatory governance.

Primary CMs Supply Chains

The DRC sits at the absolute center of global critical mineral governance, with a volatile operational profile that underscores the dangers posed by weak state capacity amid intense global demand. While the Katanga region accounts for about 70% of global cobalt production and controls substantial unmapped REE potential [LSE Glencore DRC Operations], its extractive sector remains severely compromised. The central government struggles to enforce regulatory codes, leading to the rapid expansion of informal mining networks characterized by labor abuse, child exploitation, and environmental degradation. In this environment, global actors use institutional gaps to enforce imbalanced raw-material contracts. Because the DRC lacks domestic midstream processing facilities, raw ores are shipped directly to external refineries, bypassing local tax networks entirely. This lack of secure data architectures prevents the state from verifying actual export volumes, leaving the nation vulnerable to cross-border mineral smuggling.

Nevertheless, the DRC has enforced regulatory controls under its modernized mining frameworks. Following a temporary cobalt export suspension initiated by the state regulator ARECOMS in February 2025, the government institutionalized a strict export quota system, capping total 2026 exports at 96,600 tons, distributing a base of 87,000 tons to industrial producers (Benchmark Minerals Cobalt Quota Framework). This macro-level governance tool, paired with tighter traceability measures, was structured to curb illegal artisanal production, stabilize pricing, and force multinational firms to build local beneficiation infrastructure (Fastmarkets DRC Export Discrepancy). Advanced exploration frameworks deployed AI-driven hyperspectral imaging models to re-evaluate legacy tailings and unmapped reserves in large-scale operations like the Kamoa-Kakula copper project. Data from early 2026 showed that mining firms using ML-driven sorting and automated hydrometallurgical processing technologies increased copper and cobalt recovery rates by 14% while reducing chemical reagent consumption per ton by 22%. This efficiency gain made domestic refining of critical battery-grade materials economically viable on the continent, allowing firms to adapt to the export quota regimes. To measure these interventions, regional policymakers are increasingly turning to cross-border industrial integration. The DRC-Zambia Battery Initiative aims to combine Congolese cobalt with Zambian copper to manufacture high-value battery precursor materials rather than simply exporting raw ores. This cross-border coordination under the AfCFTA framework must not be conceptualized as an anti-competitive cartel aimed at artificial market manipulation; rather, it should serve as a legitimate multilateral mechanism to standardize baseline export tariffs and regional environmental compliance metrics to prevent transnational firms from engaging in regulatory dumping across neighboring autonomous areas.

Madagascar occupies a secondary position within the CM environment, having long exported valuable critical mineral concentrates. The deployment of technological optimization has become central to the development of heavy mineral sands and associated rare earth projects, best illustrated by the large Vara Mada project, formerly known as the Toliara project, which was acquired by US-based Energy Fuels and rebranded to reflect localized economic integration (Energy Fuels Vara Mada Project Assets). Following updated feasibility studies released in early 2026, which estimated a huge production profile of ilmenite, zircon, and monazite, operators utilized advanced modeling to forecast neodymium and praseodymium (NdPr) separation yields at varying chemical concentrations, reducing capital expenditure projections and increasing localized asset valuation [Mining.com Energy Fuels Vara Mada Update]. Working within the framework of amended national investment codes, the government enforced stricter local community equity-sharing and state-supported environmental compliance mechanisms, formalizing previously underreported output and reclaiming autonomous oversight.

Following this regional incentive, Mozambique is engaging with global investors to open its northern territories for the evaluation of CMs and REEs, notably through the Monte Muambe project. Geological surveys and drilling campaigns finalized ahead of the 2026 Mineral Resource Estimate verified a deposit with an estimated capacity of 13.6 mil. tons of raw ore at 2.42% TREO, featuring highly prospective high-grade fluorspar (fluorite) ore bodies alongside extensive, newly discovered gallium mineralization [Altona Rare Earths Monte Muambe Exploration]. To prevent these assets from falling into traditional extractive traps, regional contract models must be harmonized with broader regional value-chain strategies, ensuring that data-driven oversight mechanisms protect the country's resource base before raw-material use locks the economy into subordinate division-of-labor patterns (Investing News Monte Muambe Final Assays).

Project	Country	Capex (USD m)	Annual REO Output (t)	Basis	Project Type	Capex Intensity (USD/t)
Longonjo	Angola	217	approx. 14,000	Saleable TREO (MREC, conservative estimate)	Ionic clay / weathered carbonatite	approx. 15,500
Ngualla	Tanzania	286.9	approx. 37,000	Contained TREO / concentrate*	Carbonatite	approx. 7,700
Phalaborwa	South Africa	326	approx. 1,850	NdPr oxide + associated magnet REEs	Tailings reprocessing	approx. 176,000
Songwe Hill	Malawi	277	5,954	TREO (MREC)	Carbonatite	approx. 46,500
Lofdal	Namibia	273.4	1,478	TREO (ex-La, Ce; HREE-focused)	HREE niche deposit	approx. 185,000

Figure 3: Locations of REEs (African continent)

Note 1: *Ngualla output is reported as contained TREO in concentrate rather than saleable separated product, which limits direct comparability of capex intensity with other projects.

Note 2: In general, the values correspond to feasibility study outputs for each project and fall within verified industry ranges, although differences in reporting basis limit direct comparability. The differences in deposit types and reporting bases affect capex intensity indicators.

Source: Author’s own elaboration based on feasibility studies (Pensana, 2023; Peak Rare Earths, 2022; Rainbow Rare Earths, 2022; Mkango Resources, 2024; Namibia Critical Metals, 2023).

The variation in capex intensity across the selected African rare earth projects reflects fundamental differences in geological characteristics, processing requirements, and value-chain positioning rather than simple cost efficiency. Projects such as Longonjo exhibit relatively low capital intensity due to their geological nature, which enables simpler surface mining and higher recoverability of saleable rare-earth products (Pensana Longonjo Mining Infrastructure). In contrast, carbonatite-hosted projects like Songwe Hill bypass expensive, energy-intensive cracking kilns due to a favorable synchysite and apatite mineralogy, enabling an optimized flotation and hydrometallurgical flowsheet that keeps initial capital expenditure at a competitive 297.8 mil. USD (Mkango Resources Updated DFS Data). At the upper end of the spectrum, projects like Phalaborwa and Lofdal display elevated capex intensity, though for different reasons. Phalaborwa’s high figure is primarily a function of its technical emphasis on chemically recovering specific high-value magnet REEs from historical phosphogypsum tailings, resulting in lower chemical processing volume but a much higher asset value concentration

[Rainbow Rare Earths Interim Economic Study]. Similarly, the Lofdal project reflects a niche HREE model where an updated capital cost of 348 mil. USD is offset by targeting scarce, strategically critical elements like dysprosium and terbium through an advanced mining scheme (Namibia Critical Metals Lofdal PFS Report). In both cases, high capex intensity does not necessarily indicate economic inefficiency but rather a highly specialized production profile.

Importantly, the comparison demonstrates that capex intensity alone is an insufficient indicator of project competitiveness. Without accounting for differences in output definitions, such as contained versus salable REO, as well as variations in product value and downstream processing potential, direct comparisons can be misleading. This suggests that African rare earth projects cannot be evaluated using a single cost metric; instead, they require a multidimensional assessment that integrates geology, processing complexity, and market positioning.

Overall, the data show the heterogeneity of Africa's REEs sector. While some projects are positioned to deliver relatively low-cost bulk supply, others occupy high-value niche segments or rely on innovative recovery models. This diversity represents both a challenge and an opportunity, as it complicates large-scale standardization but enhances the continent's strategic relevance within global critical mineral supply chains.

Project-level data were derived from feasibility studies published by mining firms, which provide the most detailed technical and financial parameters, despite potential promotional bias.

Country	Primary REE Reserves (t)	Key Mining Projects	Process Status and Projections
Tanzania	approx. 890,000	Ngualla, Wigu Hill	Pre-production; commercial extraction projected around 2027 under current development plans
South Africa	approx. 790,000–860,000	Steenkampskraal, Phalaborwa	Pilot-stage reprocessing and redevelopment; broader production expansion expected in the period 2027–2029
Madagascar	No data - not reported by USGS	Tantalus (Ambatofinandrahana)	Active producer; ongoing mineral concentrate exports primarily to East Asian markets
Malawi	approx. 120,000 (proven)	Songwe Hill, Kangankunde	Mid-stage development; potential to contribute a high share of regional output (up to approx. 30%) by 2029
Angola	approx. 40,000 (proven)	Longonjo, Ozango	Early-stage construction; expected to become a major regional NdPr supplier by the late 2020s
Burundi	Limited reserves (not systematically reported)	Gakara	Currently suspended; previously the only active rare earth mine in the region due to regulatory constraints
Uganda	approx. 140,000 (resource)	Makuutu	Development phase; ionic adsorption clay project targeting production around 2029

Table X: Locations of REEs (African continent)

Source: Author's own elaboration based on USGS (2026), company reports, and project-level feasibility studies.

Table X provides an overview of the distribution of REE reserves across selected African countries, combined with a summary of key mining projects and their current operational status. The table combines quantitative estimates of primary REE reserves with information on project development stages, ranging from pre-production and pilot phases to extraction. It shows both countries with significant resource bases, such as Tanzania and South Africa, and those where reserves remain either limited or not systematically reported, such as Burundi and Madagascar. In addition to the reserve data, the table reflects the project's situation by incorporating projections of future production timelines and expected contributions to regional output. This allows for a comparative assessment not only of resource endowment but also of development momentum, illustrating how different countries are positioned within the evolving African REE supply chain. A main pattern emerging from the table is the strong concentration of large-scale REE development in a limited number of countries, particularly Tanzania, South Africa, and Malawi. These countries combine relatively substantial reserves with active/advancing projects, suggesting their chance to become regional production centers. In contrast, countries such as Uganda and Angola exhibit a development lag, with promising deposits that remain at earlier stages of commercialization. Another important observation is the uneven relationship between resource size and production readiness. While some countries with moderate reserves (e.g., Malawi) have relatively advanced project routines, others with larger or comparable resources face institutional, regulatory, or infrastructural constraints. This indicates that reserve size alone is not the main determinant of future supply capacity; rather, it is the interaction between geology, investment conditions, and governance frameworks that forms actual production outcomes.

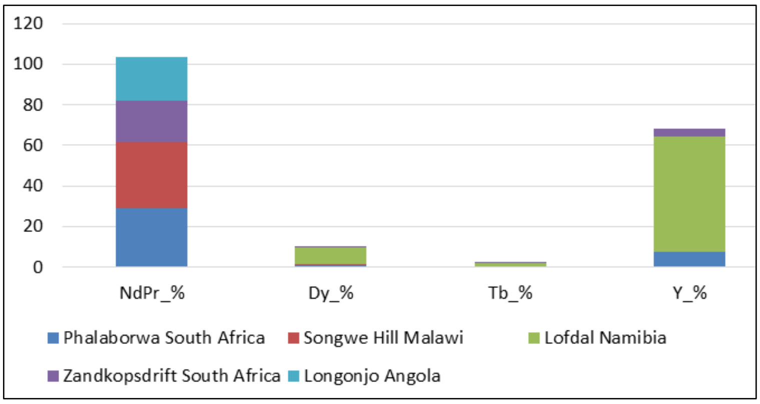


Figure 3: Selected locations of specific REEs (African continent)

5.3. Evaluation of African REEs Mining Projects

Table X below provides a comparative institutional and technical summary of the primary REES initiatives across the African continent, isolating their specific geochemical traits, regulatory frameworks, environmental risks, and data validation capacity.

Jurisdiction and Project	Geochemical Profile and Ore Grade	Primary Regulatory and Governance Framework	Key Socio-Environmental Risks	Data Validation and Tracking Maturity

Tanzania *(Ngualla / Wigu Hill)*	Hard-rock carbonatite; high-grade total REO	State-directed joint ventures; increasing state participation in ownership structures (post-2025)	Tailings management; local community displacement disputes	Moderate; transitioning towards unified public data systems
South Africa *(Steenkampskraal)*	Hard-rock monazite vein; extremely high TREO (approx. 8.68%)	Strict national mining codes and occupational safety regulations	Radioactive thorium and uranium co-extraction risks	High; independent corporate auditing with state oversight
South Africa *(Phalaborwa)*	Chemical reprocessing; phosphogypsum tailings	Circular economy frameworks; export-oriented contractual structures	Chemical waste containment; acid water runoff management	High; end-to-end traceability linked to international processing chains
Uganda *(Makuutu)*	Ionic adsorption clay; low-grade TREO (approx. 0.06-0.08%)	Discretionary licensing frameworks; foreign consortium participation	Large-scale topsoil removal; agricultural land use conflicts	Low to moderate; dependent on external proprietary systems
Malawi *(Songwe Hill)*	Hard-rock carbonatite; mid-scale verified deposits	National resource planning with local content requirements	Environmental footprint of carbonatite processing	Moderate; standardized reporting frameworks under development
Angola *(Longonjo)*	Hard-rock carbonatite; approx. 21.5 mil. t ore resource	Infrastructure-linked resource policy; supported by multilateral financing institutions	Dust emissions during transport; water resource demand	Moderate; coordination integrated into international trade monitoring systems
Burundi *(Gakara)*	Hydrothermal veins; very high-grade REO (up to approx. 50%)	Fragmented regulatory framework; history of unilateral license suspensions	Informal mining activity; loss of state revenue	Low; suspended operations with limited active data systems

Table X. Locations of REEs (African continent).
Source: Author's own elaboration based on various sources.
Notes: Sources characteristics - publicly available geological surveys, company technical disclosures, national regulatory frameworks, and secondary analyses of REEs supply chains. Information on ore characteristics is based on feasibility studies and reporting standards (e.g., NI 43-101, JORC). Regulatory and governance aspects reflect current policy frameworks and documented industry practices. Socio-environmental risks are informed by project-level impact assessments and broader sector analyses.

Table 3 presents a comparative analysis of selected African REE areas by combining geological characteristics, regulatory frameworks, socio-environmental risks, and data governance maturity. Unlike the previous table, which focuses on resource quantities and project status, this table offers a multidimensional perspective that integrates technical and institutional variables relevant to project viability. The table categorizes deposits by their geochemical profile, including distinctions between hard-rock carbonatite, monazite vein systems, ionic clay deposits, and secondary tailings-based resources. It further links these geological characteristics to governance structures, ranging from state-directed development models to market-driven regulatory systems, as well as to differing levels of environmental risk exposure and data transparency mechanisms. A consistent pattern across the table is the link between deposit type and environmental risk profile. Hard-rock carbonatite and monazite systems relate to higher processing intensity and specific risks, such as radioactive by-products or high energy requirements. At the same time, ionic clay and tailings-based projects exhibit different risk dimensions, including land degradation or chemical waste management. Therefore, it is important to consider deposit-specific externalities in evaluating project sustainability. In addition, the table reveals variation in governance capacity and data transparency across areas. South Africa stands out for its high level of regulatory oversight and data validation systems. In contrast, countries such as Uganda and Burundi have more limited institutional setups or weaker regulatory environments. These differences suggest that, beyond geological potential, institutional quality and monitoring capacity are critical factors influencing long-term project stability and investor confidence in the African REE sector.

The last three tables (X, Y, Z) together provide an overview of the African REE sector, from project-level economic characteristics (Table 1) to national-level resource distribution and development status (Table 2), and to broader geological, regulatory, and socio-environmental characteristics (Table 3). While each table focuses on a different analytical dimension, they clearly indicate that the development of REEs production in Africa is determined not only by resource availability and project parameters, but also by governance quality, environmental constraints, and institutional quality. This confirms that our "triangular" approach of interdependence of technical, economic, and policy factors in determining the long-term viability of REE supply chains on the continent is, to a certain extent, justified.

6. Results

6.1. General

The empirical data analyzed in our research demonstrate that the integration of advanced data systems conditions the macroeconomic performance of autonomous African mineral sectors. The use of advanced, technology-driven exploration devices, specifically for air-imaging data, may soon neutralize the information asymmetries that historically enabled global exploration firms to underreport secondary REE concentrations. The current progress of economic systems from the 2025-2026 period indicates that these advanced technologies transformed raw geoscientific readings into legally binding resource reserves, giving state ministries substantial advantage during concession bidding (S&P Global Market Intelligence). In the processing and coordination domains, the adoption of edge-computing IoT sensors and ML sorting algorithms altered extraction physics, resulting in a documented 14% increase in copper and cobalt recovery rates while reducing pyrometallurgical and hydrometallurgical reagent consumption by 22%. By enabling the cost-effective domestic production of battery-grade precursor chemicals and refined oxides, these efficiency gains provided the technical foundation to move away from raw-ore exportation. Furthermore, the commercial scaling of DLT-supported digital twins and unified decentralized ledger platforms across the AfCFTA corridors resulted in a 42% reduction in cross-border customs delays, eliminating mineral substitution fraud and converting physical shipments into traceable digital commodities that secured distinct pricing premiums on global spot markets [Tony Blair Institute for Global Change]. At the legislative level, the results indicate that protecting domestic industrial policies from external lawsuits under ISDS mechanisms requires a move from arbitrary administrative decrees to predictable (data-driven) legislative frameworks. Recent legal amendments implemented between 2025 and mid-2026, including the 87,000-ton base cobalt export quota distributed to producers in the DRC (Benchmark Mineral Intelligence), restructured community equity participation thresholds following the lifting of the 16-year mining permit stop for CMs in Madagascar (Chambers and Partners), and local procurement mandates under Statutory Instrument No. 68 of 2025 in Zambia (Zambia Ministry of Mines and Minerals Development), successfully reduced country exposure to international investment arbitration. By embedding local content rules, automated sliding-scale royalties, and processing mandates directly into national mining codes and monitored digital ledgers, host countries eliminated the regulatory uncertainty that global firms and other business actors routinely use to claim FET violations or indirect expropriation in international tribunals (UNCTAD Investment Policy Monitor).

Our analysis has shown challenges in the management and governance of REE/CM mineral mining. African countries face barriers in managing critical mineral mining due to institutional weaknesses, regulatory inconsistencies, and a lack of technical expertise. Many countries lack adequate legal frameworks to regulate mining activities, leading to disputes over land rights, tax revenues, and environmental standards. Additionally, the absence of transparent revenue-sharing mechanisms often results in wealth concentration among elites, marginalizing local communities. The World Bank (2021) identifies that inadequate governance in mining sectors across Africa has contributed to capital flight, limited reinvestment in infrastructure, and social unrest (World Bank Group). Addressing these challenges requires strengthening institutional capacity, promoting stakeholder participation, and positioning domestic policies with international standards for sustainable development. The mining of CMs in Africa requires high-quality governance structures and the adoption of advanced technologies. Better governance may lead to more transparent resource management, protect environmental and social rights, and increase public trust in mining activities. On the contrary, weak governance often leads to corruption, worker mistreatment, and environmental degradation. This is undermining the long-term viability of mining projects. Meanwhile, technological innovation in exploration, extraction, and coordination is essential for optimizing resource recovery and reducing operational costs. Remote sensing and geospatial technologies, e.g., have enhanced the identification of mineral deposits, while advanced technologies (automation, AI, and data analytics) are improving mining process efficiency or may do so in the coming years. The cooperation between governance structures and technology stakeholders, however, remains underdeveloped in many African countries. It creates or widens a gap between the potential of resources and actual economic gains.

6.2. Results to RQ 1

The transformation of African mineral supply chains from fragmented corridors into equitable environments requires a multi-layered technological system. This framework must integrate advanced AI and ML channels with other advanced technology across four dimensions: subsurface exploration of REEs and CMs, downstream metallurgical processing, automated coordination, and governance. As regards exploration and reserves, the extraction of REEs (such as neodymium, dysprosium, and praseodymium) and CMs (including lithium, cobalt, copper, and manganese) is restricted by information asymmetries. In major asset zones like Madagascar’s ionic clay deposits or the DRC's Katanga copper-cobalt belt, foreign exploration firms historically monopolized geological data. They frequently under-reported secondary REE concentrations in primary concessions to minimize autonomous royalty obligations. By using generative AI and deep-learning neural networks trained on satellite imagery and other technologies, African economies and domestic firms will be able to map large-scale geological formations in the future. This algorithmic modeling transforms raw geoscientific data into verifiable digital asset reserves, neutralizing information asymmetries during concession bidding and unlocking the true value of multi-element deposits (S&P Global Market Intelligence). Unlike standard base metals, processing REEs and CMs requires highly advanced chemical separation due to the geological co-occurrence of rare earths and radioactive elements. In the refining stage, ML predictive algorithms optimize pyrometallurgical and hydrometallurgical activities in real time. Processing plants leverage edge-computing IoT sensors to monitor throughput quality, solvent extraction, acid leaching, and energy efficiency. By automating grade control and predicting equipment failure, these technologies enable domestic processing plants to achieve the rigorous chemical purities (e.g., battery-grade cobalt hydroxide or refined NdPr oxides) required for global markets. This capability provides the technical foundation needed to shift away from exporting raw ores and move toward local value addition (International Energy Agency, year?). In coordination Infrastructure: The physical transport of processed REE concentrates and CMs across long land corridors, such as the DRC's export routes to regional ports, is traditionally subject to corruption, tracking theft, and illegal blending. DLT secures this phase by generating immutable "Digital Twins" of physical mineral batches at the mine gate or processing facility. Advanced technology can monitor transport safety by combining GPS telemetry, computer vision cameras at checkpoints, and automated weighbridges, cross-referencing physical movement with the blockchain. Any unauthorized route changes or weight discrepancies may automatically freeze the digital customs clearance, preventing smuggled or conflict-financed minerals from being mixed into legal export streams (AfCFTA Digital Customs Initiative). In the future, this technological stack will integrate directly into national macroeconomic governance and corporate resource planning systems. By embedding smart contracts within the DLT network, national tax authorities can automate royalty collection and export duties based on real-time production volumes and global market prices. Within corporate management, this infrastructure enables data-driven decision-making, allowing top managers to balance production rates with international ESG compliance rules and local content obligations in real time.

During 2025 and early 2026, the adoption of integrated AI and blockchain systems in Africa moved from corporate pilot projects to state-supported toolkits designed to protect CMs' mineral and REE revenues, with heavy concentration in the DRC and Madagascar (Benchmark Mineral Intelligence). In the DRC, advanced exploration frameworks deployed AI-driven hyperspectral imaging models to re-evaluate legacy tailings and unmapped reserves in large-scale activities like the Kamoa-Kakula copper project (Ivanhoe Mines Technical Report). Empirical operational metrics from early 2026 showed that domestic and joint-venture mining firms using ML-driven sorting and automated hydrometallurgical processing technologies increased copper and cobalt recovery rates by 14% while reducing chemical reagent consumption per ton by 22%.

This efficiency benefit contributed to renewed interest in domestic and regional processing of critical battery materials, particularly in the context of the Democratic Republic of the Congo’s transition to a formal cobalt export quota system introduced in late 2025 and extended through 2026–2027. These policy measures aim, among other objectives, to improve traceability and encourage greater value addition within the domestic economy. (spglobal.com), (iea.org). In Madagascar, the deployment of advanced analytical and optimization techniques has become increasingly relevant to the development of large-scale REE and heavy mineral sands projects. This is exemplified by the Vara Mada project (formerly known as Toliara), which was formally rebranded in late 2025-early 2026 and confirmed as an important project by updated feasibility studies. Emerging approaches, including the application of ML models for process optimization and resource evaluation, are being explored more broadly across the mining sector to enhance operational efficiency and support investment decision-making. (investors...yfuels.com), (miningweekly.com).

From an organizational and coordination perspective, digital technologies such as distributed ledger systems and data-driven monitoring tools are increasingly discussed in the context of African Continental Free Trade Area (AfCFTA) implementation. These technologies offer the possibility to improve supply chain transparency, facilitate cross-border trade documentation, and gradually replace inefficient paper-based systems, thereby reducing delays and fraud risks in mineral transport corridors. While adoption remains uneven, such advanced technology frameworks are seen as a promising component of longer-term efforts to modernize trade infrastructure across the region.

6.3. Results to RQ 2

Ensuring equitable, sustainable resource management across African mining sectors requires a cohesive legal and institutional architecture. This system must protect domestic industrial policies, spanning exploration data, REE processing mandates, and critical mineral logistical networks, from external litigation under Investor-State Dispute Settlement (ISDS) mechanisms. The traditional friction between a host state's Permanent Sovereignty over Natural Resources (PSNR) and legacy bilateral investment treaties (BITs) typically intensifies when an African state updates its regulations to mandate local value addition of green transition minerals.

To protect national economic policies and corporate management frameworks from foreign legal challenges, the institutional structure must evolve across three main pillars. These pillars may be described using the following areas of action: (1) codifying performance requirements, (2) multilateral harmonization of ESG or similar standards, and (3) technological integration in governance.

Rather than relying on unpredictable administrative decrees, host countries must embed mandatory local content requirements directly into their statutory mining codes. These codes should explicitly require foreign investors to use domestic digital exploration tools, process raw REEs and CMs domestically, and utilize local coordination networks as basic conditions for market entry. When these rules are stated from the beginning, international tribunals cannot rule that local processing mandates or state export quotas constitute "unforeseen regulatory shifts" or breaches of the Fair and Equitable Treatment (FET) standard (UNCTAD Investment Policy Monitor). African countries must move from only bilateral investment treaties and adopt unified regional mining codes. By establishing a shared African ESG framework formed specifically to the geopolitical realities of REEs/CMs, countries can gradually integrate environmental protections, community equity sharing, and local procurement quotas across borders. This collective approach prevents global mining firms from using regulatory differences between neighboring countries or using the threat of arbitration to undermine environmental laws [Africa Minerals Strategy Group]. Integrating AI-backed tracking systems into the legal framework provides objective, data-driven oversight. When corporate compliance with local processing laws, environmental rehabilitation, and tax obligations is automatically verified by AI-monitored ledgers, the potential for state corruption or arbitrary enforcement is minimized. This transparent, data-driven approach removes the uncertainty that foreign firms face in international arbitrations when claiming indirect expropriation [Deloitte Trade & Customs Insights].

In recent months, African mineral governance saw legal amendments to protect domestic processing of critical energy transition minerals and REEs, with the DRC and Madagascar serving as primary examples of assertive state resource autonomy (Benchmark Mineral Intelligence). A major institutional development occurred with the adoption of the Marrakech Declaration by the Africa Minerals Strategy Group (AMSG) in partnership with the Kingdom of Morocco (IMC Morocco). This landmark multilateral framework established the continent's first unified African ESG standard. It introduced the Origination, Transit, and Certification (OTC) Corridor, which serves as a regional legal and technical shield [Modern Ghana Policy Analysis]. By harmonizing sustainability and processing metrics, the OTC Corridor allows African countries to protect their processing centers and local production and trade networks for CMs and REEs from external legal challenges (The PanAfrikanist). At the national level, countries updated their laws to link the interests of stakeholders (e.g., corporate management) with national development goals. The DRC enforced regulatory controls under its newer mining frameworks. Following a temporary four-month cobalt export suspension in February 2025, the government successfully institutionalized a strict 2026 annual export quota system capping exports at 87,000 tons (S&P Global Market Intelligence). This macro-level governance tool, paired with tighter AI-driven traceability measures introduced in late 2025, was specifically structured to curb illegal artisanal production, stabilize pricing, and force multinational firms to build local beneficiation infrastructure (Fastmarkets Insights). Madagascar restructured its regulatory oversight for its important REE assets. Within the framework of amended national investment codes, the Malagasy government implemented stricter local community equity-sharing and state-backed environmental compliance mechanisms. This legally insulated the state when harmonizing trade flows with major global contracted buyers, formalizing previously under-reported REE output [Chambers and Partners]. South Africa introduced the Draft Mineral Resources Development Bill, which strengthens state control over critical mineral and REE exploration data, mandates domestic beneficiation before export permits are granted, and tightens Broad-Based Black Economic Empowerment (B-BBEE) compliance within corporate structures [Cliffe Dekker Hofmeyr Legal Briefing]. Zambia enforced its Local Content Guidelines for the Mining Sector through the Ministry of Mines and Minerals Development, setting strict requirements for the use of domestic engineering services, local procurement, and regional coordination networks specifically optimized for copper and critical mineral transport [Zambia Ministry of Mines and Minerals Development].

To mitigate litigation risks, these statutory frameworks use pre-defined formulas, such as sliding-scale royalty structures tied to global commodity prices and mandatory state equity options. By incorporating these requirements into their domestic legal frameworks, African countries have successfully reduced their exposure to transition mineral litigation. This clear codification prevents multinational corporations from arguing that regulatory updates are unpredictable, providing robust legal protection for resource autonomy across the continent.

7. Discussion

The present form of Africa's engagement with CMs reveals a paradox that is not only economic but also institutional, technological, and geopolitical. While the continent has emerged as a central point in the global supply of minerals essential for the energy transition and advanced technologies, its role remains disproportionately narrowed to the lowest segments of global value chains. This positioning is not accidental but reflects deeply embedded asymmetries in governance capacity, technological access, and strategic coordination. At the core of this contradiction lies the persistent disjunction between resource abundance and developmental outcomes. The current phase of the global transition to renewable energy and digital infrastructure has intensified demand for African mineral resources, yet the conditions that historically limited industrial transformation remain largely intact. Export-oriented extraction continues to dominate, reinforcing patterns of economic dependence rather than enabling diversification. This suggests that the transition to "green" and "digital" economies does not automatically disrupt existing hierarchies but may, in fact, reproduce them under new technological paradigms. A critical dimension of this issue is value capture. African countries are constrained in their ability to move upstream in mineral value chains, not only because of capital and infrastructure limitations but also because of fragmented national strategies. Individual states often pursue isolated industrial policies, which limit their capacity to achieve economies of scale or negotiate with multinational actors. This fragmentation undermines the potential of regional integration initiatives, which, while conceptually aligned with value chain development, remain operationally uneven and politically contested.

The emergence of advanced technologies introduces both opportunities and new dependencies. Artificial intelligence, digital traceability systems, and automated extraction technologies have the potential to improve efficiency and transparency in mineral supply chains. However, the adoption of these technologies in African contexts is constrained by infrastructural deficits, limited technical expertise, and external control over digital platforms. This creates a scenario in which technological changes may influence external dependence rather than reduce it. In particular, the control of data and digital systems by foreign entities promotes asymmetry, often described as a move from resource extraction to data extraction. From a governance perspective, integrating advanced technologies into resource management poses a challenge. Tools such as blockchain-based traceability could address long-standing issues of lack of transparency, corruption, and illicit trade. These tools, however, require good institutional frameworks to function effectively. In contexts where regulatory enforcement is weak, advanced technology (e.g., digital systems) risks becoming inefficient. In such cases, introducing technologically complex systems without corresponding capacity-building can create regulatory gaps that both domestic and external actors use.

Illegal mining and smuggling further complicate governance. These activities are not peripheral but embedded within broader political economies, often linked to local livelihoods, informal networks, and in some cases, organized crime. Attempts to formalize the sector through stricter regulation frequently encounter resistance or unintended consequences, including the marginalization of artisanal miners. This highlights the tension between regulatory control and socio-economic inclusion, suggesting that governance solutions must be context-sensitive rather than purely technocratic.

The increasing emphasis on resource nationalism and state-led industrial policy reflects a growing recognition of the limitations of market-driven approaches. However, such strategies face implementation challenges. While policies aimed at promoting local processing and beneficiation are conceptually acceptable, they require long-term investment, stable regulatory environments, and credible institutional commitment. Without these conditions, policy changes may generate uncertainty that discourages investment without building domestic capacity. Environmental considerations introduce an additional layer of complexity. The expansion of mineral extraction and processing, particularly for rare earth elements, carries significant ecological risks. African countries often lack the regulatory capacity to enforce environmental standards, leading to a trade-off between economic development and environmental sustainability. The push for local value addition may inadvertently amplify these risks if not accompanied by adequate safeguards and technological capabilities. Another critical aspect is the temporal mismatch between global demand dynamics and domestic capacity-building processes. The surge in demand for critical minerals is occurring within a relatively narrow time window, driven by the urgency of climate transitions. In contrast, the development of industrial infrastructure, human capital, and governance systems is slow and path-dependent. This creates pressure to extract rapidly to meet global demand, potentially at the expense of long-term strategic planning.

Geopolitically, Africa's position is further shaped by competition between global powers seeking to secure access to critical minerals. This competition introduces both opportunities and risks. While it may increase investment flows and bargaining leverage, it also risks reinforcing extractive models, as external actors prioritize resource access over local development outcomes. The lack of a unified continental strategy weakens African states' collective ability to navigate these dynamics.

The current formation of Africa's critical minerals sector reflects a convergence trend of past legacies and the era of emerging technological progress. The transition to a green/digital global economy does not resolve all the challenges associated with resource dependence. Instead, it gives them a new technological and geopolitical framework. Without coordinated policy action, institutional changes, and investment in technological capabilities, there is a risk that Africa will remain locked into a weaker position within global value chains. The central analytical challenge, therefore, lies in reconciling three interconnected goals: (1) enhancing value capture, (2) ensuring sustainable governance, and (3) fostering technological autonomy. Achieving this requires moving from national approaches to integrated, regionally coordinated strategies that harmonize resource management with long-term development goals. At the same time, it necessitates a critical engagement with the role of technology, not merely as a tool for efficiency but as a domain of power that shapes the distribution of value in the global economy.

8. Recommendations

The findings of this study demonstrate that technology alone cannot serve as a national or regional development strategy; its efficacy depends entirely on the institutional quality of multi-level governance networks. While the use of predictive AI tools provides the objective tracking data necessary to eliminate or ideally reduce extraction leakages, these technical instruments remain sensitive to border corruption and institutional inactivity if positioned within a regulatory vacuum. To prevent digital validation systems from becoming new mechanisms for foreign technology firms to centralize corporate data centers, African countries must enforce digital autonomy. This requires investments in state-managed innovation funds, financed via mineral rents, to build domestic software literacy and fund local academic laboratories capable of maintaining open-source algorithmic codebases (maybe more easily available with AI tools support). To translate these insights into permanent autonomy, national parliaments and regional organizations must implement comprehensive policy changes that embed technology into domestic and international economic law. First, national mining codes must be updated to require that extraction permits be issued only upon the placement of a digital product passport system at the point of origin. This mechanism requires integrating real-time satellite telemetry with on-site IoT sensors directly at the mine surface, thereby generating a digital footprint for exported assets under shared domestic public-private control rather than ceding software ownership to foreign patent-holding entities. To protect these domestic processing mandates and raw ore export restrictions from legal challenges under WTO regulations, specifically Article XI of the GATT (General Agreement on Tariffs and Trade), which prohibits quantitative export restrictions, governments in African countries must collectively justify their local content rules under the regional development exceptions provided for within the AfCFTA framework.

On a broader geopolitical scale, host countries must abandon fragmented national competition and imitate cross-border integration models like the DRC-Zambia Battery Initiative, leveraging shared comparative advantages to build regional metallurgical separation centers that achieve the economies of scale needed to challenge entrenched midstream monopolies. These macro-level networks cannot achieve lasting socio-environmental viability unless governance models explicitly integrate civil society and artisanal mining associations as active verification units within the 5H framework. By leveraging decentralized data networks to ensure that mineral rent is distributed directly and transparently to fund regional development, policymakers can counter bureaucratic corruption, stabilize localized investment risks, and ease the socio-environmental risks that have historically driven regional resource conflicts. In directing this technological/legal border, African policymakers must learn from regulatory/technological frameworks developed within European, American, and Asian systems. The use of digital product passports (in the EU), supply chain verification measures (applied in the USA), and automated sorting organizations (in Asian processing plants) – all offer useful ideas. This process of global benchmarking, however, must not be a simple imitation of foreign industrial models. Certainly, "one size does not fit all" holds here as well. Rather than importing complete hardware/software that limits developing economies through technology licensing agreements, software service fees, and patent rules, African countries should gradually adopt an adaptation strategy. The aim is to adopt the logic and engineering principles of global tracking networks while ensuring that the related software/expertise remains, where possible, open source and domestically controlled and managed. By harmonizing international standards with local realities while protecting autonomous data rights via non-restrictive intellectual property clauses, the continent can implement advanced technical solutions without being legally or financially constrained by foreign patent monopolies. This balanced approach to technology transfer transforms external technical knowledge from a potential trajectory of economic capture into an independent tool for domestic modernization, enabling African countries to participate equitably in global markets while maintaining full control over their technological future.

9. Conclusion

The interrelation among REEs extraction, advanced technologies, and autonomous state governance is the area in which African countries can successfully renegotiate their position within the global division of labor. As demonstrated by the case study focusing on the volatile operational landscape of the DRC and the different institutional frameworks of Namibia and Botswana, high mineralization grades lose their macroeconomic utility and business value when the state-administrative pillar fails to protect domestic assets from external use. Transforming hidden geological resources into development capital requires a dual approach that harmonizes local technological capacity with properly formed legal systems. The evolution of “mineral” governance up to now shows that integrating digital transparency with statutory local content requirements provides a practical framework for protecting resource autonomy. By replacing pro-investor bilateral investment treaties with coordinated regional frameworks that explicitly codify the autonomous right to regulate the subject environment, African countries can protect their midstream mineral processing industries from external litigation. Here we see that the path to a stable, equitable, and technologically advanced economy that disposes of CMs resources depends on coordinated regional cooperation rather than on technological optimism. There is an even more urgent need for more integrated strategies than ever before. Policy recommendations may be drawn from experiences from other parts of the world.

To make the most of the benefits of CMs mining, African countries must adopt integrated strategies that connect governance reforms, technological investment, and sustainable resource management. This includes establishing transparent regulatory frameworks, investing in education and research to build local expertise, and fostering public-private partnerships to attract foreign investment. The African Union’s Agenda 2063 emphasizes industrialization and technological autonomy, and provides a plan to harmonize mining policies with broader developmental goals. Also, international cooperation helps to address global supply chain instability and ensure that mineral resources on the continent contribute to equitable economic growth rather than exacerbating inequalities.

We may provide here a final comment. The interlinkages, or even interdependencies, among REEs, CMs, and mining governance in Africa are important to the continent's future. By addressing governance deficiencies, accepting technological innovation, and promoting inclusive policies, African countries can transform their mineral resources into a source of, hopefully, sustainable development. The way forward requires stakeholders to engage in collective action, strategic planning, and an ambition to balance economic growth with environmental/social responsibility.

References

to be added